



Biocrude oils from the fast pyrolysis of poultry litter and hardwood

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ABSTRACT

The safe and economical disposal of poultry litter is becoming a major problem for the USA poultry industry. Current disposal methods such as land application and feeding to cattle are now under pressure because of pollution of water resources due to leaching, runoffs and concern for mad cow disease contamination of the food chain. Incineration or combustion is potentially applicable to large scale operations, but for small scale growers and EPA non-attainment areas, this is not a suitable option because of the high cost of operation. Thus, there is a need for developing appropriate technologies to dispose poultry litter.

Poultry litters from broiler chicken and turkey houses, as well as bedding material were converted into biocrude oil in a fast pyrolysis fluidized bed reactor. The biocrude oil yields were relatively low ranging from 36 wt% to 50 wt% depending on the age and bedding material content of the litter. The bedding material (which was mostly hardwood shavings) biocrude oil yield was 63 wt%. The higher heating value (HHV) of the poultry litter biocrude oils ranged from 26 MJ/kg to 29 MJ/kg while that of the bedding material was 24 MJ/kg. The oils had relatively high nitrogen content ranging from 4 wt% to 8 wt%, very low sulfur (<1 wt%) content and high viscosity. The viscosities of the oils appeared to be a function of both the source of litter and the pyrolysis temperature. The biochar yield ranged from 27 wt% to 40 wt% depending on the source, age and composition of the poultry litter. The biochar ash content ranged from 24 wt% to 54 wt% and was very rich in inorganic components such as potassium and phosphorous.

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1. Introduction

The US is the world's largest producer and exporter of poultry meat and the second largest egg producer. The total farm value of poultry production was \$20.5 billion in 2002 (SB994, 2004). The poultry industry generates several types of wastes but the three of primary concern to growers are bedding material used for poultry housing, manure from poultry production, and dead birds common to all operations. In general, poultry litter consists of a mixture of bedding, manure, feathers, and spilled feed. In the USA, 35 million tons of litter dry matter is produced per year and in the Shenandoah Valley of Virginia, 453,000 tons are produced per year (Pease, 2000). The litter must be disposed to ensure a safe and healthy environment for the birds and the poultry workers. The major disposal methods include land application as fertilizer or soil conditioner, feeding to animals as a protein supplement, and composting of litter and mortality (Arogo et al., 2002; McCrory and Hobbs, 2001).

Land application is the most important method used to date (Keplinger et al., 2005). When used as fertilizer, poultry manure can provide valuable organic material and nutrients for crop and pasture growth. However, these same nutrients can degrade water

quality if they are over-applied to the land and enter water resources through runoff and leaching. The levels of phosphorus (P) and nitrogen (N) can become excessive after several applications and runoffs from these fields can lead to pollution of water resources and eutrophication of lakes and rivers (USA Environmental Protection Agency, 1996).

Addition of 20% or higher poultry litter to beef cow and stocker cattle rations has been found to be beneficial and a cheap source of crude proteins for the animals (Arieli et al., 1991; Brush et al., 1998). However, recent concerns about bovine spongiform encephalopathy (BSE) have cast doubt on the continued use of this material as a suitable feed supplement.

Another method for poultry litter disposal is direct combustion (Kelleher et al., 2002), which could potentially provide energy for space heating of poultry houses and large scale applications for power generation. However, these technologies require very efficient pollution abatement equipment to meet air pollution standards. Thus, poultry litter combustion is not widely practiced. Poultry litter has a low calorific value (10–16 MJ/kg), which decreases with increasing moisture content. The ash content is high (15–20 wt%) and it has low fusion temperature, which can cause fouling and slagging in conventional grate combustion systems. Some poultry litter combustion plants have been operated in the United Kingdom (UK) with capacities ranging from 13.5 to 38.5 MW (<http://www.fibrowatt.com>). Although several proposals

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have been made to develop chicken litter combustion systems in the USA, but only one unit is operational (CEP, 2000).

Other technologies such as gasification and pyrolysis have not been thoroughly investigated and no such commercial systems are operational in either Europe or USA. Pyrolysis may be suitable for small farms because a central or modular pyrolysis plant could produce liquid fuel from the poultry litter which could then be distributed to the various farms for on-farm heating of poultry houses. In addition, the pyrolysis biochars which will normally trap most of the inorganic residue could be used as a slow-release fertilizer. Furthermore, because the pyrolysis temperatures are normally between 400 and 600 °C (Agblevor et al., 1995), this will not pose any ash fusion and slagging problems associated with high potassium ashes.

The overall goal of our research is to develop a transportable pyrolysis technology as an alternative method for waste disposal and as well as generating higher-value products (energy and fertilizer) for on-farm applications. In this paper, we report results from the rapid pyrolysis of poultry litter and hardwood in a fluidized bed reactor.

2. Material and methods

Poultry litter samples (starter turkey, Broiler-1, Broiler-2, and Broiler-3) were obtained from the poultry growers in the Shenandoah Valley of Virginia. The starter turkey litter was obtained from a house where one pulley of turkeys had been raised. The Broiler-1 sample was obtained after one flock of broiler birds had been raised; the Broiler-2 sample was obtained after two flocks of broiler birds had been raised; and the Broiler-3 litter was a litter sample on which 5–6 flocks of broiler birds had been raised. The chicken bedding (hardwood) was a kiln dried hardwood shavings that was used as floor cover. Thus, the samples had different contents of manure and degraded hardwood. The samples were dried in a chemical fumehood at ambient conditions to equilibrium

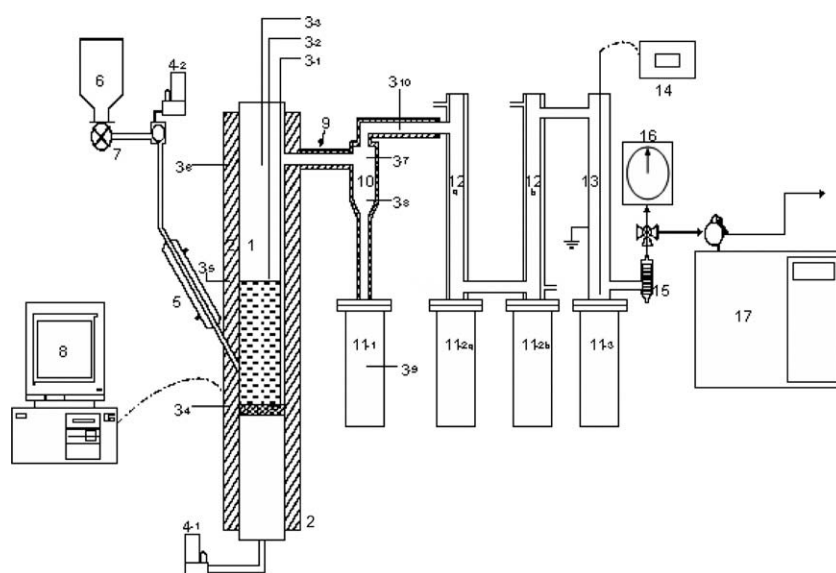
moisture content. The samples were then ground in a Wiley mill (model 4) until the entire sample passed through a 20-mesh screen. The samples were stored in plastic Ziploc bags until the time of pyrolysis. The moisture and ash contents of the poultry litter and the hardwood bedding samples were determined using ASTM E1756 and ASTM E1755 standard methods of analysis.

2.1. Fluidized bed pyrolysis of poultry litter

The pyrolysis studies were conducted in a bubbling fluidized bed reactor located at the Department of Biological Systems Engineering at Virginia Tech (Fig. 1). The reactor consisted of a 50 mm (2 in.) schedule 40 stainless steel pipe, 500 mm (20 in.) high (including a 140 mm (5.5 in.) preheater zone below the gas distribution plate) and equipped with a 100 µm porous metal gas distributor. The fluidizing medium was silica sand with a particle size of –40-mesh and the bed was fluidized with nitrogen. The reactor tube, which contained a bubbling fluid bed with back-mixing of the feed, was externally heated with a three-zone electric furnace.

The dried ground poultry litter (–20-mesh) was loaded batchwise into a K-Tron volumetric feeder (K-Tron Process Group, Pitman, NJ) and conveyed by a twin-screw into an entrainment compartment where high-velocity nitrogen gas was used to entrain the feed and carry it through a jacketed air-cooled feeder tube into the fluidized bed. The pyrolysis temperatures investigated were 450, 500, and 550 °C and the apparent pyrolysis vapor residence time was less than 5 s. The experiments lasted for 2–5 h, the feed rate was 200 g/h and the total nitrogen flow rate was 18 L/min. The feed rate, gas flow rate, and reactor temperature were maintained constant during each run. The sand bed and reactor temperatures were measured and controlled by three K-thermocouples inserted into a thermal well in the reactor.

The pyrolysis vapors exiting the reactor were condensed in a series of water-cooled condensers and an electrostatic precipita-



1- Fluidized bed reactor, 2-Furnace, 3- Thermocouple, 4. Mass flow controller, 5-Heat exchanger, 6-hopper, 7-sample feeder, 8-computer, 9-heating tape, 10-Cyclone, 11-Reservoir, 12-Condenser, 13-Electrostatic precipitator, 14-AC power supply, 15-filter, 16-Wet gas meter and 17-Gas chromatograph.

Fig. 1. Schematic diagram of the bench scale fluidized bed pyrolysis unit.

Table 1

Elemental composition and higher heating values of poultry litter and hardwood bedding samples.

Samples	Moisture (%)	Ash (%)	Elements (wt%, dry basis)					HHV (MJ/kg)
			C	H	N	S	O	
Hardwood bedding	8.08	1.36	47.24	5.94	<0.5	<0.2	45.46	19.25
Chicken Litter								
Broiler-1	22.81	15.33	34.05	4.42	2.89	0.63	42.68	15.47
Broiler-2	31.49	16.02	36.84	5.00	3.94	1.02	37.18	15.65
Broiler-3	33.35	21.17	35.33	5.40	4.10	0.70	33.30	14.37
starter turkey litter	16.25	5.42	43.65	5.71	2.57	0.36	42.29	18.47

tion unit. The biochar fraction was separated in a hot gas filter unit. The total volume of the gaseous products were measured using a flow meter but the gases were not analyzed. All pyrolysis experiments were replicated.

2.2. Higher heating values and elemental analysis of poultry litter of biocrude oils

Dried poultry litter and biocrude oil samples were shipped to Galbraith Analytical Laboratory (Knoxville, TN) where they were analyzed for elemental composition and higher heating values (HHV). The moisture content of the biocrude was determined by Karl Fischer titration.

2.3. ^{13}C NMR spectra and viscosity of biocrude oils

The dynamic viscosity of the biocrude oils were measured at 60 °C using Haake viscometer (Haake VT 501, Thermo Fischer Scientific, Waltham, MA) at shear rates of 0.9–455.7 min^{-1} . The biocrude oil samples were dissolved in deuterated acetone and their ^{13}C NMR spectra were acquired overnight using a Varian Unity 400 MHz spectrometer (Varian Inc., Palo Alto, CA). Solutions of 50 wt% biocrude oils were analyzed in 10 mm diameter probes.

2.4. Analysis of pyrolysis biochars and ash samples

Approximately 1 g biochar was placed in an alumina crucible and heated to 575 °C in a muffle furnace and held there for 1 h. At the end of the hour, the heater was turned off and the door was opened slightly to cool the sample. After 10–15 min, the crucible was transferred to a desiccator and cooled to room temperature. The ash was weighed and the ash content was calculated on dry biomass basis.

Table 2

Pyrolysis product yields of poultry litter and chicken bedding samples.

Samples	Reactor temp (°C)	Products yield (wt%)		
		Oil	Char	Gas
Hardwood bedding	500	63.3 ± 11.3	12.7 ± 2.0	24.0
Chicken litter				
Broiler-1	500	45.7 ± 2.9	40.6 ± 6.2	13.6 ± 5.7
Broiler-2	500	36.8 ± 1.2	40.8 ± 1.9	22.3 ± 2.5
Broiler-3	500	43.5 ± 5.1	32.9 ± 3.7	23.6 ± 6.4
starter turkey litter	500	50.2 ± 1.6	27.6 ± 1.7	21.7 ± 1.9

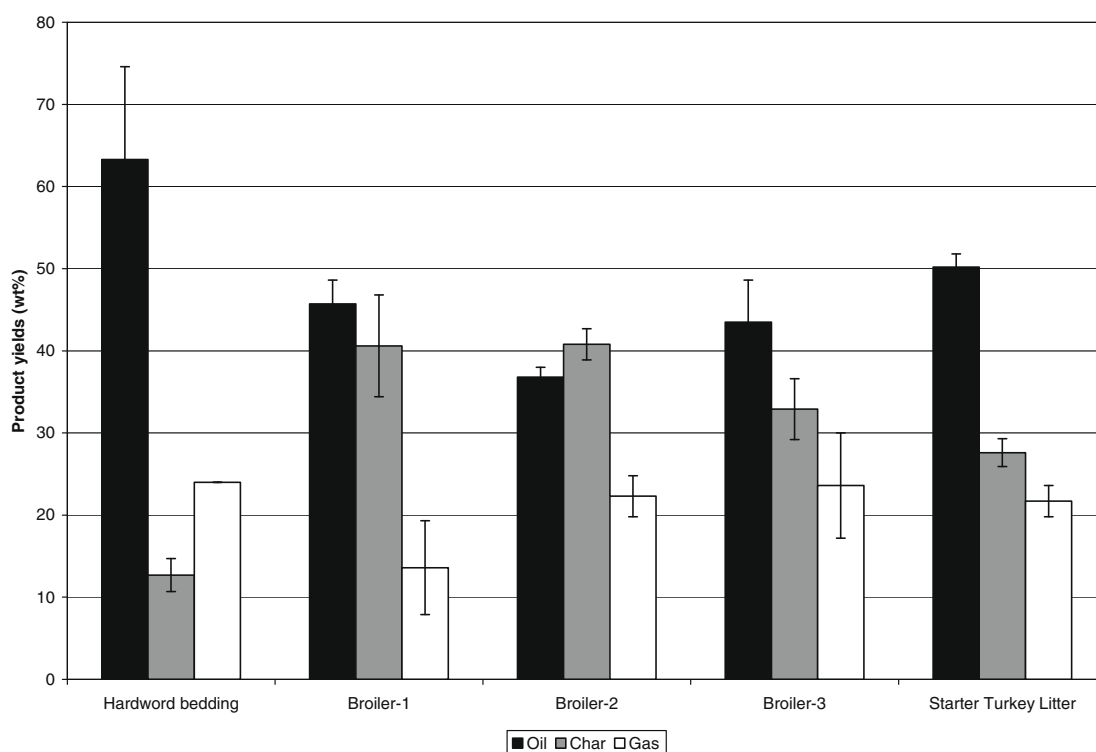
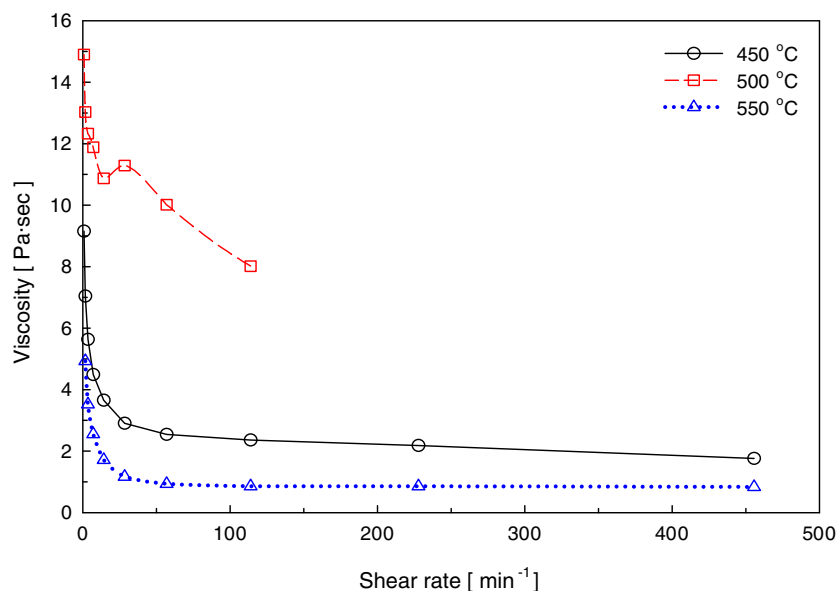
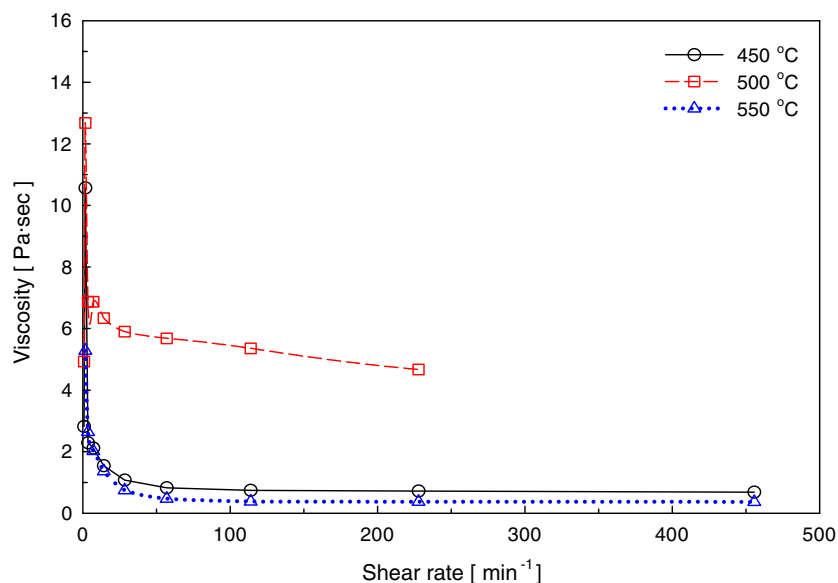
**Fig. 2.** Pyrolysis product yields of poultry litter and chicken bedding samples.

Table 3

Properties of poultry litter and hardwood bedding biocrude oils.

Property	Hardwood bedding	Chicken litter			Starter turkey
		Broiler-1	Broiler-2	Broiler-3	
Moisture (%)	5.3	4.6	4.6	4.0	3.7
pH	2.7	6.1	6.3	6.3	4.2
C (%)	55.25	63.24	64.06	62.84	60.62
H (%)	6.54	7.22	8.14	8.31	7.16
N (%)	<0.5	5.05	4.94	7.23	4.21
S (%)	<0.05	0.46	0.41	<0.09	0.4
O (%) ^a	37.58	23.89	22.27	20.72	28.68
Ash (%)	<0.08	<0.09	<0.09	0.17	0.1
HHV (MJ/kg)	22.64	28.25	28.00	29.57	26.25

^a Oxygen by difference.**Fig. 3.** Viscosity curves of Broiler-1 biocrude oil samples produced at various pyrolysis temperatures: (a) pyrolysis at 450 °C, (b) pyrolysis at 500 °C, and (c) pyrolysis at 550 °C.**Fig. 4.** Viscosity curves of Broiler-3 biocrude oil samples produced at various pyrolysis temperatures: (a) pyrolysis at 450 °C, (b) pyrolysis at 500 °C, and (c) pyrolysis at 550 °C.

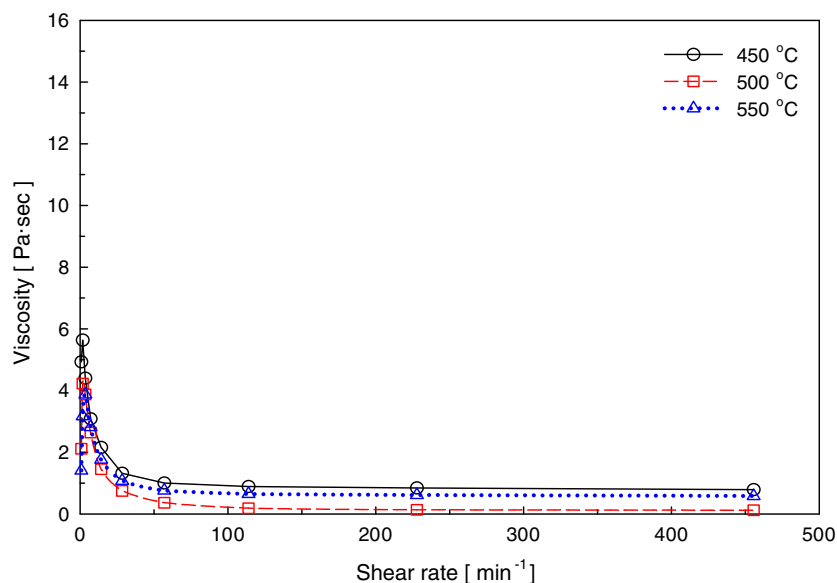


Fig. 5. Viscosity curves of Broiler-2 biocrude oil samples produced at various pyrolysis temperatures: (a) pyrolysis at 450 °C, (b) pyrolysis at 500 °C, and (c) pyrolysis at 550 °C.

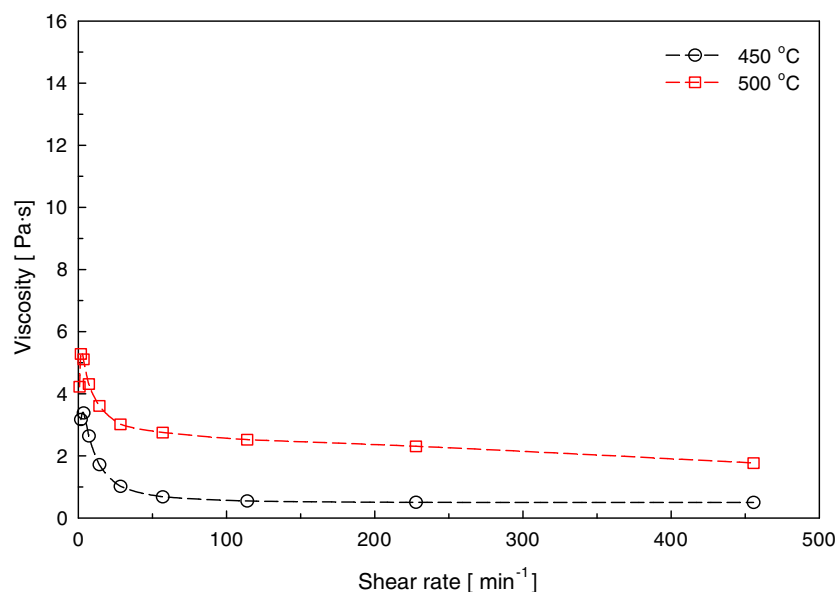


Fig. 6. Viscosity curves of starter turkey biocrude oil samples produced at various pyrolysis temperatures: (a) pyrolysis at 450 °C and (b) pyrolysis at 500 °C.

The ash was transferred to a 50 mL beaker and 5 mL of 3.0 M hydrochloric acid was added to the beaker and the mixture was heated to a very slow boil on a hot plate. After 5 min slow boiling, the beaker was removed from the hotplate and 30 mL of distilled and deionized water was added. The solution was vacuum filtered through a 30 mL medium porosity fritted glass filter. The filtrate was collected and analyzed for potassium, sodium, phosphorus, and calcium contents at the Virginia Tech Soil Testing Laboratory using inductively coupled plasma emission spectroscopic (ICPES) method.

3. Results and discussion

3.1. Physico-chemical properties of poultry litter

The moisture content of the poultry litter ranged from 16 wt% to 33 wt% (Table 1), while the bedding material (hardwood) mois-

ture content was 8 wt%. The ash content of the litters ranged from 5.4 wt% to 21.2 wt% while the nitrogen contents ranged from 2.5 wt% to 4.1 wt%. The samples from the chicken houses (Broiler-1, Broiler-2 and Broiler-3) had similar characteristics whereas the sample from the starter turkey house was different. The difference between the starter turkey sample and the chicken samples could be attributed to several reasons including: (1) the material was used for a shorter time in raising one flock of pullets compared to the chicken house samples that were used to raise flocks of birds to maturity and (2) pine wood instead of hardwood shavings were used for the bedding material.

The higher heating values (HHV) of the samples were relatively low because of their very high ash contents. The ash content was inversely correlated with the HHV (Table 1). Similar to the other data, the starter turkey sample was quite distinct; the HHV was 18–28% higher than those for the broiler litters. The higher HHV

of the starter turkey litter was attributed to its lower ash content and the higher woody material content since this litter was used to raise one flock of pullets. The HHV of the starter turkey litter material was similar to that of the hardwood (Table 1).

3.2. Fluidized bed pyrolysis products

3.2.1. Biocrude oils

There was a wide variation in the yield of poultry litter pyrolysis oils (biocrude oils) and biochars from the four samples (Fig. 2). The biocrude oil yields data showed good reproducibility for the replicate experiments and ranged from 36 wt% to 63 wt% on moisture-free whole biomass basis. However, on ash-free moisture-free basis, the differences were much lower (49.8–62.9 wt%). The correlation between the biocrude oil yield and the ash content of the feedstock was non-linear which suggests that other parameters are important in the formation of the oil (Table 2).

Table 4

Viscosities of biocrude oils from poultry litter.

Litter samples	Viscosity at different temperatures (Pa s)		
	450 °C	500 °C	550 °C
Broiler-1	2.0	8.0	1.0
Broiler-2	1.0	0.2	0.8
Broiler-3	1.0	5.0	0.5
starter turkey	0.5	3.0	10

The biocrude oils appeared brownish and viscous and had much stronger smell than the hardwood biocrude oil sample. The pH of the broiler litter biocrude oil was 6.2 ± 0.1 while that of the starter turkey litter was 4.2 and that of the hardwood was 2.7 (Table 3). It is interesting to note the large difference between the pH of the poultry litter and the hardwood biocrude oils. The starter turkey biocrude which had a considerable amount of undegraded wood had pH that was intermediate between the broiler litter and the hardwood. Thus, it appears the pH of the poultry litter biocrude oil is strongly dependent on the wood content of the litter.

The higher heating values (HHV) of poultry litter biocrude oils were relatively higher than wood biocrude oils (Table 3). The ash contents of the biocrude oils were low but their nitrogen contents were very high. The nature of the nitrogen in the biocrude oil was not determined. Whereas typical hardwood biocrude oils have HHV of about 24 MJ/kg (Agblevor et al., 1995), the HHVs of the poultry litter biocrude oils were as high as 29 MJ/kg. The higher HHVs of these samples were attributed to the higher protein content of the feedstocks or lipids content. During pyrolysis, it appeared the proteins underwent both decarboxylation and loss of nitrogen which gave rise to a higher hydrocarbon content of the biocrude oil and hence a higher HHV content. A preliminary fractionation of the biocrude oils (data not shown) showed that the poultry litter biocrude oil had more than 10-fold hydrocarbon content than the hardwood biocrude oil. Lipids were not the source of the hydrocarbons because extraction of the poultry litter with hexane showed about 2 wt% lipids whereas the protein content was

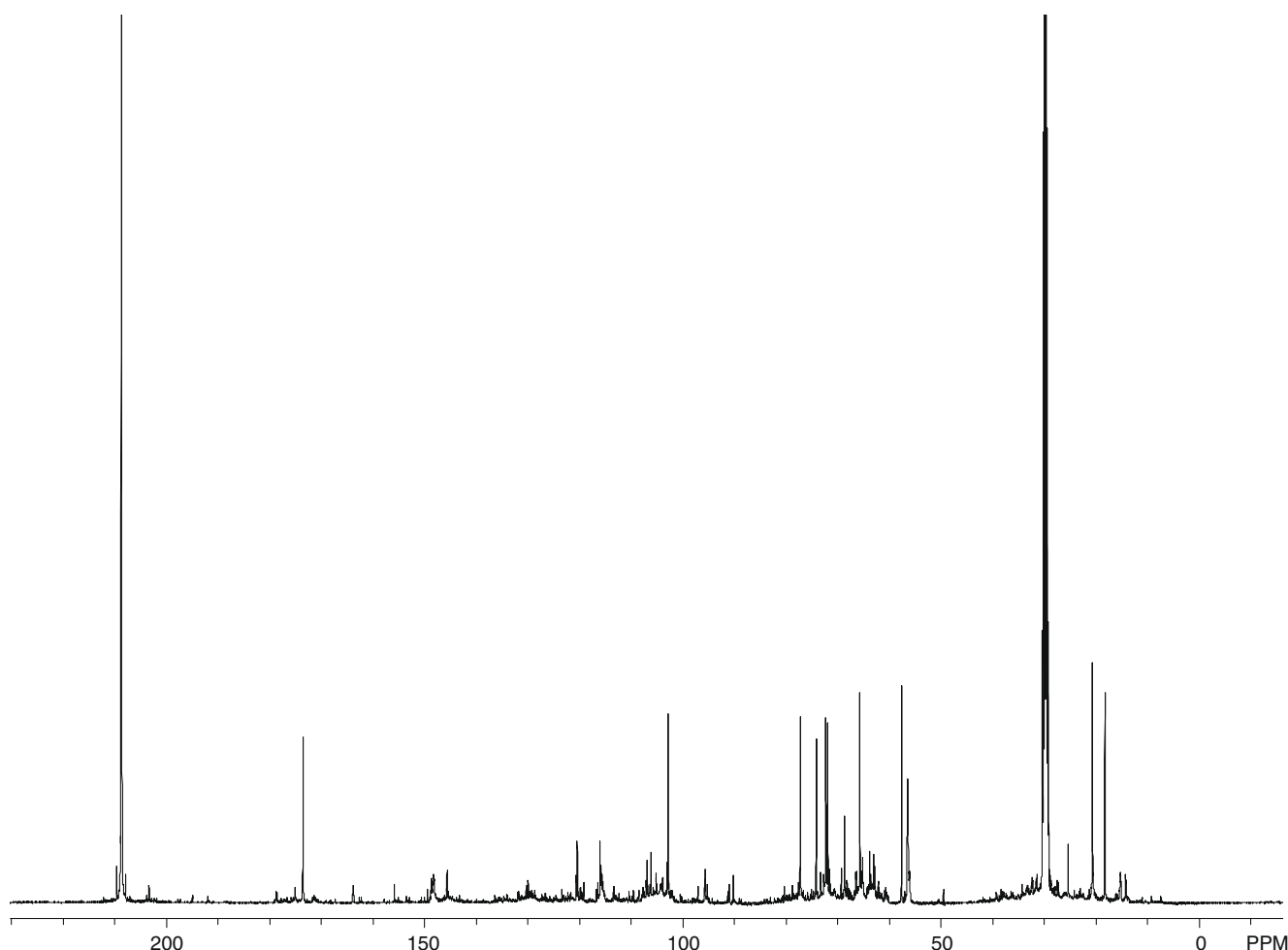


Fig. 7. ^{13}C NMR spectrum of hardwood bedding biocrude oil.

more than 20 wt%. The Broiler-3 and Broiler-2 litter samples had the highest nitrogen contents and consequently the highest protein (the protein content can be calculated by the following formula: $N \times 6.25$). Since some proteins contain hydrocarbons, their decomposition products will contain high levels of hydrocarbons and therefore samples with high protein contents will have very high HHV. However, the corresponding litter samples had low HHVs (Table 1) because of their high ash contents in comparison with the biocrude oil which contained very low ash.

The viscosities of the biocrude oils were different for the different poultry litters (Figs. 3–6). It is not clear why there were large variations in the viscosities of the biocrude oils from different poultry litters because if it is assumed that they are composed of manure and wood shavings, then they should have similar viscosities. Perhaps the differences may be due to the nature of the bedding material, lignin contents, level of microbial degradation, and the concentration of other minor components.

The viscosities of the biocrude oil were also influenced by the pyrolysis temperature (Table 4 and Figs. 3–6). The Broiler-1 (Fig. 3 and Table 4) and Broiler-3 (Fig. 4 and Table 4) biocrude oils had similar trends in viscosity variation with pyrolysis temperature. For Broiler-1, when the pyrolysis was conducted at 450 °C, the viscosity of the oil at 60 °C was 2 Pa s, but when the biocrude oil was produced at 500 °C, the viscosity at 60 °C was 8 Pa s which is four times more viscous. However, when the pyrolysis temperature was 550 °C, the biocrude oil viscosity at 60 °C was less than 2 Pa s. These changes in viscosity with pyrolysis temperature were

attributed to secondary reactions taking place in the pyrolysis vapors. The general trend in the viscosity variation of Broiler-3 biocrude oil was similar to that of the Broiler-1 biocrude oil. It appears that at 500 °C, the protein-derived products reacted with the phenolic compounds and thus making the oils more viscous. At 550 °C, there appeared to be cracking of some of the phenol/protein compounds which resulted in a decreased viscosity.

The viscosities of the Broiler-2 biocrude oils (Fig. 5 and Table 4) were lower than those for the Broiler-1 and Broiler-3 for similar pyrolysis temperatures; the trends in the viscosities of this sample were the exact opposite of those observed for the Broiler-1 and Broiler-3 biocrude oil samples. Furthermore, the viscosity of the biocrude oil produced at 500 °C was the lowest for Broiler-2 while the Broiler-1 and Broiler-3 biocrude oils had the highest viscosity at this pyrolysis temperature.

The viscosities of the starter turkey biocrude oil (Fig. 6 and Table 4) were very different from all the other samples. For this sample, the viscosities of the biocrude oils at 60 °C increased with the feedstock pyrolysis temperature. The lowest viscosity was obtained at 450 °C (Table 4) while the highest viscosity was obtained for the sample pyrolyzed at 550 °C. The viscosities of these biocrude oils were also the highest for all samples. These samples appeared to solidify after a very short storage time.

The unusual variations in the viscosities of the biocrude oils could be explained by the protein and bedding material content of each litter (Table 1). The variation in the viscosity of the biocrude oil appeared to be influenced by the quantity of the wood

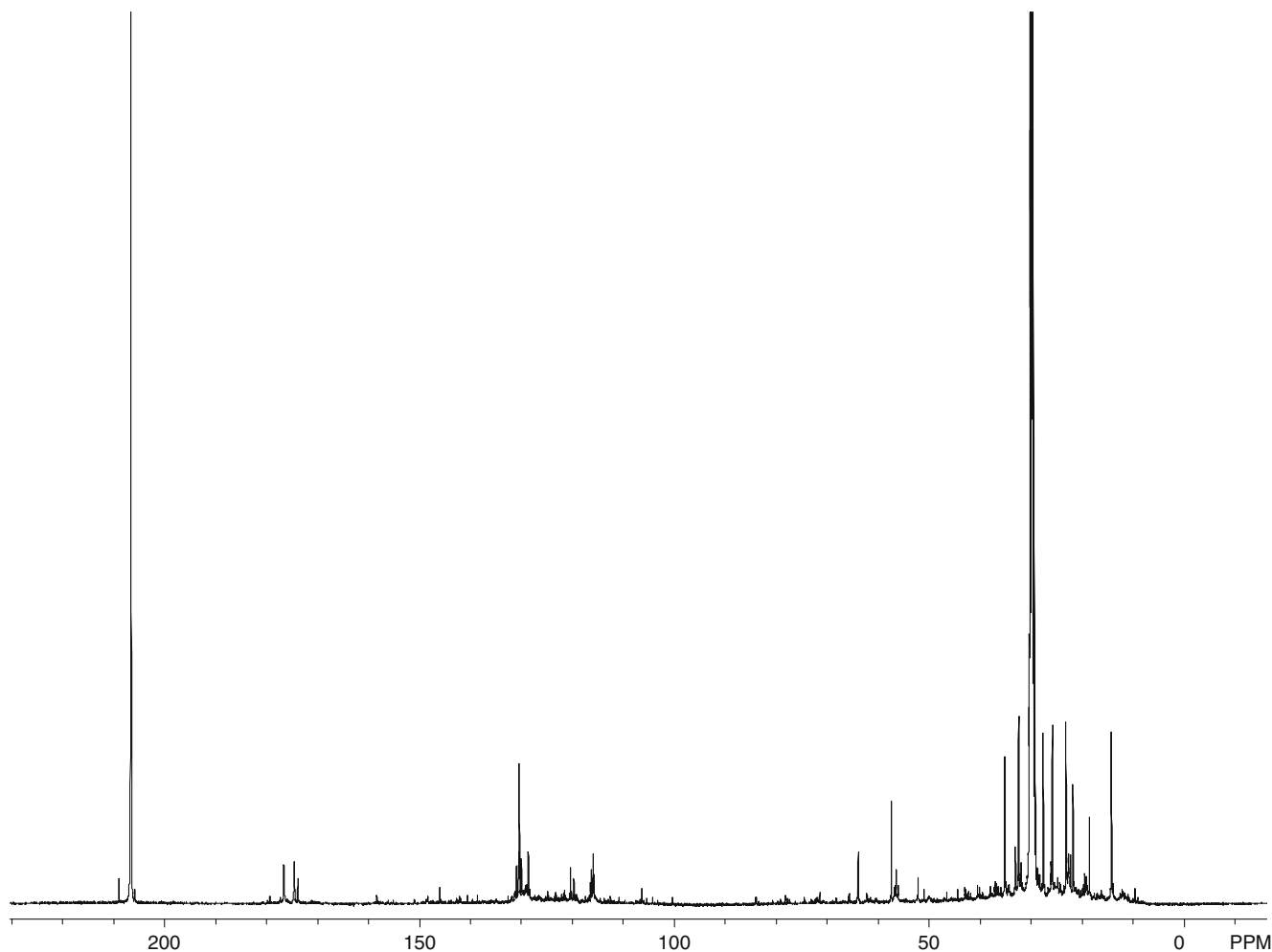


Fig. 8. ^{13}C NMR spectrum of Broiler-2 litter biocrude oil.

residue (bedding material) left in the sample. The starter turkey litter which had very high wood shavings content after pyrolysis produced a biocrude oil which had very high viscosity. Furthermore, pine shavings were used for the starter turkey litter while hardwood shavings were used for the chicken litters. Since the starter turkey litter sample was used the least for raising the pullets, the wood in this sample appeared to be the least degraded. Thus, there would be more wood decomposition products in the starter turkey litter biocrude oil than the other biocrude oil samples.

Lignins are known to react with proteins, thus it appears that in the starter turkey litter biocrude oil, the excess wood decomposition products reacted with the protein decomposition products. The reaction appeared to be promoted at higher temperatures of pyrolysis and hence the viscosity of the biocrude oil increased with increasing temperature of pyrolysis of the starter turkey litter. In the case of the Broiler-1, Broiler-2, and Broiler-3 litter samples, the wood material appeared to be more degraded than the starter turkey sample. Since we are not sure about the amount of wood in each sample, the above explanations need to be verified by more detailed experiments.

The carbon-13 nuclear magnetic resonance (^{13}C NMR) spectra of the biocrude oil samples show the presence of nitrogenous compounds. In addition, the biocrude oil appears to be rich in aliphatic hydrocarbon compounds which normally show in the 0–60 ppm region of the spectrum. In Figs. 7–9, the spectra of biocrude oil from Broiler-2 and Broiler-3 samples are compared with that from the hardwood bedding material. It is clear that there are significant

differences in the spectra. The major differences appear in the carbohydrate decomposition products region which normally lies between 60 and 80 ppm of the spectrum. In the case of the wood, the carbohydrate decomposition products were very intense whereas in the case of the poultry litter samples the peaks in this region were weak. The wood sample also had very intense peaks between 100 and 110 ppm which were due to the lignin aromatic nucleus and the peaks at 55–57 ppm due to the methoxyl component of lignin. Thus it appears that although a large portion of the carbohydrate component of the litter had degraded, some lignin fraction may still be present in the sample. There appears to be a sequential degradation of the wood. The carbohydrate components appeared to degrade first and the litter was enriched with the lignin fraction. However, the level of degradation appeared to be different for the different samples and this could help explain the differences in the HHVs of the different biocrude oil samples.

3.2.2. Biochar

The biochar yield also varied strongly among the feedstocks and these ranged from 13 wt% to 40 wt% (Table 1). The biochar yield was obviously influenced by the ash content of the sample. The ash constituted about 24–54 wt% of the biochar (Table 5). The sample with the highest ash content had the highest biochar yield. The hardwood which had the lowest ash content had the lowest biochar yield. When the biochar yields were calculated on ash-free basis the trend was similar to the combined ash and biochar.

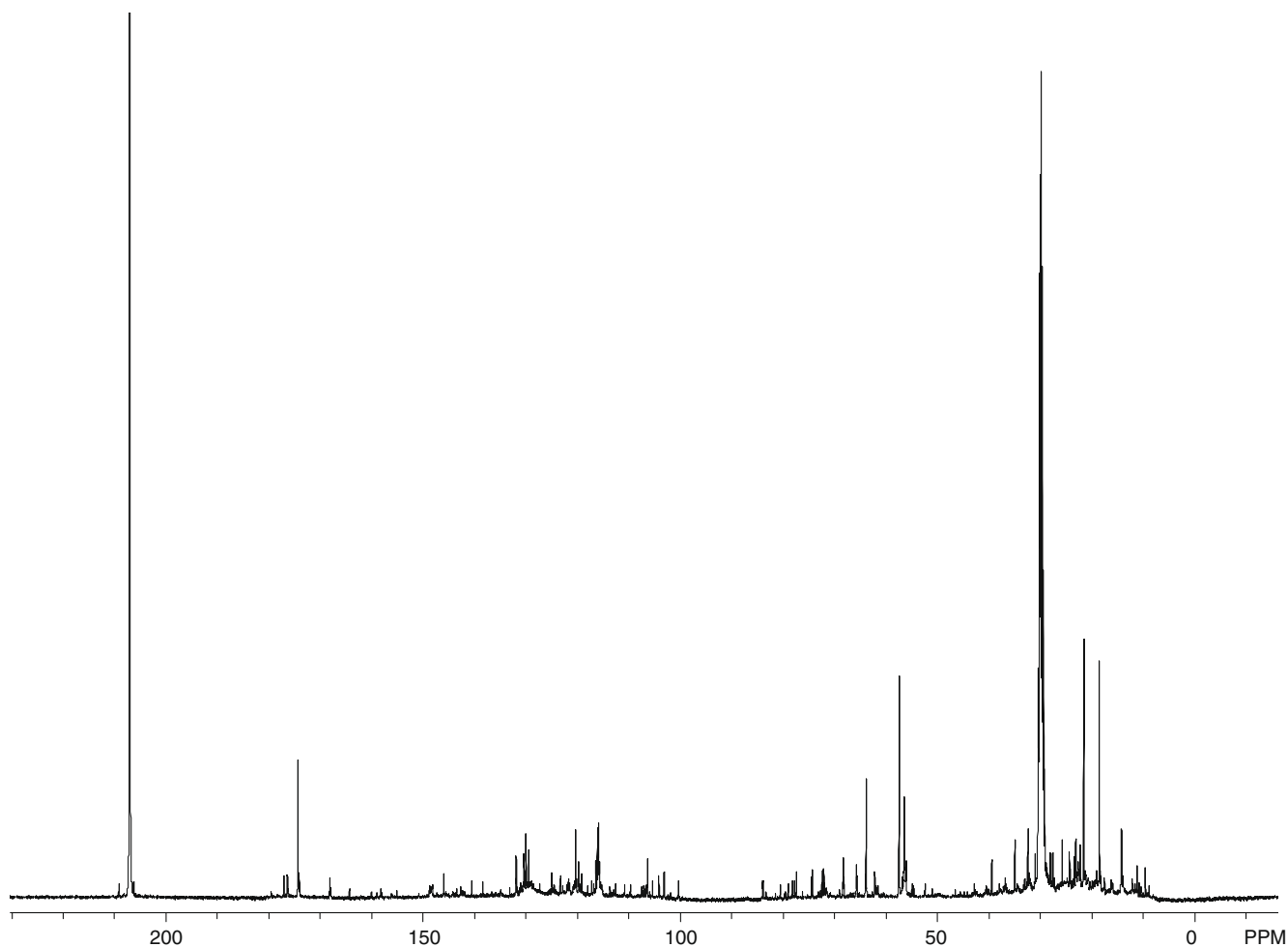


Fig. 9. ^{13}C NMR spectrum of Broiler litter biocrude oil.

Table 5

Elemental composition and higher heating values of poultry litter and hardwood bedding biochars.

Samples	Ash (wt%)	Elements (wt%, dry basis)						HHV (MJ/kg)
		C	H	N	S	Cl	O	
Hardwood bedding	27.28	44.60	1.96	1.18	0.28	0.89	23.51	23.49
Chicken litter								
Broiler-1	43.79	23.40	1.36	1.73	0.83	1.53	27.36	11.83
Broiler- 2	54.53	33.74	1.70	2.38	1.62	3.35	2.68	14.49
Broiler-3	52.4	29.00	1.10	2.00	1.38	2.36	11.76	11.55
starter turkey litter	24.64	54.37	2.70	1.82	0.36	0.88	15.23	23.41

Table 6

Inorganic components of biochars from poultry litters and hardwood bedding.

Element	Broiler-1	Broiler-2	Broiler-3	Starter turkey	Hardwood bedding
P (%)	1.68	2.59	1.73	1.30	0.09
K (%)	5.65	7.59	6.04	3.22	1.06
Ca (%)	6.55	8.64	5.73	4.37	1.56
Mg (%)	1.16	1.88	1.45	0.79	0.17
Na (%)	1.48	2.03	2.00	0.52	0.17
Al (%)	0.54	0.49	0.43	0.07	0.03
B (%)	bdl	0.01	0.01	0.01	bdl
Fe (%)	0.62	0.57	0.38	0.12	0.12
Mn (%)	0.08	0.13	0.08	0.1	0.02
Cu (ppm)	0.08	0.11	0.16	0.05	0.01
Zn (ppm)	0.08	0.13	0.08	0.08	0.01
Cd (ppm)	4	3	1.00	2.0	1.00
Ni (ppm)	45	53	32	31	26
Se (ppm)	1.2	1.5	1.4	0.6	0.2
Mo (ppm)	11	bdl	18	bdl	bdl

The biochar was composed of several elements including carbon, potassium, phosphorous, silicon, calcium, hydrogen, oxygen, and trace amounts of cadmium and arsenic (Table 5 and 6). The carbon content of the litter biochars were very low compared to that from the hardwood bedding biochar. Surprisingly, there was an appreciable amount of nitrogen in the biochar in all the poultry litter biochars, but was very low in the wood biochar (Table 5). The chlorine and sulfur contents of the biochars were also relatively high. The chlorine and sulfur were probably tied up in the biochar as chlorides and sulfates. Our X-ray microprobe analysis of the biochar showed a strong peak of potassium chloride (unpublished data).

Potassium, phosphorous, calcium, sodium, and magnesium contents were relatively high in the poultry litter biochars compared to the hardwood bedding biochar (Table 5). In general, the poultry litter biochars were richer in inorganic elements than the hardwood biochar. Thus, the poultry litter biochars could potentially be used as either a soil conditioner or a slow-release fertilizer.

3.2.3. Pyrolysis gases

The gas yields were determined by difference and ranged from 13 wt% to 24 wt% for all samples. The gas yields from the poultry litter were relatively high and did not appear to follow any specific pattern. The major components of the gas were carbon dioxide and carbon monoxide with small fraction of low molecular weight hydrocarbons. The composition of the poultry litter pyrolysis gases were similar to those from the hardwood bedding.

4. Conclusion

Poultry litter contains relatively large fractions of ash which are rich in potassium, phosphorus, calcium, and magnesium but can be pyrolyzed between 450 and 550 °C producing a viscous brown biocrude with pH about 6. The poultry litter biocrude oils have much higher calorific value than the corresponding hardwood biocrude

oil, but have relatively high nitrogen content compared to hardwood biocrude oils. The higher calorific value of the poultry litter biocrude oils appear to correlate directly with the protein content of the raw litter. The composition and properties of the biocrude oils depends on the poultry litter source and shows a considerable variation among samples.

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