USING BROILER LITTER AS AN ENERGY SOURCE: ENERGY CONTENT AND ASH COMPOSITION

J. P. Chastain, A. Coloma-del Valle, K. P. Moore

ABSTRACT. *Broiler farms produce large amounts of litter that is typically spread on nearby cropland or is sold to other farmers for use as a fertilizer substitute. Burning litter biomass to provide energy for space heating in broiler houses or for off-site electric generation has been viewed as an attractive alternative to land application and a source of renewable energy. A large litter sample was obtained from a commercial broiler farm following clean-out to evaluate the energy content, ash yield, and characteristics of ash following combustion. Litter ash was evaluated as a possible lime substitute and fertilizer. The energy content of the broiler litter was 14,425 kJ/kg$_{DM}$ and had an ash content of 24.7% dry basis. Broiler litter ash contained large amounts of Ca and a pH of 11.6, however the calcium carbonate equivalency (CCE) was only 32.4% on a dry basis. It was determined that broiler litter ash should not be used as a liming agent since it would result in excessive application of P_2O_5, K_2O, Cu, Zn, and Na. Small applications of litter ash, on the order of 2 t/ha or less, can provide the P or K needs of a crop and can serve as a source of key micronutrients without application of large amounts of Zn, Cu, or Na. A 1-MW litter fueled electric power plant would provide enough P_2O_5 in litter ash to fertilize only 1600 ha at a rate of 100 kg P_2O_5/ha. It was also estimated that only 59% of the electrical generating capacity would be available for use by the distribution system over and above the electricity required by the broiler houses that supply litter to the plant. The amount of litter produced on broiler farms is theoretically adequate to provide enough heat to eliminate the purchase of propane for space heating but is limited by heating system efficiency. The amount of land needed to accommodate the ash from an on-farm litter furnace was estimated to be about 20 ha per broiler house. Many technical and economic obstacles need to be overcome to see large scale use of litter as a source of biomass fuel.*

Keywords. *Poultry litter, Waste utilization, Bioenergy, Application to land, Application rates, Nutrient management.*

Broiler chicken litter is a mixture of manure, bedding, wasted feed, and moisture. The type of bedding used in a broiler houses varies depending on the location of the farm. The most common type of bedding material used in broiler buildings in the southeastern United States is pine shavings. However, peanut hulls, chopped straw, rice hulls, or other types of organic materials are used in areas where such agricultural residues are available (Koon et al., 1992).

Broiler farms produce 850 to 1140 kg of litter per 1,000 birds sold depending on bedding practices and frequency of litter removal (Chastain et al., 2001). Using a litter production rate of 995 kg of litter per 1,000 birds sold, a broiler house that holds 23,400 birds per flock and produces 5.5 flocks per year will produce about 128 metric tons of litter per year (t/yr). In most cases, litter is spread on adjacent cropland at the agronomic rate for nitrogen or is transported by brokers to other farmers for use as a fertilizer substitute. Application of litter at the agronomic rate for nitrogen will eventually lead to excessive amounts of plant extractable-P in the soil, due to the high concentration of P relative to N in litter.

Poultry litter contains valuable major and minor plant nutrients, and a significant amount of energy. The dry basis heat content (HHV) of broiler litter is on the order of 14,300 kJ/kg$_{DM}$ (Hegg and Gerwig, 1997; Mukhtar et al., 2002; Davalos et al., 2002; Singh et al., 2008). The net heat content (LHV) of litter at 24% moisture is compared to common solid fuels used for space heating and electric power generation in table 1. Poultry litter compares favorably with wood chips and lignite. The net heat value of wood chips with a moisture content of 35% is only 17% greater than poultry litter and the LHV of lignite is only 26% greater than litter. The significant LHV of litter combined with large quantities being available throughout the year has led many poultry producers and some power generation companies to consider using poultry litter as a combustion fuel for space heating or electrical generation. Using litter for on-farm space heating or off-site electric power generation may reduce potential negative environmental impacts on surface water associated with over-application of litter or application of litter in environmentally sensitive areas (Priyadarsan et al., 2004; Priyadarsan et al., 2005; Costello, 2007).

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Table 1. Comparison of the net energy (LHV) of poultry litter to other common solid fuels.

	Net Heat (LHV) (kJ/ wet kg)	Moisture Content (% w.b.)	Litter Required to Provide Equivalent Net Energy (t)
Litter (14,300 kJ/dry kg) [a]	10326	24	1.0
Wood chips (19,880 kJ/ dry kg) [b]	12132	35	1.17
Cord wood (19,880 kJ/ dry kg)	15452	20	1.50
Lignite [c]	14000	34	1.36
Sub-bituminous coal [c]	19600	15 - 20	1.90
Bituminous coal [c]	29100	15 - 20	2.82

[a] Mean HHV from Hegg and Gerwig (1997), Mukhtar et al. (2002), Davalos et al. (2002), and Singh et al. (2008).
[b] HHV of soft wood from White (1987).
[c] LHV from Rozgonyi and Szigeti (1984).

Combustion of poultry litter to produce electrical energy has been implemented in both Europe and the United States (e.g. Walmsley, 2006; Fibrowatt, 2008). In some cases, poultry litter from many farms was transported to a centralized location to mix with either coal or other biomass to generate electricity (Keener et al., 2002; Mukhtar et al., 2002, Priyadarsan et al., 2005; Walmsley, 2006). Furthermore, furnaces have been developed that allow litter to be used for on-farm space heating while minimizing harmful emissions to the air (e.g. Habetz and Echols, 2006).

There is a great amount of interest in burning broiler litter to provide on-farm space heating requirements for brooding due to elevated fuel prices. Over the last 10 years, the contract propane (LPG) price for poultry producers in the southeastern United States has increased from US$0.21/L of LPG to as much as US$0.52/ L of LPG. On-farm data indicated that newer, insulated broiler houses required 8,150 to 12,200 L of LPG per 1000 m^2 of house floor area per year with a typical value of 9779 L LPG/1000 m^2/yr (Tabler et al., 2001; Chastain, 2008). Consequently, a six-house broiler farm (1951 m^2/house) will required on the order of 114,471 L of propane a year that cost US$59,524/yr.

An experimental litter furnace was tested at the research broiler farm at the University of Arkansas (Costello, 2007). The experimental furnace was installed in a single commercial broiler house and used a fan to supply combustion air to the burn chamber. Broiler house air was heated using an air-to-air heat exchanger to extract energy from the hot exhaust gases into a ducted air stream that carried heated air to the house. High velocity stirring fans were used to distribute the air within the house. This study demonstrated the technical feasibility of burning broiler litter in a furnace. However, the total system delivery rate and system efficiency needed to be improved. On-farm tests indicated that only 24% of the heat extracted from the litter was actually delivered to the building. Experience gained in this study provided insights to improve system efficiency and delivery rate. The author indicated that an improved system that operates at an overall system efficiency of 40% would be able to supply at least 80% of space heating needs.

Using the litter produced on a broiler farm as a fossil fuel replacement may provide an alternative to traditional land application. However, a significant quantity of ash will be produced when litter is burned under optimal conditions (Habetz and Echols, 2006). Ash comprises 20% to 33% of the total litter dry matter depending on the amount of organic bedding used and the amount of soil incorporated in the litter mass during litter decaking, tilling, and clean-out.

Poultry litter ash has been shown to have high concentrations of plant nutrients, calcium, and minor plant nutrients (Codling et al., 2002; Mukhtar et al., 2002; Costello, 2007; Pagliari et al., 2009). The high calcium content of poultry litter ash has caused some to recommend its use as a lime substitute (e.g. NRAES, 1999). However, the liming value can only be evaluated by obtaining a measurement of the calcium carbonate equivalency. The calcium carbonate equivalency is the acid-neutralizing capacity of a liming material expressed as percent by weight of pure calcium carbonate, $CaCO_3$ (Harris and Risse, 1999).

The objectives of this project were: (1) measure energy content, ash content, and plant nutrient and mineral content of broiler litter from a commercial broiler farm in South Carolina, (2) determine calcium carbonate equivalency, and plant nutrient and mineral content of ash following complete combustion, (3) evaluate the use of broiler litter ash as a lime substitute and fertilizer, and (4) evaluate the potential energy and ash production benefits associated with burning litter for on-farm space heating and off-site electric power generation.

Methods

A large quantity of broiler litter was obtained from a commercial farm in Lexington County, South Carolina. The litter was placed in three covered plastic bins with a volume ranging from 28 to 50 L per bin. The total litter volume obtained was about 100 L. The litter was stored in the plastic bins during transport to Clemson University and in the laboratory prior to analysis and combustion.

The broiler litter used for this study was obtained after complete house clean-out. The bedding material used was pine shavings and approximately six flocks of broiler chickens were raised on the litter prior to clean-out. On-farm litter management included removing caked manure between flocks and the addition of pine shavings. Large amounts of bedding were used as evidenced by pine shavings being readily visible in the entire mass of litter that was removed from the house. Other litter conditioning practices between flocks were not documented.

The content of each of the storage bins was mixed well with a shovel and 12 samples were collected from the 3 storage bins for plant nutrient and solids analysis. An additional 16 samples were collected in the same manner to quantify the energy content of the litter.

CONSTITUENTS MEASURED IN BROILER LITTER

Twelve litter samples were taken to the Agricultural Service Laboratory at Clemson University for plant nutrient analysis. The quantities measured were: total Kjeldahl nitrogen, nitrate nitrogen (NO_3-N), total ammoniacal nitrogen (TAN = NH_4^+-N + NH_3-N), total phosphorus (expressed as P_2O_5), total potassium (expressed as K_2O), calcium, magnesium, sulfur, zinc, copper, manganese, sodium, moisture content, and pH. The organic nitrogen content was calculated as: Org-N = TKN – TAN. The total nitrogen content was calculated as: TN = TKN + NO_3-N. The total P, K, and other minerals were all determined using ICP mass spectrometry using standardized procedures (CUASL, 2006). The TAN was determined using a standard H_2SO_4 titration technique with a boric acid indicator (CUASL, 2006).

The total and fixed solids content of the litter samples were measured in the Agricultural, Chemical, and Biological Research Laboratory in the Department of Biosystems Engineering at Clemson University using standard drying and incineration techniques (APHA, 1999). Three subsamples of broiler litter were placed in porcelain dishes and dried in an oven at 105°C for a period of 24 to 36 h. Total solids were determined after the samples were allowed to cool in a desiccator. Fixed solids (FS) were determined by incinerating the dried solids in a furnace at 550°C for 2 to 3 h and allowing the sample to cool in a desiccator and weighing its contents. Volatile solids (VS) were calculated as the difference between total and fixed solids.

Bulk density was measured by placing a litter sample in a metal container with a calibrated volume and mass. The metal container had a volume of 323±1.7 mL with a mass of 57.26 g. The litter bulk density was calculated as the litter mass divided by the container volume.

MEASUREMENT OF ENERGY CONTENT OF LITTER

The energy content of broiler litter was measured using feed and forage nutrition analysis techniques. The nutrition method was selected because the available micro-bomb calorimeter could only accommodate a very small sample (25 mg or less). Therefore, the required sample size of the available micro-bomb calorimeter was judged to be too small for measurement of the energy content of broiler litter. The nutritional method allowed use of a larger ground sample (0.5 g for protein and fiber, 2 g for fat).

Total energy content of the litter on a dry matter basis was calculated by adding the energy contributions of crude protein, fat, and total carbohydrates. Sixteen litter samples were analyzed to determine crude protein, fat, neutral detergent fiber (NDF), and nonfiber carbohydrates contents on a dry matter basis. The analyses were performed using standard nutrition techniques at the Agricultural Service Laboratory at Clemson University (CUASL, 2006). The total carbohydrate content was the sum of fiber and nonfiber carbohydrates (Jenkins, 2004; Moore, 2004). The equation used to calculate the total energy content of the litter was (Jenkins, 2004):

$$TE = \left(5.65\frac{kcal}{g}CP\right) + \left(9.45\frac{kcal}{g}F\right) + \left(4.18\frac{kcal}{g}TC\right) \quad (1)$$

where
TE = energy content (kcal/kg_{DM}),
CP = crude protein content (g/kg_{DM}),
F = fat content (g/kg_{DM}), and
TC = total carbohydrate content (g/kg_{DM}).

COMPOSITION OF BROILER LITTER ASH

Burning broiler litter as an alternative fuel will generate large amounts of ash. Broiler litter ash could possibly be used as a liming agent for soil. Knowledge of nutrient content, pH, and calcium carbonate equivalency is required to evaluate utilization options for the ash.

Large amounts of broiler litter were combusted in a furnace at 550°C. Litter was allowed to burn in the furnace for two to three days to allow for complete combustion. Litter samples were burned until enough ash was generated to provide three 470-mL samples. These three samples were sent to the Agricultural Service Laboratory at Clemson University for analysis to determine the same constituents as previously described for litter (except for NO_3-N) and calcium carbonate equivalency.

Calcium carbonate equivalency (CCE) was measured to determine the acid-neutralizing capacity of broiler litter ash. The CCE is defined as the acid-neutralizing capacity of a material relative to that of pure calcium carbonate (e.g. calcite) and is expressed as a percentage. Calcium carbonate equivalency of broiler litter ash was determined by the Agricultural Service Laboratory at Clemson University using standard NaOH titration techniques. The complete procedure is provided by the laboratory director at CUASL (2006).

The effect of complete combustion of litter on constituent concentrations was determined by comparing mean constituent concentrations in broiler litter to mean constituent concentrations in litter ash on a dry matter basis. A t-test (α = 0.025) of independent samples and unequal variances was used for this comparison (Steel and Torrie, 1980). The constituent concentration was compared using a concentration ratio, CR_J, which was calculated as:

$$CR_J = \frac{C_{A,J}}{C_{L,J}} \quad (2)$$

where
$C_{A,J}$ = concentration of jth constituent in ash (g/kg_{DM}), and
$C_{L,J}$ = concentration of jth constituent in litter (g/kg_{DM}).

RESULTS AND DISCUSSION

PLANT NUTRIENT, SOLIDS CONTENT AND BULK DENSITY

Concentrations of solids, plant nutrients, and other defined constituents of the broiler litter used in this study

Table 2. Characteristics of broiler litter as removed following six flocks of broiler chickens (n = 12).

Constituent	Mean (% wet basis)	Standard Deviation (% wet basis)	Coefficient of Variation (%)
TN	2.87	0.167	5.82
Org-N	2.19	0.168	7.67
TAN	0.50	0.050	10.0
NO_3-N	0.18	0.021	11.7
P_2O_5	3.28	0.169	5.15
K_2O	2.87	0.128	4.46
Ca	2.18	0.069	3.17
Mg	0.45	0.027	6.00
S	0.53	0.023	4.34
Zn	0.03	0.002	6.67
Cu	0.03	0.002	6.67
Mn	0.03	0.002	6.67
Na	0.67	0.029	4.33
TS	75.56	0.471	0.62
VS	53.86	1.077	2.00
FS (ash)	21.70	0.900	4.15
pH	8.7	0.10	1.15
Bulk density (kg/m^3)	422.0	15.51	4.1

Mean Moisture Content = 24.4%
VS, dry basis (VS/TS) = 71.3%
FS, dry basis (FS/TS) = 28.7%
Org-N/TN = 76.2%
NO_3-N/TN = 6.4%

are given in table 2. On average, the litter used in this study was composed of 75.56% dry matter (TS), of which 71.3% was VS (VS/TS). Ash or fixed solids (FS) composed 28.7% of the dry matter (FS/TS). The litter contained equivalent amounts of TN and K_2O (2.87%) and 3.28% P_2O_5. Organic-N accounted for 76.2% of the TN and 6.4% of the TN was in the nitrate-N form. Small but significant concentrations of micronutrients and sodium were present in the broiler litter as indicated in the table. Litter pH was 8.7 and was indicative of no or minimal use of acidifying litter treatment such as aluminum sulfate.

The low bulk density of litter is one of the factors that limit how far litter can be economically transported for use as biomass fuel or fertilizer replacement. The mean bulk density of the litter used in this study was 422 kg/m^3 with a moisture content of 24.4%. Henry (1990) measured the bulk density of litter after clean-out from four broiler houses that used pine shavings for bedding and found that the bulk density ranged from 420 kg/m^3 for litter at a moisture content of 20.24% to 440 kg/m^3 for litter at 24.12% moisture. The litter used in this study agreed with Henry's observation at 24.12% within 4.3%. Bernhart and Fasina (2009) provided a detailed study of the physical properties of whole and fractionated poultry litter. They reported a whole litter bulk density of 542 kg/m^3. However, the moisture content was not provided. Moisture content affects the bulk density of all loose solid materials such as straw, litter, and grain. Therefore, the lack of agreement between the value obtained by Bernhart and Fasina (2009) and the present study may be due to a higher moisture content. For detailed information on the pressures required to compact litter the reader is referred to Bernhart et al. (2010).

Table 3. Energy and solids content of broiler litter sample using the nutrition method (n = 16)

	Mean	Standard Deviation	CV (%)
Moisture (%)	29.6	2.724	9.21
Fixed solids, ash (% dry basis)	24.7	3.079	12.5
Crude protein (g/kg_{DM})	183	16.48	9.03
Fat (g/kg_{DM})	6	2.024	35.6
Total carbohydrates (g/kg_{DM})	565	36.112	6.39
Total energy, dry basis ($kcal/kg_{DM}$)[a]	3448	131.84	3.82
Fraction of total energy from carbohydrates	68.5%		
Fraction of total energy from protein	29.9%		
Fraction of total energy from fat	1.6%		
Total energy (HHV), dry basis (kJ/kg_{DM})	14,425	551.62	3.82
Total energy per mass combusted (kJ/kg VS)	19,157		
Net energy (LHV), as sampled (kJ/ wet kg)[b]	9487		

[a] Calculated using equation 1.
[b] Net energy calculated assuming latent heat of vaporization = 2257 kJ/kg of water.

ENERGY AND ASH CONTENT

The results of the nutritional analysis are given in table 3. Broiler litter from the farm used in this study contained 14,425 kJ/kg_{DM}. The majority of the energy, 68.5%, was derived from the carbohydrate fraction of the biomass followed by protein (29.9%). Mean ash content of these 16 samples was 24.7% which was lower than the ash content of the 12 samples used for nutrient and solids content (28.7%, table 2). This discrepancy was believed to be a result of the longer combustion period (2 to 3 days) provided to yield the large ash samples for ash composition analysis. The longer combustion period allowed for more complete combustion of carbon in the samples.

The high heat value (HHV, kJ/kg_{DM}) of the broiler litter used in the present study is compared to the results obtained in other comparable studies in table 4. Only heating values obtained for fresh, whole, unprocessed litter samples were included in the table. Mean heating values from all of the referenced studies were within the 95% confidence interval about the mean of the current study. Therefore, the nutrition method was able to yield heating values that were not significantly different from a bomb calorimeter.

The nutrition method and a bomb calorimeter do not provide the chemical composition (C,H,O,N,S) or measures of fixed carbon and pure ash needed to evaluate combustion performance and potential for slag formation. Instead, proximate and ultimate analyses are required. Detailed information for broiler litter and using proximate and ultimate analyses is provided by Mukhtar et al. (2002) and Priyadarsan et al. (2004).

The heating value of coal and biomass materials is often compared by expressing the data on a dry ash-free basis. The exact value can only be obtained if the fixed carbon content of the fixed solids is provided using proximate analysis. Dry ash-free heating value of litter in the present study was estimated as energy content per unit mass of solids burned (kJ/kg VS). The value was 19,157 kJ/kg VS and agreed within less than 1% of the dry ash-free (daf) heating value of litter removed from a broiler house in Texas (19,090 kJ/kg daf, Mukhtar et al., 2002).

Table 4. Comparison of heat content of unprocessed poultry litter obtained by the nutrition method with data from the literature.

Litter Type	Mean - C.I [a] (kJ/kg$_{DM}$)	Mean HHV (kJ/kg$_{DM}$)	Mean + C.I. (kJ/kg$_{DM}$)	Method	Source
Chicken	14,009	14,425	14,841	Nutrition	Current study
Chicken		14,159		Bomb	Hegg and Gerwig (1997)
Turkey		14,376		Bomb	Hegg and Gerwig (1997)
Chicken		14,257		Bomb	Mukhtar et al. (2002)
Chicken		14,447		Bomb	Davalos et al. (2002)
Chicken		14,400		Bomb	Singh et al. (2008)

[a] The C.I. is the 95% confidence interval.

COMPOSITION OF BROILER LITTER ASH

Burning litter to produce energy for space heating on poultry farms will yield large quantities of ash that must be managed by the producer. Ash yield will be on the order of 25% of litter dry matter. Knowledge of the composition and liming value of litter ash would be required to develop environmentally sound utilization alternatives for litter ash. Nutrient and mineral concentrations, calcium carbonate equivalency, and pH of broiler litter ash after complete combustion were determined and are given on a dry basis in table 5.

For all practical purposes combustion removed all nitrogen. Total ammoniacal nitrogen was below the detection limits of the analysis method. A t-test ($\alpha = 0.025$) confirmed that the small amount of TN contained in the litter ash was not significantly different from zero. It was also determined that combustion significantly increased the concentration of all of the measured plant nutrients and minerals.

While broiler litter ash did not contain significant amounts of nitrogen, the data indicated that it contained substantial amounts of other major and minor plant nutrients. Broiler litter ash contained 9.12% P_2O_5, 7.86% K_2O, 5.81% Ca, 1.26% Mg, and 1.16% S on a dry basis. In spite of the high Ca content and high pH (11.6), the calcium carbonate equivalency of litter ash was only 32.4% (dry basis). Therefore, one metric ton of dry ash had the same liming value as about 0.3 dry metric tons of lime. It is believed that the CCE was lower than expected due to the presence of other elements that tend to acidify soil, such as S and Al. Data provided by Mukhtar et al. (2002) indicated that litter ash contained large amounts of Al (1.23% as AL_2O_3). Litter ash had a relatively large amount of Na at 1.82%. Such a high concentration of Na may be of concern if ash is to be applied to land.

The constituent concentration ratios (*CR*) provided a means to compare the composition of litter before and after combustion and they are shown in table 5. All plant nutrients and minerals in the litter ash were higher in concentration than in unburned litter. The constituent concentration ratio, *CR*, indicated that concentrations of P_2O_5, K_2O, Ca, Mg, Cu, and Na were twice as high in the litter ash as compared to litter. The S, Zn, and Mn concentrations were 65% to 80% higher in ash relative to litter. This would suggest constituents were either lost in exhaust gas, as in the case of N and S, or concentrated as a result of the combustion process.

LAND APPLICATION OF BROILER LITTER ASH

Extension literature has proposed using litter ash as a liming agent for many years (e.g. NRAES, 1999). Knowledge of the nutrient concentrations in litter ash is extremely important if ash is to be applied as a liming agent

Table 5. Comparison of the composition of broiler litter and ash following combustion on a dry basis.[a]

	Broiler Litter		Broiler Litter Ash		
Constituents	Mean (g/kg ash$_{DM}$)	SD[b] (g/kg ash$_{DM}$)	Mean (g/kg ash$_{DM}$)	SD[c] (g/kg ash$_{DM}$)	*CR*[d]
TN	31.9	5.06	0.23*[e]	0.15	0.007
TAN	6.6	0.66	ND*[f]	-----	0
P_2O_5	43.4	4.62	91.22*	5.18	2.10
K_2O	37.9	3.22	78.56*	5.23	2.07
Ca	28.9	2.80	58.10*	2.61	2.01
Mg	6.0	0.65	12.60*	0.82	2.10
S	7.0	0.57	11.57*	1.51	1.66
Zn	0.4	0.04	0.74*	0.03	1.75
Cu	0.4	0.05	0.78*	0.06	2.00
Mn	0.5	0.05	0.90*	0.04	1.80
Na	8.9	0.76	18.16*	1.05	2.04
CCE[g]	NM[h]	---	324.24	59.33	NM
pH	8.7	0.10	11.6*	0.12	1.33

[a] Moisture content of ash = 1.01% ± 0.093%.
[b] Based on 12 replications.
[c] Based on three replications.
[d] *CR* = concentration ratio defined by equation 2.
[e] Not significantly different from zero.
[f] None detected.
[g] Calcium Carbonate Equivalency (to convert to percent divide by 10).
[h] Not measured.
* Significantly different from broiler litter using a t-test ($\alpha = 0.025$).

to soil. The considerable concentrations of plant nutrients indicated that litter ash had significant fertilizer value, and misuse could pose a risk to water quality.

Broiler litter ash was found to have a mean CCE of 32.1%, on a wet basis. Table 6 compares the CCE of litter ash with different liming materials and the mass required to achieve the liming value of one ton of pure calcium carbonate, $CaCO_3$ (Harris and Risse, 1999). Broiler litter ash had a low CCE relative to other liming materials except for wood ash.

Common recommendations for lime application range from 1.0 to 4.0 t/ha. Therefore the amount of litter ash needed as a lime substitute can range from 3.1 to 12.4 t/ha. The constituent application rates resulting from litter ash application rates of 3.1, 6.2, and 12.4 t/ha were calculated and the results are shown in table 7.

The three different lime application rates shown in table 7 resulted in high applications of P_2O_5. Application of 3.1 to 12.4 metric tons of ash/ha would result in application of 280 to 1120 kg of P_2O_5/ha. The actual amount of P_2O_5 recommend for application to a particular field will depend on soil test, crop type, and anticipated yield. However, common fertilizer recommendations range from 40 to 160 kg P_2O_5/ha (Mylavarapu and Franklin, 1997). The results provided in the table indicate that use of litter ash as a lime substitute will result in P_2O_5 application rates that exceed fertilizer recommendations by 75% to 2700%. Consequently, use of litter ash as a lime substitute could be an extreme threat to surface water quality in locations where transport of soluble or organic phosphorus to streams, lakes, or wetlands is highly probable.

The application rates for K_2O indicated in table 7 were also high and are excessive since typical application rates for crop and pasture land range from 44 to 225 kg/ha (Mylavarapu and Franklin, 1997). Excessive K_2O application rates on pastures or hay fields can result in K concentrations in the plant material that can cause milk fever in dairy cows (Adams et al., 1996; Goff and Horst, 1997) and grass tetany in beef animals (Ward and Lardy, 2005). Therefore, repeated use of litter ash to raise the soil pH in a pasture or hay field is not recommended.

The results in table 7 also demonstrate that using litter ash at rates of 6.2 t/ha or more would result in high application rates for Zn, Cu, and Mn (Mylavarapu and Franklin, 1997). Supplemental application of zinc, copper, and manganese are only recommended if soil and plant tissue analyses indicate that a deficiency exists. If these minor nutrients are needed, typical supplemental rates are on the order of only 3 to 6 kg/ha (Mylavarapu and Franklin, 1997). If litter ash is applied repeatedly to a field as a lime substitute, elevated soil-test values of these minor nutrients would be expected and crop toxicities may occur. Reduced plant growth and yield due to Zn toxicity has been observed in peanuts, soybeans, and cotton in the Southeastern United States. Raising soil pH can eliminate many of these problems, but not at high soil test values. If soil pH is increased too much to deal with excess Zn, deficiencies of other micronutrients (e.g. Mn or Cu) may be induced (Mylavarapu and Franklin, 1997; Camberato, 2003).

Table 6. Comparison of calcium carbonate equivalency of litter ash with liming materials.[a]

Liming Material	CCE (%, wet basis)	Mass required to equal 1.0 metric ton of $CaCO_3$ (metric tons)
Calcite ($CaCO_3$)	100	1.0
Calcitic limestone	75 to 100	1.0 to 1.3
Dolomitic limestone ($CaMg(CO_3)_2$)	85 to 109	0.92 to 1.2
Burned quick lime (CaO)	179	0.57
Slag containing CaO + impurities	25 to 70	1,4 to 4.0
Wood ash	30 to 70	1.4 to 3.3
Broiler litter ash	32.1	3.1

[a] Mylavarapu and Franklin (1997); Harris and Risse (1999).

Table 7. Constituent application rates resulting from using broiler litter ash to provide $CaCO_3$ associated with common lime application rates (wet basis).

Lime Application Rate (t/ha)		1.0	2.0	4.0
Equivalent Broiler Litter Ash Application Rate (t/ha)		3.1	6.2	12.4
Constituent	Mean ($kg/1000\ kg_{ash}$)	Constituent Application Rates (kg/ha)		
P_2O_5	90.29	280	560	1120
K_2O	77.77	241	482	964
Ca	57.51	178	357	713
Mg	12.47	39	77	155
S	11.45	35	71	142
Zn	0.73	2	5	9
Cu	0.77	2	5	10
Mn	0. 89	3	6	11
Na	17.97	56	111	223

Magnesium and sulfur are the most commonly applied minor plant nutrients and supplemental applications are governed by soil type and results of subsoil analysis. Regular application of dolomitic limestone generally maintains the soil concentration of Mg at sufficient levels. Supplemental application rates of Mg are recommended if subsoil levels are low and lime is not required to raise soil pH. When Mg supplementation is needed the rates are in the range of 11 to 20 kg Mg/ha. Sulfur applications are common on sandy soils with clay subsoil that is greater than 51 cm from the soil surface. Soils with high clay content rarely require S supplementation. When S is required the typical rate ranges from 11 to 22 kg S/ha (Schulte and Kelling, 1992). Use of litter ash as a lime substitute will result in periodic Mg and S application rates that are over three times recommended supplemental rates. Elevated concentrations of Mg generally do not result in plant toxicity, however excess Mg can increase the rate of S leaching. Very high rates of S application can result in lowered soil pH. The persistence of the drop in pH will depend on the buffering capacity of the soil.

Using litter ash as a lime substitute at rates over 6 t/ha would result in high application of sodium and would most likely be harmful to soil and plants. Long-term use of litter ash as a lime substitute would have the potential to render a field unusable due to elevated Na concentrations due to excessive application (much in the form of NaCl).

The results of this study demonstrated that broiler litter ash should not be used as a lime substitute in spite of the high Ca content and pH. Burning litter doubles the concentration of P_2O_5, K_2O, Na, and minor plant nutrients in litter ash as compared to litter. The large amount of broiler litter ash needed to replace typical lime application rates would be expected to result in excessive P_2O_5, K_2O, Ma, S, Cu, Zn, and Mn accumulation in the soil that may reduce soil productivity and forage quality. High concentrations of phosphorus and other plant nutrients near the soil surface could be a source of increased eutrophication for nearby surface waters.

While poultry litter ash is not suitable as a lime substitute the high concentrations of P, K, and minor nutrients (S, Mg, Mn) make it a possible substitute for conventional P and K fertilizers.

Two studies evaluated the efficacy of using poultry litter ash as a source of P fertilizer. The earliest study was a controlled pot study using wheat (Codling et al., 2002) and the most recent was a field study that used poultry litter ash from a power plant to fertilize alfalfa (Pagliari et al., 2009). The P_2O_5 application rates used in these studies ranged from 84 to 181 kg/ha. Both studies concluded that poultry litter ash was an effective, plant available source of P_2O_5 fertilizer. The study performed by Pagliari et al. (2009) also demonstrated that the K, S, Cu, and Zn contained in litter ash were also well utilized by alfalfa. They also noted that Na concentrations were elevated in the soil after application of poultry litter ash, but they were less than the levels that would induce plant toxicity.

The impact of using poultry litter ash as a source of P and K was investigated by determining the ash application rate required to provide a wide range of P_2O_5 fertilization rates. The resulting application rates for each of the constituents in the litter ash were calculated. The results are provided in table 8.

In most soils and for most crops, the agronomic rate for P_2O_5 is 100 kg/ha or less. Consequently, litter ash application rates would typically be only one metric ton or less. At these rates, litter ash would provide the entire P requirement and possibly all of the K_2O depending on soil status. The amount of Ca, Mg, and S provided would be a good soil supplement without being problematic in most cases. In addition, the Na application rates would be low enough to be of little concern. A few crops, like alfalfa or coastal Bermudagrass, may require more than 100 kg P_2O_5/ha if the soil-test results are low in P. Application of litter ash would be decreased as the pool of available P is built up in the soil over a period of a few years. Therefore, application of litter ash at rates of 2.77 t/ha for only one or two years would not be expected to cause toxicity problems

Table 8. Constituent application rates resulting from application of poultry litter ash to provide fertilizer recommendations for P_2O_5.

Agronomic Rate for P_2O_5 (kg /ha)	40	60	100	160	250
Litter Ash Application Rate (t/ha)	0.44	0.66	1.11	1.77	2.77
	Resultant Constituent Application Rates (kg/ha)				
K_2O	35	52	86	138	215
Ca	26	38	64	102	159
Mg	5.5	8.3	14	22	35
S	5.1	7.6	13	20	32
Zn	0.3	0.5	0.8	1.3	2.0
Cu	0.3	0.5	0.9	1.4	2.1
Mn	0.4	0.6	1.0	1.6	2.5
Na	8.0	12	20	32	50

from Na, Zn, or Cu. The agronomic rate for K_2O for most crops is about 100 kg/ha and can be supplied by 1.28 t ash/ha. Therefore, the amount of litter ash needed to provide fertilizer recommendations for K_2O, 1.28 t ash/ha, would not be expected to be problematic. It was concluded that litter ash may be a useful source of P, K, and minor plant nutrients if applied at the agronomic rate for P_2O_5 or K_2O.

Burning litter for heat results in a loss of all of the nitrogen to the atmosphere and a two-fold increase in P, K, and other mineral plant nutrients in the ash. Combustion of litter can also be viewed as a process that repackages these mineral plant nutrients into a more concentrated, pathogen-free form that is more suitable for storage and transport than poultry litter.

A significant challenge in using this by-product lies in selection of spreading equipment that can apply this powder-like material in a uniform fashion. A possible solution would be to include poultry litter ash as a source of P, K, and minor plant nutrients in a granular fertilizer product that contains the desired percentage of N and binder. Such a product could be land applied using conventional fertilizer spreading equipment.

Energy Replacement and Ash Production for On-Farm Space Heating

A typical broiler house with a floor area of 1951 m^2 requires about 19,078 L LPG/yr at a cost of USD0.52/L (Tabler et al., 2001; Costello, 2007; Chastain, 2008). As a result, a six-house broiler farm will have an annual LPG cost on the order of USD59,523 per year. Researchers in Arkansas (Costello, 2007) concluded that it is possible to build an on-farm litter furnace and heat distribution system that can operate with an overall efficiency of 40% and that 80% of the purchased energy for space heating could be replaced. The results from the present study were used to estimate the energy savings and corresponding ash production for a single broiler house and a typical six-house farm and are provided in table 9.

Based an overall heating system efficiency of 40%, only 94.3 t of litter are required to replace 80% of the LPG used for space heating for a single broiler house and 118 t are needed for 100% replacement. Given that typical litter production on a broiler farm is about 128 t per house per year it may be possible to eliminate the purchase of LPG. The greatest challenge will be matching the heat output of the system to the variable demand for heat. If 80% of the LPG purchase could be eliminated savings for a six-house farm would be 91,576 L LPG per year with a value of USD47,600/yr.

If 92% of the litter produced on a six-house farm (708 t/yr) is burned the ash could be used to fertilize 120 ha at a rate of 100 kg P_2O_5/ha. The resultant application rate for K_2O would be 86 kg/ha (table 8) and would supply the majority of the K needs for most crops. Therefore, all of the P_2O_5 and K_2O could provide an offset in purchased fertilizer.

Rising oil prices have dramatically influenced the price of major plant nutrients (N, P, K). From 2000 to 2008 the cost of a kg of P_2O_5 increased from USD0.55 to USD1.92

Table 9. Potential energy savings (LPG) and ash production for burning litter to supply on-farm space heat.

	1 Broiler House	6-House Broiler Farm
Annual litter production (t/yr)[a]	128	768
Net energy content of litter at 24% moisture, LHV (kJ/wet kg)	10421	10421
LPG requirements for space heating (L/yr)[b]	19078	114471
Heat content of LP gas (kJ/L)	25764	25764
Litter required to off-set 80% of LPG requirement (t/yr)[c]	94.3	566.0
Litter required to off-set 100% of LPG requirement (t/yr)	118	708
Ash production if 100% of LPG is off-set (t/yr)[d]	22.1	132.8
Plant nutrient yield in ash		
P_2O_5 (t/yr)	2.00	12.0
K_2O (t/yr)	1.72	10.3
Ca (t/yr)	1.27	7.64
Mg (t/yr)	0.276	1.66
S (t/yr)	0.253	1.52
Zn (kg/yr)	16.2	97.0
Cu (kg/yr)	17.0	102
Mn (kg/yr)	19.7	118
Ash application rate to provide 100 kg P_2O_5/ha (t/ha)	1.11	1.11
Land area needed (ha/yr)	20	120

[a] Annual litter production based on measurements on South Carolina farms (Chastain et al., 2001).
[b] Based on on-farm measurements in South Carolina (Chastain, 2008) and Arkansas (Tabler et al., 2001; Costello, 2007).
[c] Overall heating system efficiency = 40%. Includes efficiency of furnace and distribution system (Costello, 2007).
[d] 0.247 kg of ash generated per kg of dry litter.

and the average price in 2011 was USD1.52/kg P_2O_5 (USDA-ERS, 2011). The average price of K_2O has followed a similar pattern increasing from USD0.45/kg K_2O in 2000 to a peak price of USD1.57/kg K_2O in 2009 (USDA-ERS, 2011). The average price for K_2O in 2011 was \$1.10/kg K_2O (USDA-ERS, 2011). Based on 2011 prices the combined value of the P_2O_5 and K_2O in the ash produced on a six-house farm would be USD29,570/yr.

One of the disadvantages of burning litter for space heating is the complete loss of nitrogen from poultry litter. The value of nitrogen fertilizer has increased over the last decade. In 2000, the average price of ammonium-nitrate was USD0.64/kg and rose to USD1.57/kg in 2011 (USDA-ERS, 2011). The plant available nitrogen content of broiler litter is about 18.9 kg/t (table 3, 66% of TN being available; Chastain et al., 2001). Therefore burning 708 t of litter on a six-house broiler farm would result in a loss of 13,381 kg of plant available N per year with a value of about USD21,008/yr.

Although there are many practical problems that are yet to be solved, combustion of litter on-farm to supply space heat has the potential to provide an energy savings of USD 47,600/yr and net fertilizer savings of USD8562/yr (USD29,570/yr - USD21,008/yr). The combined potential savings to the producer would be USD56,162 per six-house farm or USD9,360 per broiler house per year.

Litter Requirements and Ash Production for Electrical Energy Generation

Transportation of litter from a large concentration of broiler farms to an electric power plant may be another alternative to use litter as a source of biomass energy (Keener et al., 2002; Mukhtar et al., 2002; Priyadarsan et al., 2005; Walmsley, 2006; Fibrowatt. 2008). The amount of litter required to continuously fuel a 1-MW power plant was estimated using the following well known relationship (Beer, 2012):

$$FF_{RATE} = (HR / LHV)\ G_{CAP} \quad (3)$$

where

FF_{RATE} = fuel feed rate (kg/h),
HR = heat rate = 3600 / (P_{EFF}/100) (kJ/kWh),
P_{EFF} = overall generation plant efficiency = 32%,
LHV = low heat value = 10421 kJ/wet kg, and
G_{CAP} = desired generating capacity = 1000 kW.

It was determined that the biomass fuel feed rate required to generate 1MW was 1080 kg litter/h (table 10). The total amount of litter needed to operate the plant continuously for one year was 9461 t/yr. Based on the litter production assumption given previously (table 9) it was determined that 74 broiler houses would need to be located within a reasonably close distance from the plant. The results in table 10 also show that 926 kWh will be produced for every metric ton of litter burned in the plant.

One of the goals of using litter as a fuel source for electric generation is to replace a portion of the fossil fuel needed for electric power generation in a portion of a distribution area. However, the electrical energy used by the poultry houses will reduce the net available energy for distribution. The amount of electrical energy used by a 1951-m^2 broiler house was estimated to be 48,846 kWh/house/yr based on data collected on seven farms by the authors (Chastain, 2009). As a result, 3,614,604 kWh would be drawn from the electrical distribution grid by the 74 houses that supply litter for renewable fuel. The net energy to the electrical system would be about 544 kWh/t of litter. Only 59% of the electric power or 590 kW of every 1 MW of generating capacity would be available to

Table 10. Estimated litter requirements and plant nutrient yield for a 1-MW electrical generation plant.

Electrical generation capacity (kW)	1000
Biomass fuel feed rate (kg litter/h)[a]	1080
Annual litter requirement (t/yr)	9461
Electrical energy production (kWh/yr)	8,759,891
Gross kWh/t of litter	926
Number of broiler houses needed to provide litter (houses/yr)	74
On-farm electrical energy use per house (kWh/yr)[b]	48,846
Electrical energy use for 74 houses (kWh/yr)	3,614,604
Net electrical energy to grid (kWh/yr)	5,145,287
Net kWh/t of litter	544
Ash production (t/yr)	1775
Plant nutrient yield in ash	
P_2O_5 (t/yr)	160
K_2O (t/yr)	138
Ca (t/yr)	102
Mg (t/yr)	22.1
S (t/yr)	20.3
Zn (kg/yr)	1296
Cu (kg/yr)	1367
Mn (kg/yr)	1580
Land area needed to provide 100 kg P_2O_5/ha (ha/yr)	1600

[a] Based on an overall energy conversion efficiency of 32% (CIBO, 2003, Beer, 2012) and a resulting heat rate of 11,250 kJ/kWh.
[b] Based on on-farm data collected in South Carolina by the author (Chastain, 2009).

provide electric power to other farms, homes, and businesses in the region to be served by the plant. If it is desired to use litter to replace a portion of the energy needed in a distributed power generation strategy then the amount of electrical energy used by the poultry houses that provide the litter should be considered.

The amounts of important major and minor plant nutrients that will be produced as ash are also shown in table 10. A 1-MW power plant would be expected to yield 1775 t of litter ash each year. While the total amounts of plant nutrients are large and have significant value (about USD403,000/yr) they still may not be sufficient to be the sole ingredient of a granular fertilizer product. Using P_2O_5 as the limiting nutrient for land application indicates that all of the ash from a 1-MW power plant would only be sufficient to fertilize 1600 ha which is equivalent to two large grain farms in the United States. The litter ash from a small generating plant of 1 to 10 MW would most likely need to be shipped to an existing fertilizer plant and blended with conventional sources of N, P, and K to be feasible. The other alternative would be to increase the scale of the plant to 60 MW or more to yield enough litter ash to justify the cost of a fertilizer plant. However, a 60 MW plant would require litter from 4440 broiler houses located close enough to the generating plant to control litter transporation costs.

CONCLUSIONS

Combustion of poultry litter to provide heating requirements for broiler houses has been proposed as a means to reduce on-farm use of fossil fuel for space heating and to provide an alternative to traditional land application. Poultry litter is also being used as fuel in some electric power plants. In both cases, a significant quantity of ash is produced that requires a well-designed utilization plan.

Energy content of broiler litter was analyzed using the nutrition method. The mean HHV was 14,425 kJ/kg_{DM}. The value obtained using the nutrition method agreed with values using a bomb calorimeter within the 95% confidence interval of ± 416 kJ/kg_{DM}.

Broiler litter analyzed in this study contained 24.7% ash on a dry basis and was within the range published by others. Analysis of the composition of litter ash indicated that combustion of litter eliminated all but a trace of the nitrogen and increased the concentration of all other constituents in the ash by a factor of 1.7 to 2.1. The ash contained twice as much Ca as the uncombusted litter, but the calcium carbon equivalency (CCE) was only 32.4% dry basis. The high concentrations of S, and possibly Al, reduced the effectiveness of litter ash as a lime substitute.

Use of broiler litter ash as a liming agent is not a recommended practice since it would result in excessive over-application of P_2O_5 depending on liming recommendations for a particular field. In addition, the high ash application rates needed for soil pH adjustment would result in excessive Na applications.

Small applications of litter ash, on the order of 2 t/ha or less, can provide the P and K needs of most crops, and can serve as a source of key micronutrients. However, each case should be evaluated based on the resultant Na, Zn, and Cu application rates.

Production of litter at the rate of 128 t/house/yr was theoretically adequate to offset all of the propane needs for a six-house broiler farm. Provision of furnace and heat distribution technology to match heat output to house demands may limit the propane offset that can be realized. The P_2O_5 and K_2O contained in the litter ash could be used to eliminate purchase of these plant nutrients for about 120 ha.

Seventy-four broiler houses producing 128 t of litter/house/yr would be required to fuel a 1-MW power plant continuously. The gross electrical energy production was calculated to be 926 kWh per metric ton of litter burned. After accounting for the electrical use by the broiler houses, only 59% of the generating capacity would be available for use on the distribution system. Therefore, estimation of energy yield to the grid should be considered when planning the construction of a generating plant fueled by litter. The ash production from a 1-MW plant was estimated to be 1775 t/yr. The P_2O_5 contained in the ash would be adequate to fertilize only 1600 ha per year.

Additional research is needed make use of litter as a source of biomass fuel a reality. Efficient litter furnace and heating distribution systems that can automatically respond to heating demands are needed. Equipment capable of applying litter ash uniformly at low rates (1 t/ha) need to be designed, developed, and tested. Detailed economic analyses for both on-farm space heating and off-site generation of electric power are needed to identify profitable systems.

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REFERENCES

Adams, R., V. Ishler, and D. Moore. 1996. Trouble-Shooting Milk Fever and Downer Cow Problems (DAS 96-27). The Pennsylvania State University Cooperative Extension. Available at: www.das.psu.edu/research-extension/dairy/nutrition/pdf/milk-fever.pdf.

APHA. 1999. *Standard Methods for the Examination of Water and Wastewater.* 20th ed. L. S. Clesceri, A. E. Greenberg, and A. D. Eaton, eds. Washington, D.C.: Am. Public Health Assoc.

Beer, J. 2012. High efficiency electric power generation; The environmental role. Cambridge, Mass.: Massachusetts Institute of Technology Energy Initiative. Available at: web.mit.edu/mtei/docs/reprts/beer-combustion.pdf. Accessed January 2012.

Bernhart, M. E., and O. Fasina. 2009. Physical properties and pyrolysis behavior of fractionated poultry litter. *Trans. ASABE* 52(2): 531-538.

Bernhart, M., O. O. Facina, J. Fulton, and C. W. Wood. 2010. Compaction of poultry litter. *Bioresource Tech.* 101(1): 234-238.

Camberato, J. 2003. Chapt. 5A: Land application of poultry manure. In *Confined Animal Manure Managers Certification Program Manual: Poultry Version,* 5-a--1 to 5-a-12. Clemson S.C.: Clemson University Extension. Available at: www.clemson.edu/extension/livestock/livestock/camm/poultry.html.

Chastain, J. P. 2008. Fuel savings estimates for conversion from pilot ignition to spark ignition brooders for broiler production. ASABE Paper No. 083817. St. Joseph, Mich.: ASABE.

Chastain, J. P. 2009. Energy Saving Opportunities for Poultry Houses. Presentation for the Confined Animal Manure Managers Program, Clemson Extension. Clemson, S.C.: Clemson University.

Chastain, J. P., J. J. Camberato, and P. Skewes. 2001. Chapt. 3B: Poultry manure production and nutrient content. In *Confined Animal Manure Managers Certification Program Manual: Poultry Version,* 3-b-1 to 3-b-17. Clemson S.C.: Clemson University Extension. Available at: www.clemson.edu/extension/livestock/livestock/camm/poultry.html.

CIBO. 2003. Energy efficiency & industrial boiler efficiency: An industry perspective. Warrenton, Va.: Council of Industrial Boiler Owners. Available at: www.cibo.org.

Codling, E. E., R. L. Chaney, and J. Sherwell. 2002. Poultry litter ash as a potential phosphorus source for agricultural crops. *J. Environ. Qual.* 31: 954-961.

Costello, T. A. 2007. Feasibility of on-farm broiler litter combustion. *AVIAN Advice* 9(1): 7-13. University of Arkansas, Cooperative Extension Service. Available at: www.uark.edu/ua/poscext/articles.htm.

CUASL. 2006. Clemson University Agricultural Service Laboratory. Waste analysis methods. Clemson, S.C.: Clemson University Agricultural Service Laboratory. Available at: www.clemson.edu/public/regulatory/ag_svc_lab/animal_waste/waste_procedures/.

Davalos, J. Z., M. V . Roux, and P. Jimenez. 2002. Evaluation of poultry litter as a feasible fuel. *Thermochimica Acta* 394(1): 261-266.

Fibrowatt. 2008. Power from poultry litter. Langhorne, Pa.: Firbrowatt. Available at: fibrowattusa.com.

Goff, J. P., and R. L. Horst. 1997. Effects of the addition of potassium or sodium, but not calcium, to prepartum ratios on milk fever in dairy cows. *J. Dairy Sci.* 80: 176-186.

Habetz, D., and R. Echols. 2006. Successful poultry litter-to-energy furnace developed. ASABE Paper No. 064185. St. Joseph, Mich.: ASABE.

Harris, G., and M. Risse. 1999. Soil acidity and liming: Internet in-service training. Clemson, S.C.: Clemson University Extension. Available at: hubcap.clemson.edu/~blpprt/bestwoodash.html.

Hegg, R. O., and B. K. Gerwig. 1997. Assessment and Characterization of Manure in the Southeast. Summary report for the Southern Regional Biomass Energy Program, Tennessee Valley Authority, U.S. Department of Energy.

Henry, S. T. 1990. Composting broiler litter: Effects of two management systems. MS thesis. Clemson, S.C.: Clemson University, Department of Agricultural and Biological Engineering.

Jenkins, T. 2004. Personal communication on energy content of protein, fat, and carbohydrates, and calculation of total carbohydrates. Professor of Animal Science, Clemson, S.C.: Clemson University, Department of Animal and Veterinary Science.

Keener, K. M., R. Shook, K. Anderson, and C. R. Parrish. 2002. Characterization of poultry manure for potential co-combustion with coal in an electricity generation plant. ASAE Paper No. 026058. St. Joseph, Mich.: ASAE.

Koon, J. L., C. A. Flood, Jr., R. D. Trumbull, T. A. McCaskey, and R. N. Brewer. 1992. Physical and chemical characteristics of pine shavings poultry litter. *Trans. ASAE* 35(5): 1653-1657.

Moore, K. 2004. Personal communication on calculation of total carbohydrates. Director of Agricultural Service Laboratory, Clemson, S.C.: Cooperative Extension Service, Clemson University.

NRAES. 1999. *Poultry Waste Management Handbook.* NRAES-132. Ithaca, N.Y.: Natural Resources, Agriculture, and Engineering Service, Cooperative Extension, Cornell Univ.

Pagliari, P. H., C. J. Rosen, and J. S. Strock. 2009. Turkey manure ash effects on alfalfa yield, tissue elemental composition and chemical soil properties. *Communications in Soil Science and Plant Analysis* 40(17): 2874-2897.

Schulte, E. E., and K. A. Kelling. 1992. Soil and Applied Sulfur (A2525). Madison, Wis.: University of Wisconsin Extension. Available at: www.soils.wisc.edu/extension/pubs/A2525.pdf.

Tabler, G. T., I. L. Berry, and A. M. Mendenhall. 2001. Energy costs associated with commercial broiler production, Fayetteville Ark.: University of Arkansas Cooperative Ext.

Mukhtar, S., K. Annamalai, B. Thien, and S. C. Porter. 2002. Co-firing coal and broiler litter (BL) fuels for power generation: BL fuel quality and characteristics. ASAE Paper No. 024189. St. Joseph, Mich.: ASAE.

Mylavarapu, R., and R. Franklin. 1997. Nutrient Management for South Carolina: Based on Soil-Test Results, EC 476. Clemson, S.C.: Cooperative Extension Service, Clemson University.

Priyadarsan, S., K. Annamalai, J. M. Sweeten, S. Mukhtar, and M. T. Holtzapple. 2004. Fixed-bed gasification of feedlot manure and poultry litter biomass. *Trans. ASAE* 47(5): 1689-1696.

Priyadarsan, S., K. Annamalai, J. M. Sweeten, M. T. Holtzapple, and S. Mukhtar. 2005. Co-gasification of blended coal with feedlot and chicken litter biomass. *Proc. of the Combustion Institute* 30: 2973-2980. Available at: www.elsevier.com/locate/proci.

Rozgonyi, T. G., and L. Z. Szigeti. 1984. Upgrading of high moisture content lignite. *Intl. J. Mining Eng.* 2(2): 157-169.

Singh, K., M. Risse, J. Worley, K. C. Das, and S. Thompson. 2008. Effect of fractionation on fuel properties of poultry litter. *Applied Eng. in Agric.* 24(3): 383-388.

Steel, R. G. D., and J. H. Torrie. 1980. *Principles and Procedures of Statistics: A Biometric Approach.* 2nd ed. New York, N.Y.: McGraw-Hill Book Company.

USDA-ERS. 2011. Average U.S. farm prices of selected fertilizers, 1960-2011. United States Department of Agriculture-Economic Research Service. Available at: www.ers.usda.gov/ Data/FertilizerUse/.

Ward, M., and G. Lardy. 2005. Beef Cattle Mineral Nutrition (AS-1287). North Dakota State University Cooperative Extension. Available at: www.ag.ndsu.edu/pubs/ansci/beef/as1287w.htm.

Walmsley, T. 2006. Power from poultry litter: Regional-scale renewable energy plant. Presentation at the Waste-to-Energy Workshop for the Farm, Food Processing, & Wood Industries. Huntingburg, Ind., 11 Dec. Available at: www.in.gov/isda/files/Walmsley.pdf.

White. R. H. 1987. Effect of lignin content and extractives on the higher heating value of wood. *Wood and Fiber Sci.* 19(4): 446-452.