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Thermochemical characterization of separated swine manure utilized as an available energy source and its preliminary benefit analysis in Taiwan

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Abstract

In the study, the thermochemical properties of dry swine manure have been analyzed using the standard methods. A large proportion of the carbon source in separated swine manure could be directly reused a potential energy source via thermochemical conversion processes. However, the content of nitrogen in the manure biomass was slightly high, suggesting that the emissions of acidic gases from biomass-to-heat facilities will be concerned. Further, two conceptual waste-to-energy systems have been addressed with regard to the energy conversion of dry swine manure. One is to adopt direct combustion for power generation in the combined heat & power system. Another is to use slow pyrolysis for producing biochar (solid fuel) and bio-oil (liquid fuel). Based on the activity

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data (5,400 thousand swine breeding heads), the calorific value (19.0 MJ/kg-db) and available emission factors, the preliminary analysis for energy, environmental and economic benefits from the utilization of separated swine manure as an energy source in Taiwan were calculated to be around 2.7 $\times 10^4$ TJ/year, 2.6 $\times 10^9$ kg CO_2/year and 1.4 $\times 10^8$ US$/year, respectively.

Keywords: Swine manure; Energy source; Waste-to-energy; Benefit analysis

1. Introduction

The conversion of biomass into renewable energy products (e. g., biofuls and electricity) has been extensively studied in recent years because it not only enhances fuel diversification but also mitigates the emissions of greenhouse gases (GHG) and air toxics (especially in sulfur oxides) as compared to fossil fuels like coal [1-3]. In this regard, biomass such as agricultural residue and animal waste are increasingly being recognized as valuable bioresources because they are renewable and abundant in carbon sources. The organic carbon can be further reused as green energy source, which is considered to be carbon-neutral because carbon dioxide (CO_2) photosynthesized by plants is released into the atmosphere as respired CO_2 [4]. More importantly, electricity and heat thus generated from agricultural residues through the combined heat and power (CHP) systems are offsetting those generated from fossil fuels with GHG emission reduction credits.

Animal manures often contain large amounts of moisture, and organic carbon and nitrogen. As a result, these poultry and livestock manures may pose a threat to the public health and environmental quality because of the potential contamination of surface water and ambient air via discharging and disposing off from farm sites, and odor releases. Traditionally, composting as a waste management option or recycling directly into farmland for animal manure as fertilizer supplement has widely adopted to promote plant growth in agronomy and horticulture [5]. It should be noted that a large proportion of the carbon and nitrogen in manure could be directly and indirectly returned as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from manure management systems [6]. Thus, there is increasing interest in livestock waste-to-energy systems via thermochemical conversion processes over the past decade [5, 7-10]. Meaningfully, dried manure waste can be processed directly via combustion and pyrolysis technologies to generate renewable products such as heat, power and biochar.

In Taiwan, domestic livestock feeding increased significantly in the past decades due to the policy promotion, technology improvement and market demand. A total population of swine was approximately 6.2 million heads in 2010 [11]. From the viewpoint of environmental loadings by swine, Taiwan ranked as the second place among the developed countries. Owing to the high content of organic matters in swine manure, the three-step piggery wastewater treatment system, which includes the units of screening and solid/liquid separation, anaerobic treatment (biogas generation), and activated sludge process, has been used extensively to treat the animal wastewater [12]. In the earlier work [13], using the characteristics of swine discharge, the swine population data surveyed by the Council of Agriculture (COA, Taiwan) and the emission factors recommended by the Intergovernmental Panel on Climate Change (IPCC), the maximum potential of methane generation in Taiwan could reach to around 400 Gg per year, which is equivalent to 2.2×10^4 TJ per year, indicating that the manure waste-to-energy should be abundant in Taiwan.

On the other hand, total domestic energy consumption in Taiwan summed up to 120.3 million kiloliters of oil equivalent (KLOE) in 2010, in contrast to 45.7 and 83.9 million KLOE in 1990 and 2000, respectively [14]. Meanwhile, the Taiwan's dependence on imported energy increased from 95.8% in 1990 to 99.4% in 2010. For this reason, the regulatory strategies and policies for resource recycling and thus promoting biomass energy in Taiwan have been active in providing some environmental and economic incentives [15]. Therefore, the aim of this study was to investigate the thermochemical properties affecting the utilization of separated swine manure (solid form) as a potential energy source in the conceptual waste-to-energy system designs. Furthermore, the energy, environmental and economical benefits of utilizing the separated manure waste in Taiwan as solid fuel and its potential pollutant emissions were discussed in the manuscript.

2. Materials and methods

2. 1. Materials

Separated swine manure solid was obtained from a screening and solid-liquid separation system treating flushed manure in a 500-head swine raising farm at the National Pingtung University of Science and Technology (Pingtung County, Taiwan). The manure sample was then dried by solar heat in an open space. Prior to the thermochemical analysis experiments, the dried sample was stored in the desiccator.

2. 2. Thermochemical characteristics analysis of separated swine manure

2. 2. 1. Ultimate analysis

The ultimate analyses provide the weight fractions of non-mineral major elements (i.e., carbon, hydrogen, nitrogen, oxygen, and sulfur) of organic sample, which can be used to determine combustion air requirements, to examine the extent of calorific value and the organic constituents in the sample, and to evaluate the possibility of hazardous air pollutants (i.e., nitrogen oxides and sulfur oxides). The organic elements analyses of the samples (2-3 mg) were conducted by using an elemental analyzer (Model: vario EL III; Elementar Co., Germany) with accuracy of 0.1% and precision of 0.2%. For each analysis, the standard samples (i.e., sulfanilic acid and benzoic acid) were first analyzed for checking the experimental error within ±0.1 % for C/H/N/S elements and O element, respectively.

2. 2. 2. Calorific value analysis

Due to the energy initially released by the condensation of water present in the biomass sample and the water product formed from the combustion reaction of hydrogen in the biomass, higher heating value (HHV), also called gross calorific value, was measured with an adiabatic oxygen bomb calorimeter (Model: CALORIMETER ASSY 6200; Parr Instrument Co., USA). In the experiments, about 0.3 grams of the dried swine manure were conducted in the calorimeter to measure the constant volume heat released by the combustion of the biomass fuel with oxygen. In order to evaluate the precision of measurement, the analysis was carried out in duplicate

3. Results and discussion

3. 1. Thermochemical characteristics of separated swine manure

In the study, the target biomass was swine solids, which are produced from the screening/solid-liquid separation system treating flushed swine manure. The data in Table 1 indicated the results of ultimate analysis and calorific value for the separated swine manure. Obviously, these results were comparable with those obtained from chemical analyses of separated swine manure in USA [16, 17]. It can be seen that the ultimate analyses revealed the high contents of carbon (C), hydrogen (H) and oxygen (O) in the manure biomass on a dry basis with the values of 42.25, 6.6% and 36.4% by mass, respectively, supporting that the dried swine manure was abundant in lignocellulosic contents. As a kind of biomass, the components of swine manure may include celluloses, hemicelluloses, lignins, lipids, proteins, ash and other constituents [18]. As compared to 75.3% C, 5.4% H and 15.6% O for coal [19], the manure biomass has much higher oxygen content and lower carbon content than coal while the hydrogen content in both biomass and coal is comparable.

Nitrogen oxides (NO_x, including NO and NO_2) belong to the most important gaseous pollutants from combustion processes. NO_x, which may cause ground-level photochemical smog, ozone formation and acid rain, is mostly formed by combining nitrogen in fuel and oxygen in air at a moderate temperature. Concerning the acidic elements in the manure biomass listed in Table 1, the nitrogen concentration (i.e., 4.0 % by mass) is relatively higher than those in the forestry and crop residues (i.e., < 1.0 % by mass) [20]. The separated swine manure had higher nitrogen content because it could contain higher protein content. As a result, fuel-bound nitrogen will contribute to the emissions of nitrogen oxides (NO_x) and traces of N_2O from biomass combustion facilities where they could have a need for installing NO_x control systems such as combustion modification and selective catalytic/noncatalytic reduction [21]. Just like common biomass fuels, their sulfur contents are very low compared with that of coal. It should be therefore expected that sulfur oxides (SOx) would not be emitted in a large extent due to extremely low concentrations of sulfur in the swine manure. It should be noted that these elemental compositions in the manure biomass are dependent on the dietary feeds, swine species and breeding regions. From the standpoint of conversion of biomass to energy and synfuels, the calorific value of biomass is a very important property. For the separated swine manure, its higher heating value (HHV) was 19.4 MJ/kg on a dry basis, which was slightly higher than 17.5 MJ/kg for cellulose [22]. This data was consistent with those in the elemental analyses as described above.

Table 1. Thermochemical characterization of separated swine manure solid

Property	This study	Other researches [a]
Ultimate analysis [b]		
Carbon (wt%)	42.2 ± 0.1 [d]	47.3 ± 0.3
Hydrogen (wt%)	6.6 ± 0.1	5.9 ± 0.1
Oxygen (wt%)	36.4 ± 0.1	20.1 ± 0.4
Nitrogen (wt%)	4.0 ± 0.1	4.58 ± 0.13
Sulfur (wt%)	0.0 ± 0.0	0.93 ± 0.04
HHV [b,c] (MJ/kg)	19.4 ± 0.5	19.5 ± 0.2

[a] Sources [16,17], [b] Dry basis, [c] Higher heating value.

[d] Average ± standard deviation (for two measurements).

3. 2. Concepts of swine manure–to-energy systems

From the standpoint of energy use of dried swine manure in replacement of coal, its heating value is the most important fuel property. From the data in Table 1, it can be seen that the calorific value (＞19 MJ/kg) of the manure waste was lower than those (i.e., about 28 MJ/kg) of fossil coal [22]. Due to the high organic content, large abundance and associated environmental concerns with current management methods (i.e., three-step manure treatment system), separated swine manures from screening and solid-liquid separation processes can be considered as a low-cost energy source in the direct combustion systems such as industrial boiler, municipal solid waste incinerator and coal-fired power plant.

In the work, swine manure waste-to-energy treatment concepts were addressed with considerations of combustion technology for the production of heat & power. The process system can have a more efficient nutrient recovery in concentrating the plant nutrients (e.g., P, K, Mg, and Cu) into the residual ash. Fig. 1 showed an applicable manure-to-energy flow diagram, including pretreatment, combustion, and energy recovery (combined heat & power) units. The dry waste-to-energy treatment system was simply described as follows:

(1) Pretreatment unit is intended to lower the moisture content of the collected manure (i.e., coarse residue and separated manure) using solar heating or recycled heat from combined heat & power (CHP) unit.

(2) Combustion unit may be an industrial boiler, or municipal solid waste incinerator via co-fired operation method. It meant that dried manure solid was reused as an auxiliary solid fuel. The combustion system using the dry manure feedstock produces high-temperature flue gas that is further pumped into CHP system for recovering process waste heat.

(3) Energy recovery (i.e., CHP) unit is the simultaneous production of electricity and heat in one single process for dual output streams so as to maximize its thermal efficiency of up to 70% or more. The flue gas from the CHP system will be further treated by the advanced air pollution control systems for removing acidic gases (e.g., nitrogen oxides) and particulates.

(4) Another manure waste-to-energy concept was depicted in Fig. 2. This system focused on the slow pyrolysis for converting swine manure into biochar, which can provide farmers with potential environmental and economic benefits due to carbon sequestration and biochar ("green coal") energy production. The resulting biochar can be applicable to the following cases [9]:

   (1) It can be used an auxiliary feedstock for existing CHP plants such as coal combustion power plant and MSW incineration plant.

   (2) It can be applied to farmland as a soil amendment to improve fertility due to its pore properties and abundance in the mineral nutrients.

   (3) It can become a precursor source of activated carbon or activated char, which had greater adsorption capacity as compared to commercial granular activated carbon.

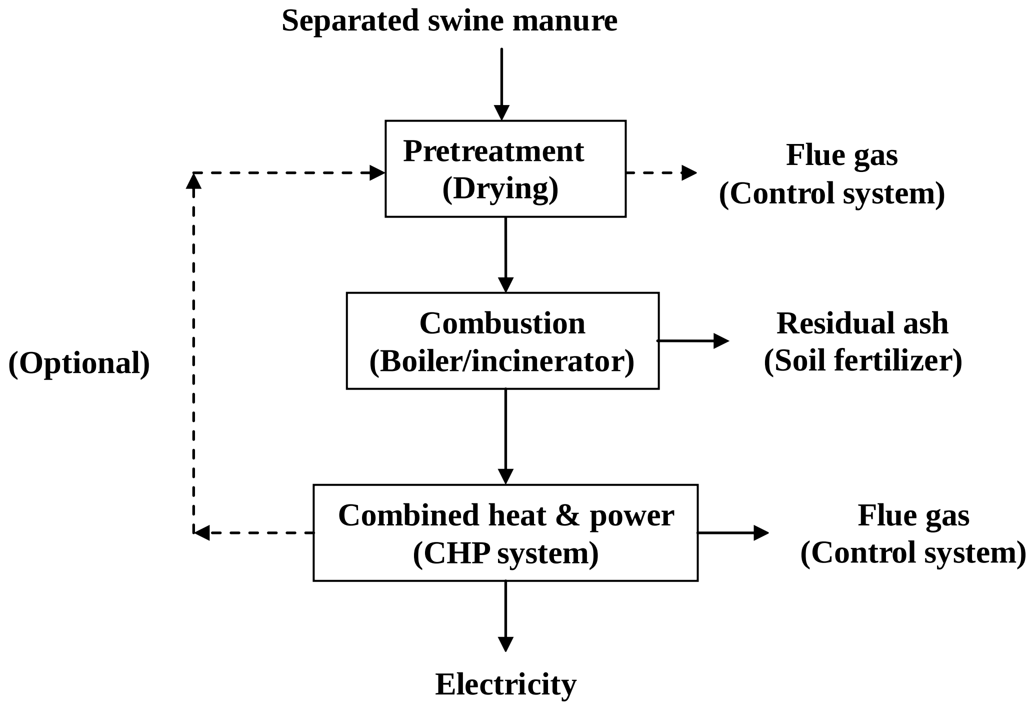

Fig. 1. Conceptual flowchart of swine manure-to-energy system using combined heat & power.

3. 3. Potentials for energy, environmental and economical benefits of utilizing swine manure

Table 2 listed the updated data on swine farms in Taiwan [11], showing that the large quantities of manure waste (including feces and urine) will be thus generated from the swine farms. In the past, the biogas from swine manure management was viewed as an odorous nuisance, one of major GHGs (especially in methane) emission sources, and even became a safety hazard in Taiwan. In the study, the separated swine manure provides a unique green energy as auxiliary fuel. With respect to the benefits from the utilization of separated swine manure as an energy source and its equivalent oil output, it was first converted to annual energy activity (output) unit (i.e., TJ or GJ) based on the following data:

- Swine breeding population over 500 heads on farm: around 5,400 thousand heads (Table 2).
- Swine emission factor: 260 kg head $^{-1}$ yr $^{-1}$ (dry basis) [23].
- Calorific value for separated swine manure: 19.0 MJ/kg-db.
- Power efficiency in Taiwan's MSW incinerator: 20% [15].
- Heating value for crude petroleum: 6 GJ/barrel.

Energy output (TJ) = Amount (head) × Manure emission factor (kg-db/head·yr) × Heating value (MJ/kg-db)

= 5,400,000 head × 260 kg-db/head·yr × 19.0 MJ/kg-db

$\fallingdotseq$ 2.7×10^{7} GJ/yr
$\fallingdotseq$ 2.7×10^{4} TJ/yr
$\fallingdotseq$ 1.5×10^{9} kW-h/yr
$\fallingdotseq$ 4.5×10^{6} barrels oil equivalent/yr

Table 2. Updated statistics on swine farms in Taiwan[a]

Swine farm scale (Head)	Numbers of swine farm		Heads on farm	
＜ 99	3,789	(38.5%)	107,814	(1.7%)
100 ~ 199	1,183	(12.0%)	172,981	(2.8%)
200 ~ 299	638	(6.5%)	155,242	(2.5%)
300 ~ 499	859	(8.7%)	342,346	(5.5%)
500 ~ 999	1,656	(16.8%)	1,225,426	(19.8%)
1,000 ~ 1,999	1,191	(12.1%)	1,646,262	(26.6%)
2,000 ~ 4,999	406	(4.2%)	1,193,108	(19.3%)
＞ 5,000	120	(1.2%)	1,352,042	(21.8%)
Total	9,842	(100.0%)	6,195,221	(100.0%)

[a]Surveyed by the official agency on May 2011 [11].

Concerning the benefits of mitigating CO_2 emissions to the environment, it was assumed that separated swine manure substitutes for fuel coals when burned in the industrial processes for energy use. Further, a simple method (Tier 1 method) adopted by the Intergovernmental Panel on Climate Change (IPCC) was used in the present work to estimate equivalent CO_2 emissions mitigation from the utilization of separated swine manure as energy source [24-27]. According to the IPCC methodology, this method is based on the consumed quantities of manure-based fuel and average default emission factor (DEF). Therefore, the anthropogenic CO_2 emissions from the combustion activity of separated swine manure for energy use were calculated by multiplying levels of activity (calorific basis in TJ) with default emission factor (DEF in kg CO_2/TJ). The default value for coal has been estimated to be 95,000 kg CO_2/TJ by the IPCC. Therefore, the equivalent mitigation of CO_2 (in kg) derived from the energy utilization of separated swine manure was thus estimated in 2010 as follows:

Equivalent mitigation of CO_2 (kg) = Energy output (TJ) × DEF-$_{coal}$ (kg CO_2/TJ)
$\fallingdotseq$ 2.7×10^{4} TJ × 95,000 kg CO_2/TJ
$\fallingdotseq$ 2.6×10^{9} kg

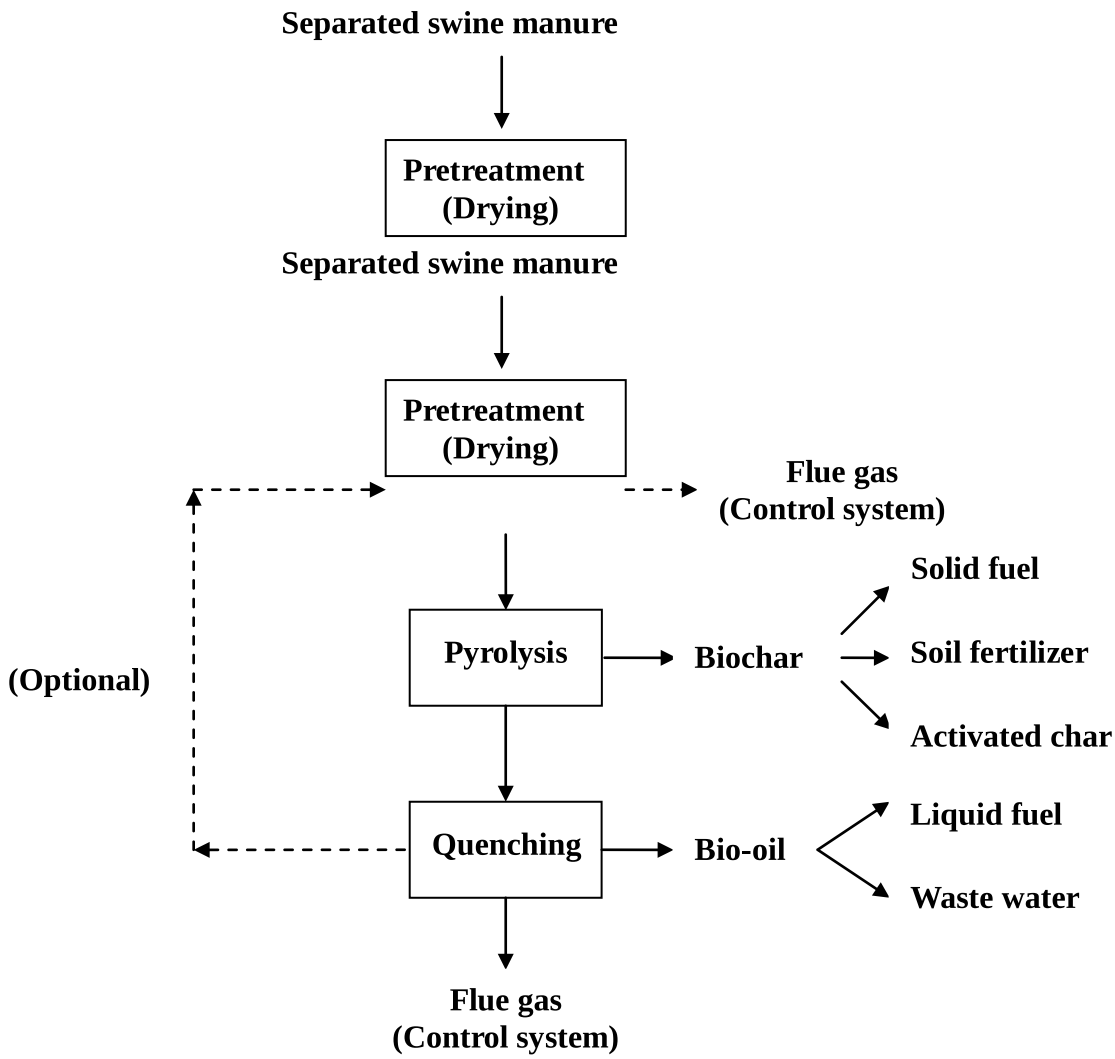

Fig. 2. Conceptual flowchart of swine manure-to-energy system using slow pyrolysis.

In order to encourage the energy use from the cogeneration (CHP or power generation) in Taiwan, current promotion regulations on waste-to-energy utilization are mainly based on the Renewable Energy Development Act passed in Jun. 2009. The power sector may ask the local vertical integrated utilities to purchase its surplus electricity at a rational fee. The current rate of purchasing electricity energy is close to 2.69 NT$//kWh, or 0.093 US$ /kWh. As a result, the economic benefits of generating electricity from co-combusting dried swine manure with coal or municipal solid waste can be further estimated as follows:

$$\begin{aligned} \text{Economic gain (US\$)} &= \text{Power (kW-h)} \times \text{Purchase fee (US\$ /kWh)} \\ &= 1.5 \times 10^{9} \text{ kW-h/yr} \times 0.093 \text{ US\$ /kW-h} \\ &\fallingdotseq 1.4 \times 10^{8} \text{ US\$/yr} \end{aligned}$$

4. Conclusions

1. The separated swine manure obviously comprised a large percentage of carbon content at about 42 wt%, showing that it is abundant in lignocellulosic constituents with high heating value (i.e., 19.0 MJ/kg-db).
2. The nitrogen content in the separated swine manure was about 4.0 % by dry mass because it could contain high protein content. Therefore, the biomass-to-heat facilities could have a need for installing nitrogen oxides (NOx) control systems during thermochemical conversion.
3. Integrating thermochemical technologies into separated swine manure treatment, there are two conceptual waste-to-energy flowcharts addressed in the work. One is to adopt direct combustion for power generation in the CHP system. Another is to use slow pyrolysis for producing biochar (solid fuel) and bio-oil (liquid fuel).
4. The results of a preliminary benefit analysis showed that a total energy output of 2.7×10^4 TJ/year can be gained on a basis of swine breeding of 5,400 thousand heads in Taiwan, which is equivalent to the environmental and economic gains of 2.6×10^9 kg CO_2 mitigation/year and 1.4×10^8 US$/year, respectively.

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