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EVALUATION AND ANALYSIS OF THE SUSTAINABLE WASTE-TO-ENERGY SYSTEM PERFORMANCE FOR THE POULTRY FARM

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ABSTRACT

Poultry litter is one type of biomass and waste generated from the poultry farms. However, excess land application of poultry litter caused eutrophication problems of surface waters coming from the watershed and destroyed the aquatic ecology. Co-combustion of poultry litter and coal were widely studied in fluidized bed combustor as an alternative disposal method during last two decades. However, there are severe environmental problems (i.e., gaseous emissions) and public health impact associated with the poultry litter and coal co-combustion process. In this study, poultry litter and natural gas co-combustion was investigated in the lab-scale waste-to-energy system to provide a sustainable and cost-effective disposal route for poultry farms. This waste-to-energy system integrates the Stirling Engine (SE), Shell-Tube Heat Exchanger (STHE) and the lab-scale Swirling Fluidized Bed Combustor (SFBC) with other systems (e.g., cyclone, air supply system, fuel feeding system). Measures of heat transfer effect, electricity output and gas emissions levels were used to evaluate the lab-scale waste-to-energy system performance. Results indicated that lab-scale waste-to-energy system can produce electricity (close to 1 kW) and hot water (57.2°C) while reducing NOx and SO2 emissions during the poultry litter and natural gas co-combustion process. In addition, energy flow analysis indicated that SE and STHE system might use 14.7% and 21.0% of total energy input in fuels, respectively, to generate useful energy. In addition, a sustainable life cycle of poultry litter was built and suggested to process poultry wastes in the poultry farms.

Keywords: sustainable energy systems, electricity, hot water, poultry litter, emissions

1. INTRODUCTION

Fossil fuel depletion and adverse environmental impacts (i.e., greenhouse gas emissions causing climate change) are stimulated to seek renewable energy sources that can replace fossil fuels during energy production process (Patel et al., 2016). Among all the renewable sources, there is an increasing interest in biomass utilization for energy production due to the benefits of CO2 neutral effect, and large availability and low cost of biomass fuels all over the world. Biomass is the name given to any organic matter which is derived from plants and animals (Saidur et al., 2011). Biomass energy sources are classified into five categories including woody biomass, agricultural biomass, aquatic biomass, animal and human waste, and industrial waste (Patel et al., 2016; Tripathi et al., 2016). Poultry litter is one type of biomass and animal waste during the poultry farming process. Using a litter production of 995 kg per 1,000 birds, a broiler house holds 23,400 birds/flock and produces 5.5 flocks/year

(6-7 week/flock, 5-6 flock/year) will produce about 128 tons/year of poultry litter (Chastain et al., 2012). Excluding states producing less than 500,000 broilers, poultry litter production were estimated about 10.8 million tons in 2008 and 10.3 million tons in 2009 from top poultry production states in U.S. (Perera et al., 2010). In most cases, the poultry litter is spread on cropland as an organic fertilizer due to its rich nutrients of nitrogen, phosphorous, potassium, sulfur and calcium (Henihan et al., 2003; Li et al., 2008). However, over-application of poultry litter to the soil can results in enrichment of water-soluble nutrient and eutrophication of water sources. When eutrophication occurs, algae living within the water will reproduce excessively under aerobic metabolism, effectively using large quantities of the dissolved oxygen in water, creating dead zones and destroying the aquatic ecology (Jia and Anthony, 2011). Eutrophication further degrades ground water quality, which is threating to human health. Due to excess production and associated problems of land application, it has stimulated interest into sustainable disposal options for poultry litter.

Kelleher et al. (2002) introduced an excellent review of alternative poultry litter disposal methods, include the compositing (or aerobic digestion), anaerobic digestion and combustion. Gasification is another main alternative disposal method of poultry litter (Topal et al., 2012). Among four main alternative disposal methods, one of the most widely used methods is combustion. Qian et al. (2018) collected higher heating values of the existing 49 poultry littler samples and found that higher heating value of poultry litter was between 6.78 and 27.90 MJ/kg with an average of 14.08 MJ/kg. With relative high energy content, combustion is able to provide a sustainable, cost-effective, environmentally benign disposal route for the poultry litter while providing for both space heating of poultry houses and large-scale schemes involving combined heat and power production (Li et al., 2008; Topal et al., 2012). However, there can be problems on maintaining steady and complete combustion of poultry litter due to the high moisture and ash contents, as well as low heating value of the poultry litter (Kelleher et al., 2002; Li et al., 2008). Therefore, co-combustion of poultry litter with fossil fuels (i.e., coal) has been considered to increase the heating value and solve technical challenges during the combustion process. Table 1 provides summary and major findings of poultry wastes and coal combustion studies in the last two decades. However, there are severe environmental problems (i.e., gaseous emissions) and public health impact associated with the poultry litter and coal co-combustion process.

Table 1: Summary of Co-combustion Studies of Poultry Litter and Coal

Fuel Type	Major Findings	References
poultry litter + peat	Secondary air in two stages reduced NO_x and CO emission.	Abelha et al., 2003
chicken litter + peat	CO and volatile organic compound decreased with primary air/secondary air is 0.4.	Henihan et al., 2003
chicken litter + coal	Increasing of chicken litter mass fraction in coal increased CO.	Li et al., 2008
poultry wastes + coal	Excess air had a remarkable effect on CO and CH_4.	Topal et al., 2012

Co-combustion of poultry litter with natural gas has following advantages: (1) reduce gas emissions since natural gas is cleaner than coal; (2) reduce transportation cost because natural gas is available in most poultry farms; (3) reduction of the anaerobic release of CH4, NH3, H2S, volatile organic acids and other chemicals since the storage time is reduced (Zhu et al., 2005). Stirling Engine (SE) is an external combustion engine and used pressurized working fluids (i.e., helium) to convert residual heat energy into combined heat and electricity (CHP) (Thombare and Verma, 2008). In the previous studies, SE was observed to have the following advantages: smoothness, reliability, flexible external heat source, and high thermodynamic efficiency (Miccio, 2013). In addition, SE is capable of being manufactured in a low-power range of 1-10 kWe that is suitable for residential use. As a result, SE has attracted increasing attention as an alternative option for micro-CHP systems (Corria et al., 2006; Miccio, 2013). Recently, SE has been integrated into fluidized bed combustor (Miccio, 2013), wood pellet burners (Cardozo et al., 2014), and combustion chambers (Damirchi et al., 2016) to produce heat with power for residential usage. Heat exchangers are used for transferring thermal energy between two or more fluids, or solid particulates and a fluid, at different temperature in thermal contact (Bichkar et al., 2018). Different types of heat exchanger are used worldwide that differ from each other because of their specific requirements, such as the double pipe, shell and tube, plate fin, plate and shell, pillow plate, etc. (Salahuddin et al., 2015). Shell and tube heat exchanger (STHE) are the one of the most common type of exchangers widely used in the industrial processes (Salahuddin et al., 2015; Zhang et al., 2009; Duan et al., 2016). According to Master et al. (2003), more than 35-30% of heat exchanger are the STHE type due to their robust geometry construction, easy maintenance and possible upgrades. In addition, STHEs are used in all sorts of industries because they have much lower production cost, can be easily cleaned and are considered more flexible with adaptability compared with other heat exchanger. There are limited studies on the integration of SE and STHE with swirling fluidized bed combustor during the poultry litter combustion process.

The objective of this study is to develop and evaluate the sustainable lab-scale waste-to-energy system. SE and STHE were integrated into the advanced lab-scale swirling fluidized bed combustor to generate useful energy, including electricity and hot water during the poultry litter and natural gas co-combustion process. Water temperatures, heat transfer effect, logarithmic mean temperature difference, gaseous emissions, and quantity of energy flow during the co-combustion process of poultry litter and natural gas were investigated and evaluated. In addition, the sustainable life cycle of poultry litter was designed and applied for this study.

2. METHODOLOGY

2.1 Materials

Poultry litter samples were collected from the poultry farm sheds (Bethel Farms, Salisbury, MD, USA). Then, poultry litter samples were tightly sealed, transported to laboratory, and stored in the room temperature condition. Before combustion testing, poultry litter samples were pre-sized by using sizer and crushed into smaller size while removing bulk samples, dead birds, and stones to prevent clogging and damaging of fuel feeder auger. Table 1 summarize the proximate analysis results and analysis methods of each composition for the poultry litter sample. Heating value of poultry litter was used to calculate the heat transfer and energy flow in the later section.

Table 2: Proximate Analysis of Poultry Litter Sample

Composition (wt. %)	As Received	Dry Basis
Moisture (D3302/D3173)	21.20	N/A
Volatile Matter (D3175)	50.40	63.96
Fixed Carbon (diff., Calculated)	9.44	11.98
Ash (D3174)	18.96	24.06
Heating Value (D5865/5864)	11.30MJ/kg	14.34MJ/kg

2.2 Experimental Setup

As shown in Figure 1, the sustainable lab-scale waste-to-energy system was developed. This system consists of the advanced lab-scale swirling fluidized bed combustor, air supply system, fuel feeding system, SE, STHE, cyclone, and instrumentations. Free-piston SE was acquired from Microgen Engine Corporation in the Netherlands and integrated into the cylinder combustor at height of 120.0 mm above the primary air distributor. The lab-scale STHE was designed and fabricated along with six tubes, five segmental baffles and multiple tube connections and one shell. A cylinder carbon steel pipe was used as shell to cover tubes, baffles and connection parts. The fabricated lab-scale STHE system was inserted between combustion chamber and cyclone to capture residual heat from the hot flue gas and generate hot water during poultry litter combustion process. Then, hot water was sent to the radiators inside the mobile mini trailer house and returned to the lab-scale STHE system. During the co-combustion process, poultry litter and natural gas were supplied into the combustion chamber through the double concentric anger-based volumetric feeder (Acrison, USA) and natural gas pipe (Constellation, USA). Primary air and secondary air were supplied into the chamber via blowers. K-type thermocouple (OMEGA Engineering, USA), emission analyser (Enerac, USA) and water flow rate sensors (Ifm electronic, Germany) were used to measure inlet/outlet temperatures, gaseous emissions (e.g., CO, NOx, SO2), and water inlet/outlet flow rates along with temperatures. Heat transfer and logarithmic mean temperature were calculated using equations in the Section 2.3.

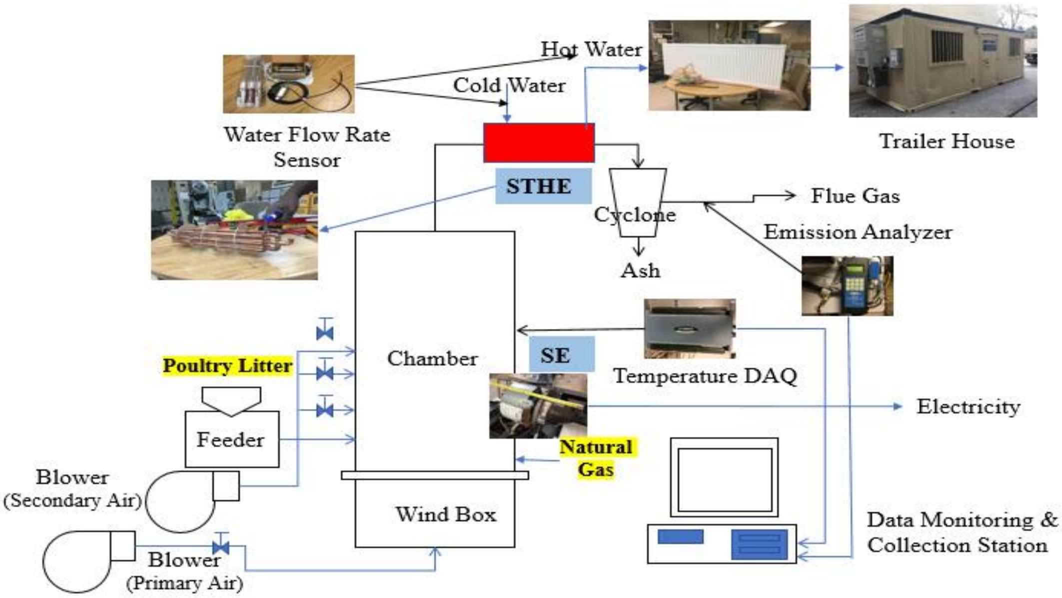

Figure 1. Schematic Diagram of Experiment Setup

2.3 Equations

Heat transfer is the measurement of the thermal energy transferred from one point to another and determined by specific heat, mass, and temperature change. The heat content, Q, is calculated as follows:

$$Q = m \times c_p \times \Delta T \quad (1)$$

where Q = heat content of medium, in Joules; m = mass, in kg; c_p = specific heat, in J/g°C; and ΔT = change in temperature, in °C. Specific heat of flue gas and water were assumed as 2.01 J/g°C and 4.186 J/g°C, respectively. Heat capture efficiency was calculated by dividing of flue gas heat content by water heat content.

The logarithmic mean temperature difference (LMTD) is determined from two temperature differences Δt_1 and Δt_2 at each end of the heat exchanger.

$$\text{LMTD} = \frac{\Delta t_1 - \Delta t_2}{\ln\frac{\Delta t_1}{\Delta t_2}} \qquad \Delta t_1 = T_1 - t_2 \quad \Delta t_2 = T_2 - t_1 \quad (2)$$

where T_1 = shell-side inlet temperature (°C), T_2 = shell-side outlet temperature (°C), t_1 = tube-side inlet temperature (°C) and t_2 = tube-side outlet temperature (°C).

3. RESULTS AND DISCUSSION

Performance of the lab-scale STHE system was evaluated under the various water flow rates (e.g., 1.89×10-5 m3/s, 2.90×10-5 m3/s, 3.78×10-5 m3/s, 5.05×10-5 m3/s, 6.31×10-5 m3/s) and fuel combinations (e.g., 2.52×10-4 m3/s natural gas, 2.83×10-4 m3/s natural gas, 2.83×10-4 m3/s natural gas and 7.08 kg/hr poultry litter). As shown in Figure 2, results indicated that the lab-scale STHE system can provide hot water (up to 42.8 °C from 20.6°C cold water) under various water flow rate and fuel combinations. It is obvious that hot water outlet temperature of the STHE system was decreased by increasing water flow rates from 1.89×10-5 m3/s to 6.31×10-5 m3/s under different fuel combinations. In addition, co-combustion of poultry litter and natural gas has relatively higher outlet temperature than the natural gas combustion because the total heat input were increased by adding the poultry litter into natural gas. System performance among the case of 113.6 L water tank, 37.8 L water tank, and no water tank between the lab-scale STHE system and mobile mini trailer were compared. Results indicated that the lab-scale STHE system without water tank is able to provide highest hot water (around 58.3 °C, from 20.6°C) than the other two cases with water tanks while increased room temperature of mobile trailer house from 16.7°C to 33.3°C within 120 minutes combustion process (outside temperature 13.9 °C).

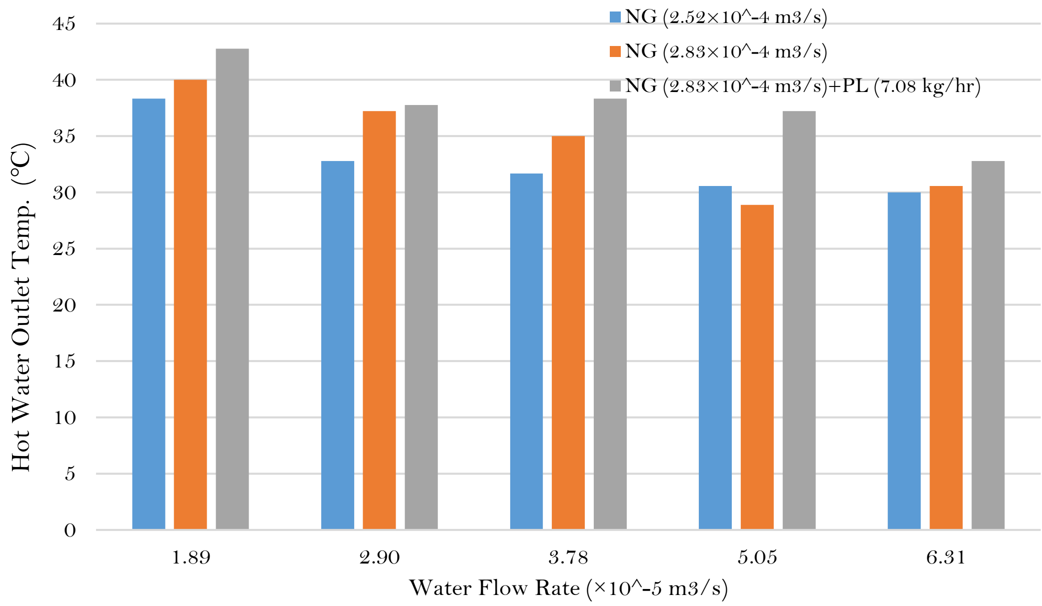

Figure 2: Hot Water Outlet Temperature of the STHE System

Table 3: Gas Emissions from Combustion Process

Fuel Combinations	CO (ppm)	NO_x (ppm)	SO_2 (ppm)
NG (2.52×10^{-4} m^3/s)	80-100	28-50	10-22
NG (2.83×10^{-4} m^3/s)	126-240	32-60	15-30
NG (2.83×10^{-4} m^3/s) + PL (7.08 kg/hr)	300-480	10-35	8-15

Gaseous emission results under different fuel combinations were collected and summarized in Table 3. Results indicated that average emission of NOx were decreased from the 39 ppm to 22.5ppm. The possible reduction of NOx can be explained by the combination effect of decreased freeboard temperature to reduce small amount of thermal NOx formation and increased species, such as char and CO in the fuel bed region to form a reducing environment. Therefore, NO can be reduced by the char suspended within the freeboard, i.e., $2NO + 2C \rightarrow N_2 + CO$. In addition, NOx reduction appears when a large amount of CO emissions splashed and entrained into the freeboard and interact with NO emission ($2NO+2CO \rightarrow 2CO_2+N_2$). There is small amount of SO_2 emission during the natural gas combustion because the sulphur containing mercaptan may be existed in natural gas for the leakage detection and lead to small amount of SO_2 emissions. However, it was observed that SO_2 emission decreased with an addition of poultry litter into natural gas. Two possible reasons may cause this fact. First, poultry litter ash has strong retention for sulphur due to relatively high Ca and Mg present in poultry ash. Second, high volatile in poultry litter creates strong reducing atmosphere above the bed that inhibits the oxidation of H_2S to SO_2 (Li et al., 2008).

In order to increase the water outlet temperature of the STHE system, poultry litter was fed at rate of 7.07 kg/hr and natural gas was increased to 2.83×10^{-4} m3/s. LMTD under different flue gas and water temperature changes were calculated by using the equation (2) and used to evaluate the heat transfer of the STHE system. Results indicated that the LTMD was increased from 409.0 °C to 482.2 °C when the flue gas inlet was increased from 588.4°C to 701.2°C. This trend infer that the larger flue gas inlet temperature will increase LMTD and more heat is transferred from flue gas in the shell to water in the twisted tubes. Therefore, co-combustion of poultry litter and natural is preferred to increase total heat output and improve the heat transfer process of STHE system as well as the overall efficiency of the waste-to-energy system.

Table 4: LMTD Summary of the STHE System

Flue Gas Inlet (T_1, °C)	Flue Gas Outlet (T_2, °C)	Water Inlet (t_1, °C)	Water Outlet (t_2, °C)	LMTD (°C)
588.4	321.5	27.2	38.3	409.0
618.8	357.6	31.7	44.4	438.5
658.4	372.9	38.3	51.1	457.8
691.2	387.8	40.6	53.9	477.7
701.2	399.2	48.3	57.2	482.7

As shown in the Figure 3, energy flow during the poultry litter and natural gas co-combustion process was calculated and analysed. Heating value of poultry litter and natural gas are 11.30MJ/kg and 46.52MJ/kg, respectively. Density of natural gas (0.8 kg/m3) and air (1.225 kg/ m3) were used to calculate the total mass of fuels and air. Total energy generated from the combustion chamber was divided into the flue gas stream (60.3%), SE (14.7%) and heat loss in chamber surface (25.0%). Total heat of 18.0MJ/hr was required to produce electricity (about 1 kW) during the poultry litter co-combustion process. Then, the STHE system was used to collect 21.0 % of residual heat from the flue gas stream to produce hot water (about 57.2 °C). There was 57.2 % of residual heat from the flue gas stream was sent to the chimney. Thus, additional heat transfer devices can be used to collect this waste heat.

Based on the farm visits, farmer interviews, literature reviews and lab-scale implementations, a sustainable life cycle of the poultry litter was developed. As shown in the Figure 4, poultry litter originally produced from poultry house and cleaned out to the poultry farm sheds for short period storage before utilization and conversion process. Large quantity and volume of poultry litter caused high transportation cost along with severe environmental problems during the land application. This study found that poultry litter could be burned in the combustor to produce useful energy (electricity and hot water) and biochar with lower gaseous emissions. Reduced volume of biochar with high nutrient concentration may help to reduce transportation cost and assist plant growth on cropland.

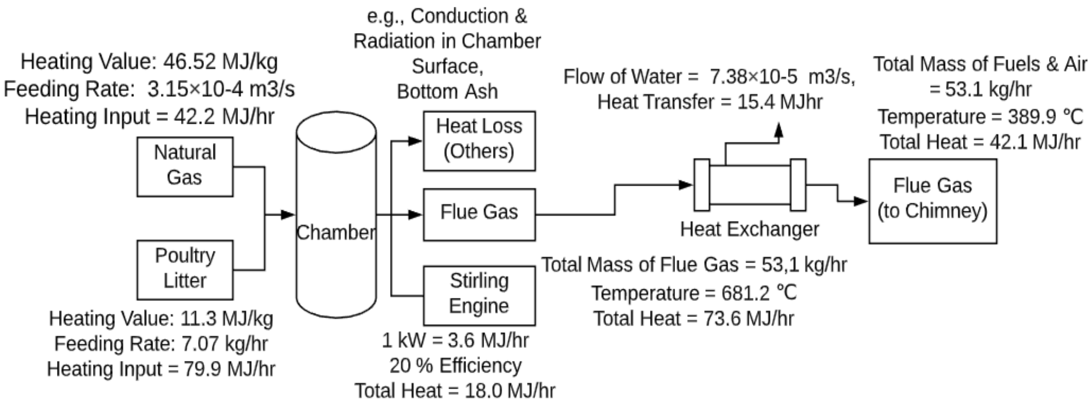

Figure 3. Energy Flow Analysis of Poultry Litter and Natural Co-combustion Process

The feeding materials (i.e., corn) will be returned into the poultry house as feeding materials of chickens. SE could be used to produce on-farm electricity and compensate partial electricity consumption on the ventilation fan and lighting. In addition, STHE system can be used to produce hot water, which will be sent to the radiators in the poultry house for space heating. Conventional propane-based space heating systems produced a high concentration of $CO2$ and moisture as well as room-relative humidity (Smith et al., 2016). Increased air moisture and room-relative humidity content can react with poultry litter, resulting in increased ammonia production and potentially negative effects on both bird health and welfare (Estevez, 2002). High concentrations of ammonia (above 70 ppm) can reduce growth performance, which result in lower body weight gain and higher feed conversion ratios (Yi et al., 2016). Thus, using poultry litter as a source of space heating can reduce propane consumption and address the run-off issues while providing a drier heat to mitigate ammonia concentration in poultry house. It is believed to save energy cost and also provide effective yield of chickens based on the sustainable waste-to-energy system in the poultry farm.

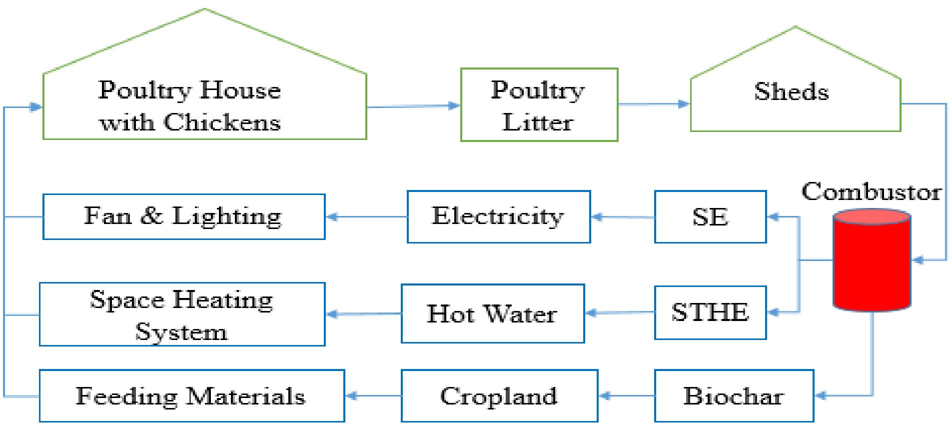

Figure 4. Sustainable Life Cycle of Poultry Litter in Poultry Farm

4. CONCLUSIONS

The sustainable waste-to-energy system was developed by integration of the existing lab-scale swirling fluidized bed combustor, SE and innovative STHE. System performance, such as electricity output, hot water temperature and gaseous emissions was investigated and evaluated under various operating conditions. Results indicated that electricity from SE was close to 1 kW and hot water from was close to 58.3 °C in the lab-scale sustainable waste-to-energy system during the poultry litter and natural gas co-combustion. Both SO2 and NOx emissions were decreased by addition of poultry litter in the natural gas combustion. It was found that co-combustion of poultry litter and natural gas was increased total heat output and flue gas inlet temperature. This inlet temperature increased LMTD and more heat was transferred from flue gas in the shell to water in the twisted tubes. In addition, a sustainable life cycle of poultry litter in poultry farm was designed and applied for this study. It is believed to reduce environmental problems of poultry litter and save energy cost by using the sustainable waste-to-energy system in poultry farm.

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