INVESTIGATION OF POULTRY LITTER CONVERSION INTO USEFUL ENERGY RESOURCES USING FAST PYROLYSIS

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ABSTRACT: The present study explored a thermochemical treatment method as an alternative approach to process animal feedlot (poultry litter). Fast pyrolysis of poultry litter experiments was conducted using a Pyroprobe 5200 reactor in the temperature range of 400-600 °C. The influence of reactor temperature on the yield of pyrolytic gases, condensate (bio-oil) and biochar yield was reported along with the mass balance. The biochar yield decreased consistently with an increase in temperature (from ~62 wt.% at 400 °C to ~ 40 wt.% at 600 °C), whereas the maximum bio-oil yield 23.2 wt.% was reported at 600 °C. The evolved pyrolytic gases were dominated by CO and CO_2 and have shown an increasing trend with the temperature. Evolved gases were measured by a micro-gas Chromatograph. The yield of the liquid fraction (bio-oil) and biochar were quantified for the mass balance analysis. The yield of liquid and biochar are in agreement with previous work.
Keywords: thermochemical conversion, fast pyrolysis, animal residue, pyrolysis oil, biochar.

1 INTRODUCTION

Following the mad cow disease, poultry meat dominated the meat market share over beef. DEFRA (Department for Environment, Food and Rural Affair**s** of UK) reported that the production of poultry meat increased by 4 percent from 2012 to 2015 [1]. To cope with the increased demand for poultry meat, intensive poultry farming has become a necessity. With intensive poultry farming, the increased demand is met by shortening the batch period time. However, this creates a significant waste disposal problem originating from poultry farms and its impact on the environment [2]. The United Nations Food and Agriculture Organisation estimated that emissions from global livestock production represent 15% of total anthropogenic greenhouse gas (GHG) emissions (amounting to 7.1 Gigatonnes of CO_2 equivalent per year) [3]. The GHG emission arising from animal feedlot can be reduced by employing bioenergy conversion technologies for such feedstock which can increase the share of renewable energy production.

Since animal manure accumulation leads to a massive disposal problem, the development of new and innovative treatment technologies is imperative in order to avoid adverse environmental impact [3]. At the farm level opportunities have been identified to use the animal waste for heat and power generation through thermochemical conversion and the subsequent utilisation of the produced biochar as an organic fertiliser in the agriculture systems [4,5].

The bedding material used in a poultry farm blended with the manure makes the poultry litter a more suitable energy feedstock for an on-farm heat and power production unit [6]. The European Parliament has adopted the animal by-product Regulation (1069/2009/EU) supplemented by the new Regulation (142/2011/EU), paving the way for processing animal by-products locally for nutrient recycling while producing bioenergy. The conversion of chicken litter into a fuel can be divided into two main groups. (i) bio-chemical conversion and (ii) thermochemical conversion. Microbial digestion is considered as biochemical conversion, while combustion, gasification and pyrolysis belong to the category of thermochemical conversion processes.

Poultry litter consists of manure and bedding material and it generally contains a high ash content which could cause ash sintering in thermochemical conversion processes at high temperatures due to the presence of phosphorous, potassium, sodium and other alkali metals in the ash in combination with chlorine [7]. Moreover, the by-products (char and ash) originating from poultry litter thermochemical conversion can be used as fertilisers in agriculture systems due to the significant presence of primary nutrients (N-P-K) [8].

Pyrolysis technology is regarded to have technical and environmental advantages over direct incineration, including lower volumes of product gas and char/ash generation with better properties for further use in agriculture and avoiding landfill. Pyrolysis processes can be broadly divided into two types: slow and fast pyrolysis. Slow pyrolysis occurs at low temperature and long residence time with char as the main product. In contrast, fast pyrolysis occurs at moderate to high temperatures with a very short vapour residence which aims to maximise the fraction of liquid products. In fast pyrolysis, the liquid (bio-oil) phase carries the majority of the energy or higher heating value (HHV) and offers higher flexibility for storage, upgrading and transportation [9]. In particular, for poultry litter, if it is subjected to slow pyrolysis it can produce a high-quality oil improver. It has also been estimated that the calorific value of evolved pyrolysis syngas can sustain the energy demand for continuous operation of the process [10].

This opens the prospect of slow pyrolysis as a disinfection treatment of bio-hazardous materials as well as waste-to-energy utilisation of chicken litter [11,12].

Recently, fast pyrolysis of poultry litter was investigated experimentally in a bubbling fluidised bed reactor. The maximum reported bio-oil yield was 27.62 wt.% but in contrast to woody biomass, the biochar yield was comparatively higher than the bio-oil due to its high ash content [5].

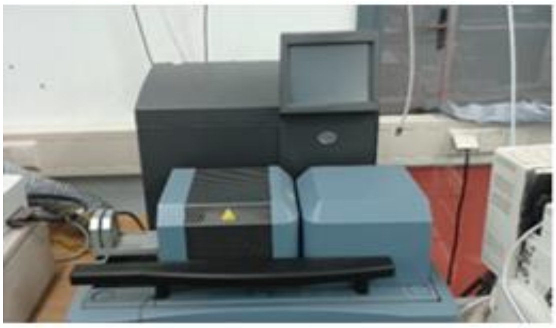
This paper focuses on the fast pyrolysis of poultry litter and investigates the influence of temperature on the evolution of pyrolysis gases and their composition, as well as the liquid and biochar yields using a pyroprobe reactor. A schematic diagram of the pyroprobe reactor is given in Fig. 2

2 MATERIALS AND METHODS

2.1 Feedstock and Thermogravimetric Analysis (TGA)

Poultry litter is a heterogeneous feedstock, therefore the chemical composition of the poultry litter is dependent on the feeding, bedding material, batch cycle and moisture content. The moisture content in poultry litter can vary between 20 and 26 wt.% [13]. Since pyrolysis is an endothermic process, high moisture content will increase the energy consumption resulting in low-quality bio-oil (higher water content). Poultry litter used in this study was collected from a Finnish poultry farm where peat was used as the bedding material. The feedstock was supplied by Biolan Finland in a pelletised form with a size of 0.50 mm diameter and 0.98 mm length. For all the experiments, poultry litter was ground and sieved into fine particles with a size of less than 100μm (Fig.1a).

(a)



(b)

Figure 1: (a) Pelleted and ground poultry litter (b) Thermogravimetric analyser (TGA)

The feedstock was characterised by its proximate and ultimate analysis while the calorific value was determined by bomb calorimeter. Moisture content was determined according to BS EN 14774-3:2009 (105±2 °C), whereas ash and volatile matter were measured according to BS EN 14775:2009 (550±10 °C) and BS EN 15148:2009 (900±10 °C) respectively. The chlorine content in poultry litter was measured according to the CEN/TS 15408:2006 protocol. The ultimate and proximate analysis along with the heating value of the poultry litter is presented in Table I.

Table I: Proximate and ultimate analyses and calorific value of poultry litter

Proximate analysis (wt.%)	
Moisture content (ar)	8.4
Ash content (db)	14.3
Volatile matter (db)	72.8
Fixed carbon* (db)	12.9
Ultimate analysis (wt.%, db)	
Carbon	42.72
Hydrogen	5.5
Nitrogen	3.93
Sulphur	0.64
Chlorine	0.30
Oxygen*	32.6
Higher heating value (MJ/kg)	18

*Calculated by difference, ar – as received, db – dry basis

Additionally, the determination of the devolatilisation behaviour of poultry litter during the heating process was performed by the means of Thermogravimetric analyser (TGA) (Fig.1b). Poultry litter was heated at 10 °C/min under a nitrogen atmosphere. The poultry litter was heated from room temperature to 1200 °C and combusted at the end of the experiments at a constant temperature of 1200 °C.

2.2 Experimental facility and test procedure

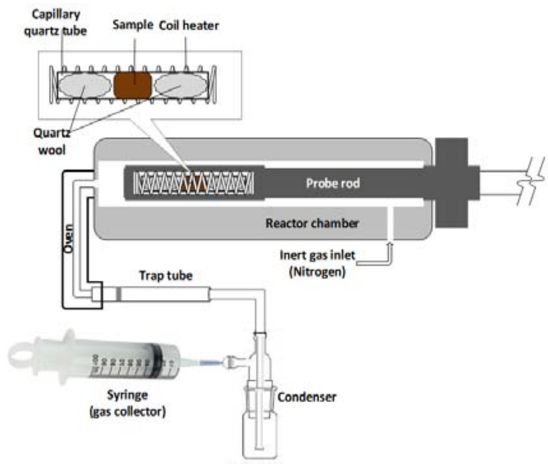


Figure 2: Schematic diagram of the pyroprobe reactor

Fast pyrolysis experiments were performed at the TU Delft by using the pyroprobe reactor 5000 series (the schematic diagram is shown in Fig.2). The heating rate was set at 600 °C/s and the working temperatures (pyrolysis temperature) were set at 400, 500 and 600 °C.

For each experiment, 30 mg of ground poultry litter (<100 μm) was placed in a 2.1 mm quartz tube sample holder and inserted into the pyroprobe reactor. The pyrolysis chamber was initially heated at 300 ºC, while the temperature of the oven was heated to 325 ºC to avoid condensation of the produced tars. The experiments were carried out in triplicate to reduce the uncertainties involved in measurements and results are reported with the mean and standard deviation.

Condensable gases from the pyrolysis process were condensed initially by a glass-frit trap and subsequently by an isopropanol filled condenser. Non – condensable gases were collected into a syringe prior to the gas analysis. Once the experiment was completed, the syringe was removed and connected to the inlet of a micro gas chromatogram (Micro-GC). A Micro-GC Varian CP-4900 was used to identify and quantify the non-condensable gas from the pyrolysis process. Furthermore, the solid and liquid yields of the pyrolysis process were measured gravimetrically, by weighing the sample holder and the trap tube before and after each experiment.

3 RESULTS AND DISCUSSION

3.1 TGA Analysis and devolatilisation

Poultry litter consists of fixed carbon, protein, hemicellulose, cellulose, lignin, water, extractives and minerals [10]. Except for fixed carbon and non-volatile minerals, all components decompose during the pyrolysis process in the TGA. Following the drying process, poultry litter pyrolysed into two regime condition, rapid and slow pyrolysis. In rapid pyrolysis, hemicellulose decomposed followed by the decomposition of cellulose, whereas in slow pyrolysis the decomposition of lignin occurs [14].

Fig 3(a) shows the mass loss during the drying process, rapid pyrolysis, slow pyrolysis and terminated with the combustion of fixed carbon. In this TGA analysis, rapid and slow pyrolysis occurred between 100 and 500 °C and being the main part of the total mass loss devolatilised during this interval.

Hemicellulose in poultry litter is thermally unstable and degrades faster and at lower temperatures compared to the cellulose and lignin [15], while the lignin is a comparatively stable component, hence requires high temperature to decompose [16,17].

In Fig.3 (b), the evaporation of water in poultry litter is apparent at the first peak (around 100 °C) while the peak (shoulder) number 2 indicates the decomposition of hemicellulose, which continued up to the decomposition of cellulose until peak number 3. The peak number 4 shows the decomposition of protein from the manure (including lignin) until around 500 °C [18]. Several small peaks above 600 °C are indicative of the decomposition of fixed carbon and inorganic compounds (e.g. metal carbonates) [19].

3.2 Product yield distribution

The fast pyrolysis yield obtained by conversion in the Pyroprobe was measured and presented as a fraction of the initial mass (Fig.4). Mass fraction yields of char and liquid were measured gravimetrically, while the gas yield was evaluated based on its composition identified by the Micro-GC.

It is evident from Fig 4 that the product yield distribution pattern was affected by the pyrolysis temperature. An increase in the pyrolysis temperature reduces the char production [20], whereas the liquid and gas yield increased significantly with an increase in temperature, in particular from 400 to 500 °C.

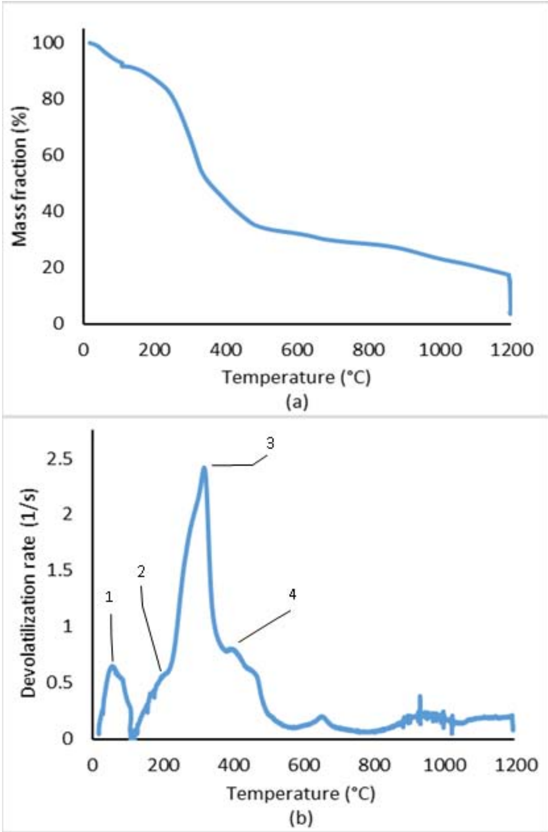


Figure 3: (a) Mass loss of poultry litter (b) Devolatilisation rate from TGA

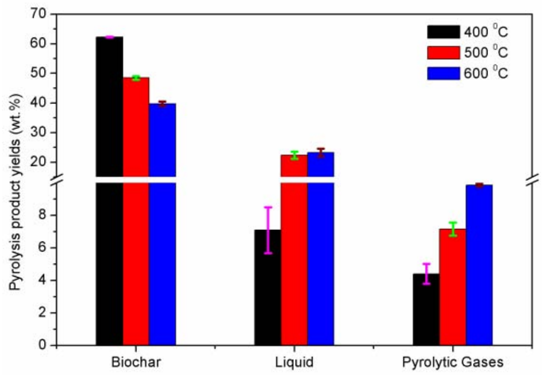


Figure 4: Product yield distribution of poultry litter pyrolysed in the Pyroprobe at 400, 500 and 600 °C

A comparative analysis of the poultry litter fast pyrolysis is presented in Table II. It can be seen from Table II that the yield of biochar and liquids were comparable and are in a reasonable agreement with previous work. However, a significant difference is evident in the gas yield, which is over ten percent. The method used in some experiments [21] is calculating the gas yield by subtracting the total mass of feedstock with biochar and liquid yield, while in this study, the gas yield was obtained from the gravimetric calculation method [5]. It is worth to mention that the observed higher deviation in the gas yield could be due to the escape of light gases, non-measurement of higher hydrocarbons produced such as C_2H_4, C_2H_6, NH_3 and sulphur containing species as well as the loss of water during the experiments.

Table II: The comparison of product yield distribution

Feed-stock	Temperature (°C)	Biochar (wt.%)	Liquid (wt.%)	Gas (wt.%)	Ref.
Poultry litter	600	39.8	23.2	9.9	This study
Poultry litter	550	39.98	26.98	33.04	[21]*
Poultry litter	530	31.5	27.6	21.9	[5]*

*fluidised bed reactor

3.3 Syngas production

The effect of temperature on the pyrolysis gases was investigated. The major gaseous species identified were carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), nitrogen (N_2), and methane (CH_4). CO_2 is mainly released during the decomposition of hemicellulose and cellulose while CO and CH_4 are produced in high temperature during the decomposition of lignin and the secondary cracking of primary tars [22]. Since nitrogen was used as a carrier gas during the experiments, the composition of the product gases is reported on a nitrogen-free basis to avoid error reading for another gas fraction and the dilution effect [21].

It can be seen from Fig.5 that the gas is predominantly composed of CO_2 while a small fraction of H_2 was produced during all the three pyrolysis experiments. Methane was produced only at the highest temperature (600 °C). According to the literature, the initiation of tar cracking (heavy hydrocarbon) can occur at elevated pyrolysis temperatures, which is indicated by the increase of CO and H_2 [5,23].

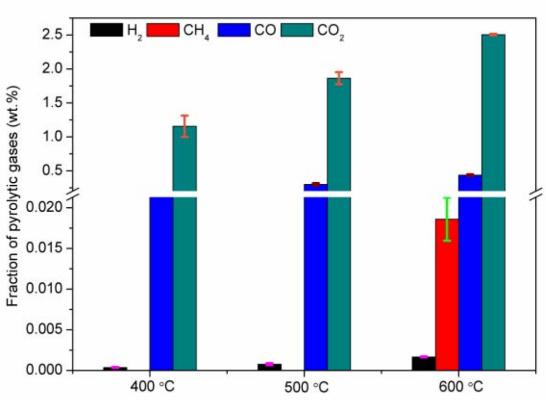


Figure 5: Fraction of pyrolysis gases in the pyroprobe.

3.4 Mass balance analysis

Table III shows the mass balance calculation of the poultry litter fast pyrolysis experiments on the three different temperatures. The input stream consists of the poultry litter on an as received basis, whereas the outlet stream consists of the gaseous, liquid and solid (biochar) yield. The sum of pyrolytic water and condensable volatile compounds are regarded as the liquid product. It is evident from Table III that mass closure has a relative error of 22-27%. The possible reasons for the observed error could be due to the condense tar adhered inside the oven line (before the trap tube), escape of light gases during the dismounting of the tar/condenser assembly as well due to the difficulties in measuring gravimetrically pyrolytic water, higher hydrocarbon gases and light tar compounds [24]. The best mass closure was obtained at a temperature of 500 °C over the tested range of temperature.

Table III: Mass balance of poultry litter pyrolysis

Temperature (°C)	Input (%)	Biochar (%)	Liquid (%)	Gas (%)	Error (%)
400	100	62.2	7.1	4.4	26.3
500	100	48.5	22.3	7.2	22.0
600	100	39.8	23.2	10	27.1

4 CONCLUSION

Preliminary tests of fast pyrolysis of poultry litter have been conducted successfully in the temperature range between 400 and 600 °C. The feedstock was characterised using TGA and it is known that the main pyrolysis process occurred between 200 and 500 °C.

From the fast pyrolysis process and the quantification of gas yield, it was evident that the maximum yield of evolved gases and bio-oil occurred at the highest temperature. Moreover, pyrolysis temperature had an adverse effect on the biochar yield over the tested range of temperatures. Future research related to the fast pyrolysis of poultry litter could be performed to obtain the balance of energy consumption and production during the pyrolysis process and to analyse the water in the final bio-oil yield. Furthermore, the analyses of both the biochar and the ashes from the pyrolysis of poultry litter are required to ascertain if it is safe to use as a fertiliser in agriculture system and its potential effect on plant growth. It is also recommended to perform the leaching test to understand the long term effect of heavy metals on the water bodies (surface and ground), environment and air pollution [25].

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