What is the most effective use of wastes from the poultry industry, as a bioenergy resource or filler for polymer production?

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1. Introduction – With increasing popularity of poultry meat coupled with technological advances in production processes, the poultry industry is one of the largest and fastest growing in the agri-food sector worldwide [1]. The growth of the poultry industry has been accompanied by a corresponding increase in poultry waste, including litter, blood, carcass, feathers, eggshell and wastewater; inadequate management of these wastes can result in pollution of soil and water with nutrients, pathogenic micro-organisms and heavy metals [2]. Agri-environmental legislation and targets for increased use of renewable energy (along with specific incentives for energy from wastes) have led to the implementation of waste-to-energy processes in the poultry sector, such as anaerobic digestion to produce biogas, direct combustion for heat and power generation, and gasification for syngas production.

Energy conversion is not, however, the only possible route for poultry waste utilisation nor for fossil fuel displacement; wastes from the poultry industry have the potential to displace petroleum by providing a source of sustainable raw materials for use in polymer production, an industry which uses 5.7 billion barrels of oil annually [3] to produce ~300 million tonnes of polymers [4]. In the UK ~929 million birds with an average weight of around 2 kg are slaughtered each year [5], producing ~1 billion tonnes of waste, which includes bone, feather, offal, and blood (Table I). These wastes, or materials extracted from them, can be used as functional additives or fillers in the polymer mixture. Traditional fillers are used as a cheaper substitute for raw polymer feedstock and, although they tend not to give new properties to the final polymer, they may alter the existing properties of the material. Functional additives can be used in high compositional amounts and, through the use of particular minerals, can modify properties of the polymer. Functional additives can result in improved mechanical properties, altered surface properties or appearance, easier processing and reduced production costs, improved degradation properties, and/or increased lifespan [6].

Table I. Slaughter waste quantity (and dry matter (DM) content) for a typical UK broiler

Material	% of bird	kg per bird	% dry matter
Offal[a]	23.7	0.483	34.7
Bone	18.4	0.375	90.1
Feather	5.5	0.112	27.6
Blood	2.4	0.049	19.1

[a]Offal is typically rendered to produce meal and oil (33.4% and 10.8% of offal respectively, estimated from data in [7, 8, 9]).

The aim of this paper was to identify the most efficient routes for bone, meal (produced from offal) and feather utilisation in terms of oil displacement in the energy and polymer production sectors. The objectives were to: ascertain through laboratory testing the chemical properties of wastes from typical UK broiler chickens; discuss the suitability for use in polymer production and calculate the potential for oil displacement; and analyse the potential energy output and oil displacement if used as renewable fuel. The research showed that all three waste streams have the potential for use in polymer production, where bone, meal and feather could displace around 2600 toe per day, more than three times the quantity displaced if used as renewable fuel.

2. Experimental – The potential of a functional additive in polymer production depends on its morphology, particle size and chemistry. Although information on the chemical composition of poultry wastes can be found in the literature [7], data are currently quite limited and values can vary [10] due to differences in poultry production practices. Testing was therefore undertaken to characterise poultry wastes typical of the UK broiler industry. Three characterisation techniques were used: x-ray powder diffraction (XRD), x-ray fluorescence (XRF) and scanning electron microscopy (SEM). Samples of bone, feather, and meal were tested. For XRD and XRF, bone and feather were broken down into a fine powder using a pestle and mortar. Meal was already in powder form.

XRD outlines the compounds present and their individual quantity and form. Samples of 3 g were placed into the XRD tester. An x-ray of wavelength λ was projected at an angle θ (between 5 and 65°) towards samples. When this x-ray interacted with the waste sample, a diffraction ray was sent back and picked up by the detector. Using Bragg's equation ($n\lambda = 2d\sin\theta$), a d-spacing value was calculated and compared to the XRD library database to identify the mineral compound. The process was repeated to determine major mineral compounds and produce a compositional review.

XRF outlines the elements present and their quantities (in parts per million). Samples of 3 g were placed in small plastic containers (with content compressed to 4 mm thickness to enable good x-ray diffraction) in a desktop XRF tester, along with two samples of known composition (to determine mineral recovery efficiency). An x-ray was projected towards the waste, and a diffraction ray was sent back and then picked up by the detector. Data were compared to the XRF database and an algorithm was used to work out composition. The results were exported to Excel and adjusted to determine raw mineral values (using the mineral recovery efficiency). As XRF only detects raw minerals, results were compared with the results of the XRD and adjusted to account for the undetected proportion. For example, for calcium carbonate, XRF only detects calcium so the carbonate portion needs to be factored in. This adjustment was carried out for all mineral quantities that were higher than 1% of the total inorganic content.

SEM provides information on morphology (texture), chemical composition and crystalline structure. SEM testing was carried out on the various waste streams with images taken at magnifications of 250, 500, 1000, 3000 and 10000. A thin layer of the sample material was glued to the SEM stubs and coated with gold to improve image quality. The stubs were then transferred into the SEM machine, where an accumulating voltage of 3 kV projected a focused electron beam onto the sample surface to produce an image. These images from the microscope were projected onto a computer screen and were adjusted towards areas of significance, with the magnification and focus tuned to produce clear images. Once suitable images were set-up, pictures were taken and saved for review.

3. Results and Discussion – Bone consisted of substantial organic and inorganic proportions – the only waste stream with high proportions of both (Table II). The inorganics consisted mainly of calcium phosphate (hydroxyapatite). Sulphate, sodium fluoride and potassium bicarbonate were also detected in low amounts. The wide range of inorganic minerals present indicates that there is potential to improve numerous polymer properties if used as a polymer additive (Table II). In particular, the high calcium phosphate content could increase the strength of the polymer (an important property for avoiding ruptures in packaging), while the organics could be used to improve the bio-degradation properties of the material. The SEM results showed that the bone broke down into a powder of uniform shape and size (Image 1). The particles had a solid appearance and integrated well together, implying they could be incorporated successfully into a polymer mixture. Although there is limited literature on the use of poultry bone as a polymer additive, tests on composites incorporating bovine bones [11] found that the developed composites had better properties at the ranges of 5-15 wt% bone particle addition. Other research [12] investigated the use of hydroxyapatite whiskers in composites containing 20 and 40 vol% hydroxyapatite, and found that the whiskers improved the fatigue life and damage tolerance of the reinforced polymers.

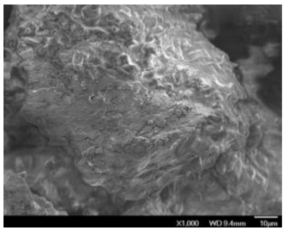

Image 1. SEM image of bone

Approximately three quarters of the meal was organic material (Table II), consisting of both proteins and fats. The main inorganic material present was calcium phosphate, with the remainder of the inorganic portion comprising principally sulphate, potassium bicarbonate and chloride. The SEM for meal showed uniform circular particle sizes with smooth surfaces (Image 2), implying minimal pre-processing would be required for use as a polymer additive. There is currently limited information in the literature on the use of meal in polymer processing. However, due to its high organic content, it is likely that processes which have been used for transforming feathers into thin thermoplastic films (e.g. cyanoethylation [13] (treating with alcohol) or thermal extrusion [14] (treating with plasticizer)), may also be suitable for meal. The process that thermally extrudes chicken feathers into thin film works due to the hydrophilic amino acid composition of the feathers, suggesting that meal, which has a similar amino acid composition, may be processed in the same way. The high organic content suggests that meal could be incorporated into polymers as a bio-degradation aid.

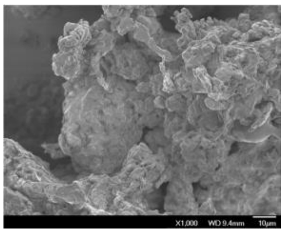

Image 2. SEM image of meal

Table II. Composition of bone, meal and feather, including inorganic compounds, and the possible effect on polymer properties when used as functional additives

Component	Bone	Feather	Meal	Polymer properties potentially improved when used as functional additive
	% of total			
Moisture	9.9	72.4	8	-
Organics	38.8	24.1	75.1	Bio-degradability [15]
Inorganics	51.3	3.5	16.9	See below
	% of inorganics			
Calcium phosphate	76.78	--	52.10	Tensile strength, hardness, flexural strength, flame retardant [11, 16]
Calcium carbonate	--	8.40	--	Impact strength, Young's Modulus [17]
Phosphorus oxide	--	2.29	--	Flame retardant [18]
Sulphate	6.19	58.39	14.00	Anti-oxidant [19]
Sodium fluoride	3.35	4.16	5.94	Water absorption [20]
Potassium bicarbonate	6.14	4.24	15.75	Flame retardant [21]
Aluminium oxide	1.78	7.54	--	Flame retardant [21]
Chloride	1.53	3.83	9.39	Anti-oxidant [22]
Other	4.23	11.15	2.82	-

Feather was found to consist principally of organic matter (87% of dry weight) (Table II), the primary component of which is keratin (keratin is a natural polymer that is already used to improve polymer properties [23]). The inorganic portion comprised mainly of sulphate, which has anti-oxidant properties. The SEM results showed that the whole barb sections consisted of long thin fibres, with thinner barbules splitting out (Image 3). These 'branches' can result in improved reinforcement of the polymer, a benefit that would not be achieved if using the powdered form [13]. In terms of use in polymer production, feather is the most commonly reported poultry waste stream in the related literature. Feathers can be used directly as a functional additive in polymers, and substitution rates of up to 40-50% have been reported without a detrimental effect on tensile strength [13]. Feathers can also be transformed via cyanoethylation or thermal extrusion to produce a 'petroleum free' polymer.

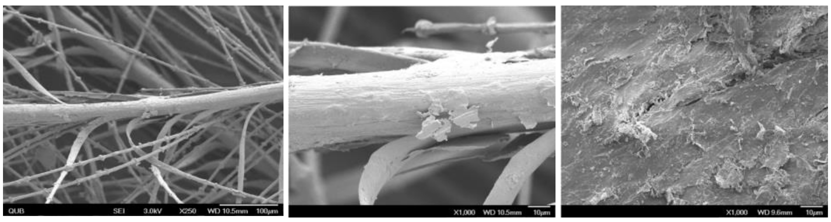

Image 1. SEM images of feather barbs (left, centre) and feather powder (right)

From the laboratory testing, it can be seen that bone, meal and feathers all have potential to be used in polymer manufacturing. Based on current UK poultry production, these feedstocks could replace over 2600 toe per day in the polymer industry (Table III).

Table III. Potential quantity of oil displaced per day if UK poultry bone, feather and meal were used in polymer production

Material	Quantity per bird (kg)	Dry matter content (%)	UK production[a] (kgDM/day)	Oil displaced[b] (toe/day)
Bone	0.375	90.1	859,961	1720
Meal	0.161	92.0	377,411	755
Feather	0.112	27.6	78,677	157
Total	-	-	971,457	2632

[a]Based on 929 million birds slaughtered each year in UK [5], or 2.55 million per day. [b]Assumes 1 tDM replaces 1 t polymer. A typical value of 2 toe required per t of polymer production [24] is assumed. 1 toe = 41.868 GJ.

The energy conversion technology suitable for each feedstock depends on the properties of that feedstock. The high content of volatiles (organics) in feathers, along with a low amount of ash, indicates that they are suitable for fixed bed gasification [25]. Due to its relatively high moisture content and low lignin content, offal is technically suitable for anaerobic digestion, but this pathway has not been considered here due to restrictions on processing and handling in the UK. Both bone and meat-and-bone-meal (MBM) are commonly combusted to generate heat, but can also be used as a feedstock for gasification or pyrolysis to produce a higher value energy product, such as syngas or bio-oil. Depending on the energy conversion technology used, bone, meal and feathers could displace between around 320 (syngas + bio-oil) and 750 toe per day (heat + syngas) (Table IV), which even in the best case scenario is less than a third of the displacement possible if the feedstocks were used for polymer production (Table III).

Table IV. Potential quantity of oil displaced per day if UK poultry bone, feather and meal were used for renewable energy via various routes

Waste stream	Energy conversion process	Product	Energy output (MJ/kgDM)	Oil displaced[a] (toe/day)
Bone	Combustion	Heat	18.4[b]	472[c]
MBM	Combustion	Heat	19[b]	702[c]
MBM	Pyrolysis	Bio-oil	10[d]	296
Feathers	Gasification	Syngas	15.2[e]	29
Total (high-value)	MBM bio-oil + feather syngas	-	-	324

[a]Based on 929 million birds slaughtered each year in the UK [5] – see Table III. [b]Estimated from data in [26]. [c]Assumes a boiler efficiency of 80%. [d]Estimated from data in [27]. [e]Based on energy output of 7.6 MJ/kgDM for turkey feathers (assumes losses in the gasifier of 3.89%) [25]. Although the composition of turkey and chicken feathers is similar, there is evidence to suggest that chicken feathers might not be as good a substrate as turkey feathers [28] so this estimate may be optimistic. 1 toe = 41.868 GJ.

4. Conclusions – The analysis showed clear potential for the use of bone, meal and feathers in polymer production. Further work is needed to investigate polymer applications for bone and meal, and to research new and develop existing polymer applications for feathers. All three wastes can also be used in the bioenergy sector, either through direct combustion for heat generation or through more advanced processes to generate higher value products such as syngas or bio-oil. Although both the polymer and bioenergy routes offer potential for oil displacement, it is interesting to note that the calculations showed over three times the oil displacement was possible when the wastes were used in polymer production rather than as a renewable fuel. Driven by concerns over climate change, energy security and peak oil, global targets for reducing fossil fuel use have to date been largely focused on the energy sector. This analysis shows the importance of the materials sector when tackling environmental issues.

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