Utilisation of Poultry Litter as an Energy Feedstock

Authors:

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Abstract

This paper examines poultry litter (PL) as a resource in fuel quality terms and illustrates how the small scale application of fluidised bed technology solves both energy and waste problems, while producing a nutrient rich ash. PL was found to have a higher heating value (HHV) of 18 GJ t^{-1} on a dry basis (db). On an as received basis (ar), it had an ash mass fraction of 9 % and the elemental phosphorous content of the ash was 110 g kg^{-1}. The resultant mineral matter can be utilised as a nutrient substitute for mineral fertiliser.

Keywords: Energy, poultry litter, phosphorous, fluidised bed combustion.

1 Introduction

1.1 Background:

Approximately 56 billion land animals are raised and slaughtered worldwide each year for human consumption [1] and livestock inventories are expected to double by 2050, mostly in developing countries [2].

The growing demand for animal protein products has led to the intensification of the agricultural industry, leading to the birth of the so called “factory farm” or “CAFO” (concentrated animal feeding operation). These farms allow meat and eggs to be produced at a much lower cost than traditional methods. The animals on these farms are usually confined for most of their life span, under increased stocking densities, leading to large volumes of excreta being accumulated in concentrated areas.

Manure generated from CAFOs consists of both solid and liquid fractions. The solid fraction mainly consists of faeces and bedding material recovered from the floor of the houses while the liquid contains a mixture of water, urine and soluble faecal components, and is drained through gutters [3, 4]. This manure is considered an industrial waste and must be managed in an environmentally responsible way [5]. Animal excreta are high in nutrients such as nitrogen, phosphorous, potassium, calcium and sulphur, and as such, are generally spread on land as an organic fertiliser. However, manure production from CAFOs is often greater than local crop and proximal pastureland nutrient requirements. Over-application of manure can lead to eutrophication, nitrate leaching, high biological oxygen demand (BOD), ammonia toxicity, high chlorine concentrations, pathogen contamination, nuisances (e.g. flies and odours), crop toxicity (due to high concentrations of ammonia, nitrite, nitrate and soluble salts), fish kills and human and animal health impacts [6].

1.2 Phosphorous Recovery:

Phosphorous (P) is perhaps the most important nutrient in animal manure, not only due to its agronomic benefit, but also its status as a non-renewable resource. Current global reserves may be depleted within 50 – 100 years [7]. The merging of food and fuel economies has seen an increased demand for mineral P fertiliser, and its price increased by over 200 % in 2007 [8]. The expected global peak in phosphorus production is predicted to occur around 2030. The quality of remaining phosphate rock is decreasing due to some trace element impurities; while production costs are also increasing as removing these impurities generates hazardous waste and may require high energy input [7-9].

1.3 Poultry Litter:

Poultry litter is one of the drier and bulkier manures produced in intensive agriculture. It consists of a mix of bedding material, excreta, waste feed and feathers. Bird mortalities may also be present, however under EU Regulation 1774/2002 [10] these must be removed and disposed of separately. According to Szogi & Vanotti [8], recoverable P from poultry litter is about 39 % of the total recoverable P from all animal manures in the U.S. because of its high P concentration with respect to other manures. Phosphorous in poultry litter is present as both solid phase organic P and inorganic P (2:1), it can vary with diet and husbandry practices, and has a reported mass fraction range of 0.3 %

– 2.4 % on a dry basis [11, 12]. However, this P is largely present in the acid soluble fraction, limiting its bioavailability [13].

A total of 18 billion meat chickens were slaughtered in Europe and the USA in 2009 [1]. Using the calculation of 1.4 t of litter per 1000 birds, this amounts to a reserve of litter of 25,000,000 t as received (moisture unspecified) in the USA and Europe combined in a single year.

Agriculture is the single largest source of waste in Ireland. According to the EPA National Waste Database, of a total of 85,256,685 t of waste generated in 2004, 60,170,025 t (70.6 %) were generated in a managed environment from agriculture. Poultry litter represented 0.3 % (172,435 t) of the total managed agricultural waste produced in 2004 [14]. The majority of the litter generated was derived from chicken (broiler) production [15].

1.4 Poultry Production:

In northern and temperate climates, temperature control in the initial stages of broiler production is paramount and involves the use of an external heat supply for the first four weeks of the production cycle. The requirement for heat is normally reduced in the later stages of the cycle. Typically, fossil fuels (such as propane or diesel) are used to heat the poultry houses directly. Rising energy costs have led to some farmers reducing ventilation of the sheds as a cost saving measure. This can be detrimental to bird health as it can increase the moisture content of the litter, leading to hock burn and dermatitis and can also lead to the build up of harmful emissions such as ammonia and carbon monoxide, increasing bird mortality [16, 17].

1.5 Poultry Litter as a Fuel:

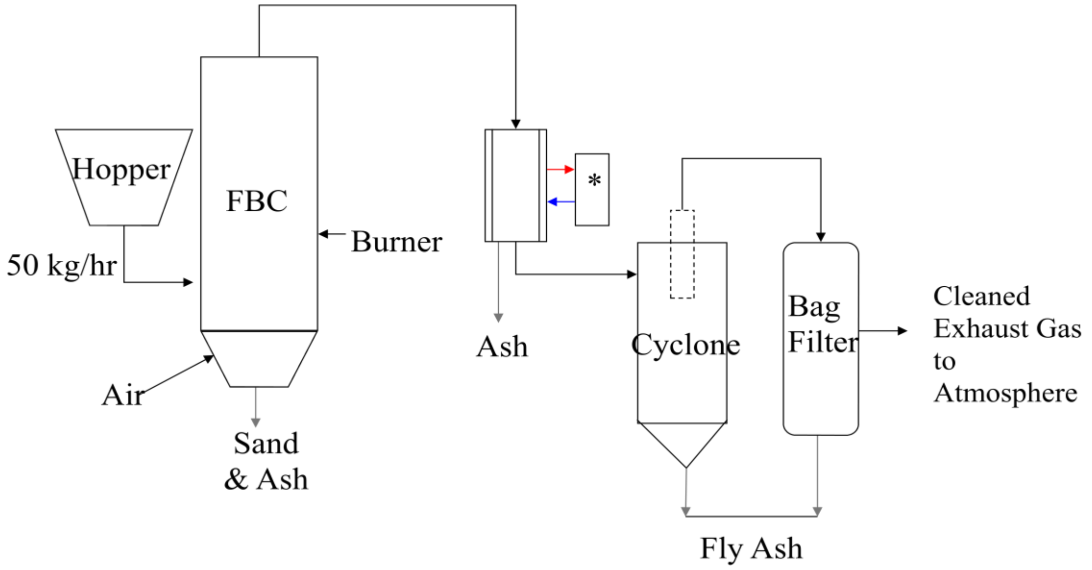
Poultry litter is recognised as a biomass fuel, and is generally a free-flowing, granular material, with a consistency and physical appearance similar to a mixture of wood chips and sawdust. It can vary from wet compacted manure to a dry dusty powder. It is generally recognised as a low value fuel due to its relatively high moisture and ash contents. The moisture content of poultry litter is highly variable and this impacts on the homogeneity and the lower heating value (LHV) of the fuel, which can range from 9 GJ t^{-1} – 13 GJ t^{-1} [18, 19]. The use of poultry litter as an alternative fuel source on a large scale basis has been carried out since Fibropower opened their poultry litter-fired power plant, at Eye in Suffolk UK in November 1993 [6].

Use of poultry litter as a combustion fuel concentrates the nutrients of the litter in an inorganic, sterile form. Nitrogen is lost during combustion, however; phosphorous and potassium are both retained, as well as several other macro and micro nutrients.

1.6 Fluidised Bed Combustion of Poultry Litter:

For the purpose of this research a 200 kW atmospheric bubbling fluidised bed combustion (FBC) unit was employed. FBC technology was selected as it is well documented as being suitable for low value fuels such as poultry litter [6, 20, 21]. The unit used in this work was a commercial unit, operated by Biomass Heating Solutions Ltd., Ireland. The FBC was located adjacent to a broiler operation and as such the litter did not leave the site of production. The design of the FBC made it suited to on-site location for small scale operations (30,000 birds) which are common across Ireland. A schematic of the FBC is shown in Figure 1. The resultant ash was collected via a series of heat exchangers, a cyclone and a bag house filter.

Fluidised bed combustors have been shown to be a versatile technology capable of burning practically any fuel or biofuel combination while producing low emissions [22].



* Heat exchanger connected to buffer tank and poultry houses

Figure 1: Schematic of Process

1.7 Overview:

This paper examines the suitability of poultry litter for use in FBC technology in terms of its basic fuel characteristics. It is clear that managed agriculture faces many problems, primarily energy generation and waste disposal. This paper shows how the small scale application of FBC technology can solve both energy and waste problems, and create an additional revenue stream in the form of a mineral rich ash suited for fertiliser substitution.

2 Materials and Methods

Poultry litter samples were collected from broiler production facilities, following the guidelines of BS EN 14778:2011, ‘Solid biofuels – Sampling ’[23], and prepared according to BS EN 14780:2011, ‘Solid biofuels – Sample preparation’[24].

The methodology for testing poultry litter followed the standards set out under CEN TC 335. Moisture content was determined by the weight loss of the sample at 105 °C [25]; ash by the weight loss at 550 °C under a controlled heating regime [26], and volatiles via the weight loss at 900 °C [27]. Fixed carbon was determined by calculation. Carbon, hydrogen, nitrogen and sulphur were determined using an elemental analyser - Elementar Vario EL CUBE [28]. Chlorine content was determined using Ion Chromatography (IC) [29]. Samples for Cl determination were generated via combustion in a Parr 6200 oxygen bomb calorimeter. Higher heating value (HHV) was determined simultaneously [30].

Due to the heterogeneity of poultry litter numerous (30) samples were analysed to establish the fuel properties.

Elemental content of the ash was determined using ICP/OES and ICP/MS [31, 32], sulphur content was determined via combustion [29] and neutralising value via titration.

Microbial counts on the ash were conducted by placing 1 g of ash in a flask containing 99 ml of sterile Ringers Lactate solution. Serial dilutions were then carried out to 10^{-5}. 1 ml of liquid was spread on Plate Count Agar (PCA) plates and these were incubated at 37°C for 72hrs [33]. Tests were conducted in triplicate and read at 24 and 72 hours.

3 Results and Discussion

3.1 Feed stock characterisation

3.1.1 Proximate analysis

The average results obtained for the proximate analysis of poultry litter with wood shavings (*Picea abies* and *Pinus sylvestris*) as the bedding material are presented in Table 1. The data is presented on an as-received (ar) and on a dry weight basis (db). For comparison, results from literature are also given. The wood shavings used were kiln dried and milled from imported Finnish softwoods (redwood and whitewood), sold in 25 kg bales as animal bedding from a local distributor.

Table 1: Proximate Analysis of Poultry Litter and other Fuels

Proximate Analysis	Units	Result	Range	Std Dev	Wood Shavings	Poultry Litter[1]	Poultry Litter[2]	Miscanthus[3]	MSW[5]	Peat[4]	Coal[4]
Moisture Content	% (ar)	41.82	18.68 - 51.8	8.88	49.69	10.47	9.29	11.5	n/a	14.6	5.5
Ash Content	% (ar)	9.13	5.95 - 15.15	1.98	0.23	35.08	34.28	2.5	n/a	3.3	19.8
Volatile Matter	% (ar)	41.9	35.01 - 56.83	5.98	44.13	48.31	43.48	59.12	n/a	57.8	30.8
Fixed Carbon	% (ar)	7.81	5.03 - 11.72	1.61	5.95	n/a	13.06	14.07	n/a	24.3	43.9
HHV	GJ t^{-1} (ar)	10.55	8.75 - 14.27	1.37	10.27	n/a	13.52	16.37	n/a	n/a	n/a
LHV	GJ t^{-1} (ar)	8.75	6.93 - 12.79	1.48	8.46	n/a	12.69	n/a	n/a	n/a	n/a
Ash Content	% (db)	15.49	10.61 - 19.58	1.59	0.46	39.18	37.79	2.8	n/a	3.9	20.9
Volatile Matter	% (db)	71.26	67.77 - 73.87	1.75	87.71	53.96	47.82	66.8	n/a	67.6	32.8
Fixed Carbon	% (db)	13.36	9.94 - 15.87	1.36	11.83	n/a	14.4	15.9	n/a	28.5	46.3
HHV	GJ t^{-1} (db)	18.02	16.49 - 20.4	0.7	20.40	n/a	14.9	18.5	13.59	n/a	n/a

[1] [34]

[2] [35]

[3] [36]

[4] [37]

[5] [38]

Moisture content is perhaps the most important fuel parameter particularly when pre-treatment options are not available or desirable. Moisture in the feedstock results in a lowering of temperature inside the combustion unit as evaporation, as well as the reaction of steam with char, is endothermic [39]. High moisture content in fuels leads to an increased fuel throughput, increasing the volume of flue gas released [40]. Wet biomass needs longer residence time for drying before gasification and char combustion take place, resulting in a requirement for larger combustion units. The efficiency of the combustion system also decreases as the fuel moisture content increases. Heat recovery options are available to partly compensate for the loss in efficiency, e.g. flue gas condensation units, however for small scale applications this can prove too costly [41].

The moisture content of poultry litter ranged from 18.7 % to 51.8 %; however, the average was closer to 40 %. This results in approximately 700 kg of water vapour produced per tonne of poultry litter combusted, based on moisture and hydrogen content. This moisture is a mineralised aqueous solution, containing soluble phosphates, carbonates, sulphates, chlorides and nitrates, which are present in biomass [37].

The ash (A) mass fraction of poultry litter studied for this research ranged from 5.95 % to 15.15 % (ar) (see Table 1) with an average of just over 9 %. Wood shavings contained only 0.23 % (ar), indicating that the majority of ash forming compounds originate in the birds’ excreta. When utilising poultry litter as a fuel, heat exchanger design, dust collection equipment and also the design of the combustion unit itself must be able to cope with the dust/ash load. Agglomeration and corrosion must also be monitored, as the ash load, coupled with high alkali (see Table 3) content mean than ash deposition on boiler and heat transfer surfaces can quickly build up. The ash that remains after combustion represents a reduction in the original material of over 90 % by weight, and is a sterile, powder like material, with high levels of macro and micro nutrients, with potential for re-use as a soil additive. Sterility of the ash was verified via microbial tests, with no colonies visible after 72 hours of incubation.

Volatile matter (VM) is the percentage of combustible gaseous products, exclusive of moisture content, present in a fuel. High VM, as seen in poultry litter (35.01 % to 56.83 % (ar), Table 1), indicates that it is an extremely reactive fuel. The major part of poultry litter is vaporised before homogeneous gas phase reactions take place, and the remaining char then undergoes heterogeneous combustion reactions [41]. VM comprises a number of hydrocarbons which are released in steps. The first release occurs around 500 °C to 600 °C and the final occurs at temperatures in excess of 800 °C [39]. Although proximate analysis provides an estimate of the VM, the actual yield can be affected by the rate of heating, initial and final temperature, exposure time at final temperatures, particle size, type of fuel and pressure inside the combustion unit. Although volatile material oxidises faster than char, it can result in lower combustion efficiency if there is insufficient mixing, leading to increased CO emissions [39]. The combustion unit must therefore be chosen to manage mostly gas phase combustion, and care must be taken to prevent heat loss due to plug flow behaviour within the unit.

Fixed carbon (FC) is the solid residue other than ash, remaining after the volatile matter has been liberated from the fuel during combustion. VM and FC represent the combustible fraction of the fuel, and together provide an indication of the value of the fuel. FC represents the fraction of fuel which will undergo heterogeneous combustion reactions, normally in the lower part (bed) of the combustion unit. Also referred to as char; FC burns quite slowly. Char combustion begins after the evolution of the VM, although the two processes can sometimes overlap. As the combustion of char takes much longer in comparison to VM, care must be taken to ensure it is not elutriated before being completely combusted, as this would result in combustion losses [39]. Poultry litter contains on average 7.81 % FC (ar) and 13.36 % (db) (see Table 1). The selected combustion unit must be capable of maintaining thermal inertia in order to compensate for such low fixed carbon content; in the case of poultry litter with a low fixed carbon a relatively shallow bed is necessary. The mass of bed material creates a thermal inertia that absorbs moderate swings in fuel moisture contents and heating values without adverse output changes.

Ultimate analysis determines the exact concentration of carbon, hydrogen, nitrogen, sulphur, chlorine and oxygen, present in fuel. These are the basic elemental components of the fuel, and are important in understanding the value of a fuel. The results from poultry litter are presented on a dry basis (db) and a dry ash free basis (daf) in Table 2. The results shown in these tables show that the reported values for poultry litter differ from those collected in the current research. The primary reason for these differences could be climatic conditions and husbandry practices.

Table 2: Ultimate Analysis of Poultry Litter and other Fuels

Ultimate Analysis	Units	Result	Range	Std Dev	Wood Shavings	Poultry Litter[1]	Poultry Litter[2]	Miscanthus[3]	MSW[5]	Peat[4]	Coal[4]
Carbon	% (db)	45.17	42.02 - 48.61	1.55	52.37	27.82	37.38	48.1	43.9	54.1	61.86
Hydrogen	% (db)	5.85	4.97 - 6.55	0.49	5.67	5.08	4.19	5.4	5.6	5.57	4.11
Nitrogen	% (db)	5.16	3.83 - 6.4	0.57	0.12	4.25	3.76	0.5	1.1	1.44	1.03
Sulphur	% (db)	0.45	0.29 - 0.6	0.09	0.00	1.14	0.74	< 0.1	0.3	0.19	1.34
Chlorine	% (db)	0.35	0.23 - 0.52	0.23	n/a	n/a	0.5	n/a	n/a	0.04	0.03
Oxygen	% (db)	27.25	25.08 - 31.09	1.41	38.53	n/a	15.64	42.2	32.1	34.79	10.75
Ash	% (db)	15.49	10.61 - 19.58	1.59	0.46	39.18	37.79	2.8	17.1	3.9	20.9
Carbon	% (daf)	53.45	49.7 - 57.52	1.35	52.61	45.75	60.09	49.49	52.95	53.6	78.2
Hydrogen	% (daf)	6.92	5.88 - 7.75	0.55	5.70	8.37	6.73	5.56	6.75	5.8	5.2
Nitrogen	% (daf)	6.11	4.53 - 7.57	0.66	0.12	6.98	6.04	0.51	1.33	1.5	1.3
Sulphur	% (daf)	0.53	0.34 - 0.71	0.09	0.00	1.87	1.19	< 0.1	0.36	0.2	1.7
Chlorine	% (daf)	0.41	0.27 - 0.61	0.09	n/a	n/a	0.8	n/a	n/a	0.042	0.038
Oxygen	% (daf)	32.25	29.68 - 36.79	0.27	38.71	n/a	25.14	43.42	38.72	36.2	13.6

[1] [34]

[2] [35]

[3] [36]

[4] [37]

[5] [38]

The carbon (C) content of poultry litter was found to be in the range of 42.02 % - 48.61 % (db) and 49.7 % to 57.52 % (daf) (Table 2). Tortosa Masiá et al. [35] found the C content of poultry litter to be 37.38 % (db) (Table 2). The variation in litter analysed, while not huge, suggests differences in the bedding materials, husbandry practices and possibly storage conditions of the litter. The C content in the wood shavings was found to be 52.37 % (db) (Table 2), and the lower C content in the poultry litter reflects the dilution effect of the excreta. This confirms the work carried out by Quiroga et al., [42] who reported results for the C content of poultry layer manure to be 36.2 % (db), as poultry layer operations generally use minimal bedding. The carbon in biomass tends to be present in partly oxidised forms, which is what lends to the low heating value (LHV) [41], especially in comparison to coal (approximately 62 % to 85 % C (db) LHV of ~35 GJ t^{-1}) [37, 43] which is included with miscanthus and peat in Table 2 for comparison. Peat is a fuel indigenous in Ireland, used traditionally for heat in homes, and now also used for power generation, both on its own and co-fired with miscanthus. The C content measured in poultry litter samples (45.17 % (db)) is higher than the reported values for poultry litter from literature (27.8 % to 37.4 % (db)) (see Table 2). This indicates the differences in husbandry practices in different broiler farms, namely the amount of bedding material used which significantly increases the C content.

The hydrogen (H) content of poultry litter measured varied between 4.97 % to 6.55 % (db) and 5.88 % to 7.75 % (daf) (Table 2). This range is similar to that found in peat (5.6 % H (db) and 5.8 % H (daf) Table 2). Tortosa Masiá et al. [35] found the hydrogen content in poultry litter to be 4.19 % (db), which is slightly lower than the observed result in this research.

Nitrogen (N) content in most biofuels is much higher than coal (1.03 % (db) and 1.3 % (daf), Table 2), with poultry litter measuring in the range of 3.83 % to 6.4 % (db) and 4.53 % to 7.57 % (daf) (Table 2). According to Oberberger et al. [44] these levels may result in emission related problems, as these can generally be expected for solid biofuels with a fuel N content above 0.6 % (db). In comparison, miscanthus was found to have only 0.5 % (db) and 0.51 % (daf) N (Table 2). Wood shavings N content was measured at 0.12 % (db) (Table 2) indicating that excreta is the source of the high N.

Nitrogen oxide (NO_x) emissions are considered a major environmental pollutant. The three primary mechanisms for NO_x formation are: fuel NO_x, thermal NO_x and prompt NO_x [45]. The majority of NO_x emissions during combustion, and the primary cause for concern, originate from the fuel-bound N [46]. At temperatures of 800°C to 1100 °C, fuel N is converted to NO (> 90 %) and NO_2 (< 10 %). The primary N containing elements are NH_3 and HCN which are oxidised to NO with sufficient oxygen. Thermal NO_x occurs at temperatures above 1300 °C when N in the air starts to react with O radicals and forms NO [41]. A key advantage of using FBC is that the lower operating temperatures, typically around 850 °C to 950 °C, limits the formation of thermal NO_x which can be an issue for fixed grate combustion units [47]. Prompt NO_x is due to N in the air reacting with CH to form HCN which then follows the steps of the fuel NO_x mechanism. The prompt NO_x mechanism is much faster than the thermal NO_x mechanism and is less temperature dependent. However, it is only important in fuel-rich conditions, is dependent on CH concentration; and is not a significant issues for biomass combustion, in comparison to fossil fuel combustion applications [41]. The fuel/air stoichiometry is closely linked to the relationship between CO and NO_x emissions; lower combustion temperatures (high fuel/air ratio) mean less NO_x

emissions, however, this leads to decreased combustion efficiency and increased CO emissions. Reversing the ratio (low fuel/air ratio) means that formation of thermal NO_x will increase, especially when injection of secondary air is used as a combustion aid [48]. This can cause localised temperatures of over 1300 °C. The volume of flue gas at lower temperatures can mask the increase, but the concentration of NO_x may rise markedly. This is an important consideration when using poultry litter as a fuel, as typically high air/fuel ratio is chosen for this application with air being introduced in two stages. Careful operational control is needed to ensure the level of NO_x does not exceed legislative limits [48].

Sulphur (S) content of poultry litter was measured in the range of 0.34 % to 0.71 % (daf) (Table 2). In comparison, coal has a much wider range of 0.1 % to 10 % [39]. Upon combustion, S will form acidic SO_x (SO_2 and SO_3) gases and basic alkali and alkaline earth – sulphates [49]. Generally levels of S in excess of 0.1 % (db) and 0.2 % (db) can lead to corrosion and SO_x emissions respectively [44].

SO_x emissions are linked to smoke type smog, acid rain and climate change. S in fuels can cause major issues for combustion units as it can volatilise from the fuel and condense on the cooler surfaces of the combustion unit or on bed particles, leading to agglomeration and slagging, as a result of inertial impaction and other chemical reactions [50]. SO_2 can also be bound to the fly ash by sulphation reactions. According to Loo and Koppejan [41], between 40 % to 90 % of S from biomass is bound in the ash while the rest is emitted with the flue gas. The efficiency of S fixation in the ash depends on the concentration of alkaline earth elements, especially calcium (Ca) in the ash as well as the efficiency of dust collection equipment [41].

The oxygen (O) content in biomass is generally calculated by difference i.e. 100 % - (C + H + N + S + Cl + Ash). Poultry litter measured between 25.08 5 to 31.09 % (db) and 29.68 % to 36.79 % (daf) (Table 2). In comparison, coal has been found to contain 10.75 % (db) 13.6 % O (daf) (Table 2). A fundamental difference between biomass fuels and fossil fuels is the higher proportion of oxygen and hydrogen, and the reduced amount of carbon in biomass fuels. This reduces the energy value of a fuel, due to the lower energy contained in carbon-oxygen and carbon-hydrogen bonds, than in carbon-carbon bonds [36]. Coal typically has a carbon content of approximately 85 %, whereas poultry litter has a carbon content of approximately 45% (db). Additionally, the greater the amount of hydrogen and heteroatoms, particularly oxygen and nitrogen, the greater the volatility; hence poultry litter has a greater level of volatile matter than fuels such as coal [36, 51]. The O_2 level in fuel dictates the air/fuel ratio necessary for combustion.

Chlorine (Cl) is perhaps the most problematic of elements found in biomass fuels with respect to deposition, corrosion and fouling of combustion units. Upon combustion it will vaporise almost completely, forming HCl, Cl_2, and alkali chlorides [41]. It can facilitate the mobility of many inorganic compounds, particularly potassium (K), which is the dominant alkali source in most biomass fuels [40]. As the flue gas temperature decreases, alkali and alkaline earth chlorides will condense on boiler surfaces, as a result, part of the Cl will become bound to the fly ash and the rest will be emitted as

HCl [41]. Deposit formation will increase with increasing degree of vaporisation of alkali compounds, and thus with increasing chlorine content of the fuel [50].

Another concern with Cl is the possibility of polychlorinated dibenzo-ρ-dioxin and diobenzofuran (PCDD/F) emissions. Commonly known as ‘dioxins’, PCDD/F’s are considered a major environmental pollutant. Some isomers of dioxins are highly toxic and are thought to be carcinogenic, mutagenic and teratogenic. They can cause chloracne, damaged immune systems, endometriosis, birth defects, diabetes, and liver and thyroid cancer. They are known to bio-accumulate and due to their strongly lipophilic nature, they can climb the food chain rapidly and persist, making their way into the general population through humans consumption of contaminated food, such as fish, meat and dairy products [40].

It is generally accepted that three primary mechanisms lead to the formation of dioxins/furans in combustors: (1) homogenous gas-phase reactions involving chlorinated organic precursors such as chlorobenzenes and chlorophenols; (2) heterogeneous reactions between chlorinated organic precursor compounds and fly ash-based metallic catalysts such as copper; and (3) de novo synthesis involving fly ash containing residual carbon in the post combustion zone, e.g. dust collectors, at temperatures in the region of 250 °C to 500 °C in the presence of flue gases containing HCl, O_2 and metallic catalysts [41, 52]. The complexity of the reactions leading to dioxins/furans and the multiplicity of factors determining their formation has made it difficult to determine causal relationship between emissions and fuel input parameters; variability in parameters such as combustor design and operating conditions generally have a greater influence on emissions than fuel chlorine content [53]. However, the key factor is that chlorine is an integral atom for dioxin/furan formation.

Poultry litter was found to have Cl content in the range of 0.23 % to 0.52 % (db) and 0.27 % to 0.61 % (daf). This relatively high Cl content (coal ranges from 0.005 % – 0.11 % [37]) coupled with the high ash and moisture content found in the litter, indicate that both corrosion and PCDD/F emissions are significant concerns when utilising poultry litter as a biomass fuel. According to Obernberger et al. (2006) the guiding concentration for Cl in a fuel is < 0.1 % (db) for corrosion, < 0.1 % (db) for HCl emissions and < 0.3 % (db) for PCDD/F emissions. However, if care is taken to ensure complete combustion and that rapid cooling of the flue gas takes place, alongside adequate fly ash collection facilities; then the risk of harmful emissions can be decreased considerably.

The heating (calorific) value of the fuel is also listed in conjunction with the proximate analysis. It is an expression of the energy content, or heat value, released when burned in air and is derived from the combustible portion (volatile matter and fixed carbon) of the fuel. Reference is usually made to two heating values – a higher or gross heating value (HHV) and a lower or net heating value (LHV). The difference between these values is essentially the latent heat of vaporisation of the water vapour present in the exhaust products when the fuel is burned in dry air. In an actual combustion system, this includes the water present in the as-burned fuel (the moisture) and the water produced from the combustion of hydrogen. Most combustion tables list the higher heating values for fuel because the moisture content can vary so widely [43].

The lower heating value of poultry litter was found in the range of 8.75 GJ t^{-1} to 14.27 GJ t^{-1} (ar) (Table 1). In comparison, the miscanthus referenced was measured at around 16.37 GJ t^{-1} (ar) (Table 1) and natural gas can measure 49.8 GJ t^{-1}[39]. HHV can be determined directly or it can also be calculated from the elemental composition on a dry basis (db). Numerous formulae exist for its calculation, and an extensive investigation was conducted by Channiwala and Parikh [54] which derived the following formula which holds true for most solid, liquid and gaseous fuels, within the defined limits.

$$\mathbf{HHV = 0.3491\,C + 1.1783\,H + 0.1005\,S - 0.1034\,O - 0.0151\,N - 0.0211\,A} \qquad (1)$$

Based on this formula, the theoretical HHV for poultry litter was calculated to be 19.5 GJ t^{-1} (db) versus 18 GJ t^{-1} as obtained from testing.

It is also possible to calculate directly from proximate analysis, as given by the following equation [55]:

$$\mathbf{HHV = 0.3536\,FC + 0.1559\,VM - 0.0078\,A} \qquad (2)$$

This equation gives a calculated HHV of 15.7 GJ t^{-1}. The percentage error for the first equation lies at 8.3 %, while for the latter it stands at 12.8 %, which may indicate the unsuitability of these indicators when utilising a fuel such as poultry litter.

3.1.2 Bulk Density

The bulk density of poultry litter was found to be 670 kg m^{-3} at 50 % moisture, which is relatively low compared to coal (900 kg m^{-3}). A SEI (Sustainable Energy Ireland) report on dry agri-residues reported poultry litter to have a bulk density of 400 kg m^{-3} at 35 % moisture. The low bulk density results in low energy density and impacts on the economics of the transportation of the material to a centralised treatment facility [15, 21].

3.1.3 Elemental Content

The elemental content of the ash showed there to be high levels of phosphorous, potassium and calcium, (110 g kg^{-1}, 170 g kg^{-1} and 160 g kg^{-1} respectively). Table 3 shows the results of analysis on fly ash samples, and also compares these values to given values for Fibrophos® which is a marketed mineral fertiliser. As they blend their product to suit different agronomic needs they do not report a value for potassium or phosphorous. Instead they report to the typical fertiliser ratio N:P:K. The values that have been determined here 0:11:17 (almost 0:2:3) is close to the blend that fibrophos market as “extra K” “perfect for lower potassium soils, silage, or where extra potassium is required”.

Table 3: Elemental Content of Poultry Litter Ash

Determinant	Unit	Method	Results	Fibrophos□
Phosphorous (Total)	mg/kg	ICP/OES	110000	□
Boron	mg/kg	ICP/OES	270	150
Calcium	mg/kg	ICP/OES	160000	250000
Potassium	mg/kg	ICP/OES	170000	□
Magnesium	mg/kg	ICP/OES	39000	50000
Selenium	mg/kg	ICP/OES	12	5
Sodium	mg/kg	ICP/OES	20000	30000
Cobalt	mg/kg	ICP/MS	8.8	10
Copper	mg/kg	ICP/MS	590	500
Iron	mg/kg	ICP/MS	6500	4000
Manganese	mg/kg	ICP/MS	4200	2500
Molybdenum	mg/kg	ICP/MS	79	30
Zinc	mg/kg	ICP/MS	3800	2000
Sulphur (Total)	%	Combustion	2.6	7
Neutralising Value	%	Titration	19	15

4 Conclusion

The results presented here show that poultry litter is a useful biomass source where produced locally. A key factor in selection of FBC is the ability to operate on a small scale, on-site application as described here. Transport of the litter off site is costly and fuel heavy. Care must be taken to minimise harmful emissions during combustion, and adequate dust collection must be employed. Using the litter in the manner described here reduces waste to 10 % of original mass, mitigates environmental pollution caused by land spreading and concentrates nutrients in a sterile and easily transportable ash.

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Figure Captions

Figure 1: Schematic of Process

Table 1: Proximate Analysis of Poultry Litter and other Fuels

Table 2: Ultimate Analysis of Poultry Litter and other Fuels

Table 3: Elemental Content of Poultry Litter Ash

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