Nutrient Availability from Poultry Litter Co-Products

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Contents

Abstract

Phosphorus is a nutrient of concern in the Chesapeake Bay watershed, largely due to nutrient imbalances in areas with confined animal feeding operations. By converting poultry litter to an ash or biochar, nutrients are concentrated into a form that can be economically shipped out of nutrient-dense areas to nutrient deficient regions, such as the corn belt. In nutrient deficient regions, these poultry litter co-products have potential use as fertilizer with less impact on water quality.

The Virginia Tech Eastern Shore Agricultural Research and Extension Center initiated a study to compare poultry litter co-products to industry standard fertilizers. Seven poultry litter ash products, derived from different sources using different combustion techniques, and two biochar products were characterized. Both were compared to fresh poultry litter, as well as industry standard fertilizers for inorganic phosphorus (triple super phosphate or TSP) and inorganic potassium (muriate of potash or KCl).

There was variability between all ashes and biochars based on the thermal conversion system and the composition of the original poultry litter. On an elemental level, the inorganic fertilizers had the highest concentrations of nutrients, the ash products were the best complete fertilizers, and the biochars had less nutrients available for plant up-take than the ashes. Nutrient density in the ash and biochars varied between systems: phosphorus was concentrated between 4-10 times its original density; potassium was concentrated between 2.5-5 times its original density, and sulfur was concentrated between 2-3 times its original density. Additional, water-soluble based extractions found deceased solubility of the ash and biochar products compared to the industry standard fertilizers.

In conclusion, nutrient concentrations in the ash and biochar derived from poultry litter indicate that these co-products are comparable sources of phosphorus and potash fertilizer. However, further testing is needed to determine plant availability and nutrient uptake.

1.   Introduction

Phosphorous and nitrogen are both nutrients of concern to water quality (US EPA, 1988) and are most often connected with eutrophication (Levine and Schinder, 1989; Pote et al., 1996). Areas of intensive animal production often have the greatest potential for eutrophication due to non-point nutrient sources (Pote et al., 1996; Duda and Finan, 1983). Phosphorus is also an important because it is an extremely valuable agronomic nutrient and is considered a non-renewable resource. Current research estimates that within 50 to 100 years we will have mined all of our current known phosphorus supplies (Lynch et al. 2013).

Poultry litter, which contains phosphorus, has been well researched and vetted as a satisfactory fertilizer (Reiter et al., 2013; Sharpley et al., 2007; Revell et al., 2012). However, in regions with intensive animal production, land application of poultry litter is not a viable option due to high residual nutrient levels in the soil. Historically, most manure applications were applied to crop lands at a rate that correlates with the nitrogen requirements of the crops, which typically leads to an over application of phosphorus (Maguire et al., 2007; Sims et al., 1998). The over application of phosphorus is often due to the nitrogen-to-phosphorus ratio. The phosphorus content of manure is typically higher than the ratio that plants require, leaving a surplus of phosphorus (Pote et. al 1996). The average nitrogen-to-phosphorus ratio plants require is approximately 8:1 (Zhang et al., 2002; Bryson et al., 2014), and the average range of poultry litter is 1:1 (Zhang et al., 2002). When applying poultry litter to meet the nitrogen requirements of a crop, you will be providing 8 times more phosphorus than required. In a study by Sharpley (2007) on the effects of poultry litter applications on bermudagrass [*Cynodon dactylon* (L.)], applying poultry litter to meet nitrogen requirements resulted in an excess of 365 kg phosphorus ha^{-1} that was not removed by the bermudagrass.

Due to nutrient management regulations (VA-DCR, 2014), poultry litter is often transported off of the farms. Transportation from nutrient-rich areas is difficult, though, because poultry litter has a low nutrient density in a large, bulky volume of poultry litter. A solution to this issue is the thermal conversion of poultry litter into co-products: ash and biochar. The combustion of poultry litter is a viable approach to alternative energy generation, while at the same time reducing the total volume of the product into an easily transportable ash that remains high in key crop nutrients like phosphorus and potassium (Sharpley et al., 2007; MacDonald, 2007).

Poultry litter ash has proposed agronomic value as a fertilizer. There is significant research describing the analysis of wood-based ash co-products, but very little for manure-based ash. Crozier (2009) studied a granulated manure ash in three different experimental systems (greenhouse low-phosphorus soil, long-term phosphorus research sites with established phosphorus gradients, and agricultural fields with prior phosphorus fertilization at agronomic rates); when compared to industry standard fertilizer for inorganic phosphorus (triple super phosphate or TSP), source differences were infrequent and relativity minor. Codling (2002) compared the effectiveness of poultry litter ash as a fertilizer with an industry standard fertilizer for potassium phosphate, as a phosphorus source for wheat. The two fertilizers were applied at three rates (0, 39, and 78 kg P ha^{-1}) in

a wheat-based [*Triticum aestivum* (L.)] trial. No significant difference was found between the two fertilizers. A study by Reiter et al. (2004) comparing poultry litter ash to traditional fertilizer in a rice [*Oryza sativa*(L.)], wheat, and soybean[*Glycine max*(L.)] rotation found that the ash had slightly less short-term availability but increased residual soil phosphorus. In studies by Pagliari (2006, 2008), turkey [*Meleagris gallopavo*(L.)] manure ash was found to have no statistical differences in plant yield and uptake when compared with TSP in corn [*Zea mays*(L.)] and alfalfa [*medicago sativa*(L.)] trials. These studies are a step in proving that poultry litter ash co-products have a similar value to farmers as traditional fertilizers. Research indicated that ash could be a viable phosphorus source, but needs further testing to explore optimum application rates. Ash applications act not only as fertilizers but also as soil amendments. Demeyer et al. (2001) found that ash worked as a liming agent increasing the pH of the soil from 4.5 to 7.0 with the highest application rate of 44 Mg ha^{-1}, stimulated the microbial activities and increased water holding capacity by increasing soil aeration.

Biochar is another co-product of the thermal conversion of fresh poultry litter. There is interest in biochar for a multitude of uses, including bioenergy, carbon sequestration, soil amendment, and fertilizer (Maguire and Agblevor, 2010). Biochar is voluntarily regulated by the International Biochar Initiative, which established regulations for creating, sampling, testing, and using biochar worldwide. Biochar is defined by the International Biochar Initiative (2015) as the carbon-rich product that results from heating biomass with little or no oxygen. After pyrolysis, the inorganic components of poultry litter are significantly concentrated, although less concentrated than ash, and the densification increases the co-product's value as an agronomic nutrient source (Revell et al., 2012b; Agblevor et al., 2010). The main difference between biochar and ash is the creation temperature, as variations in temperature during production will impact the quantity and quality of the end product (Maguire and Agblevor, 2010). Biochar is the product of a lower burning temperature during combustion at 400-500°C, as compared to ashes that are produced at temperatures greater than 1000ºC (Gaskin et al., 2008).

Studies proposed that biochar can be used to improve soil productivity and sequester carbon (Atkinson et al., 2010; Laird, 2008). It has been found, mainly by scientists in the tropics, that biochar and charcoal created by pyrolysis will improve soil health and crop production (Chan et al., 2007; Lehmann et al., 2003; Oguntunde et al., 2004; Steiner et al., 2007; Yamato et al., 2006). This process forms hydrogen and organic carbon bonds that will sequester carbon for more than 100 years (International Biochar Initiative, 2015). By increasing the active surface area of the soil, its capacity to retain nutrients and water increases water holding capacity and nutrient uptake (Maguire, 2010). In a study by Revell et al. (2012b), biochar was found to decrease the bulk density of the soil by increasing aeration, the water holding capacity increased linearly with rates of (0, 4.5, and 9 Mg ha^{-1}), pH was increased, and the cation exchange capacity of the soil increased only when applied above agronomic rates. Increased water holding capacity is one of the major benefits to using biochar, as drought is a major reason for decreased crop production in non-irrigated lands (Revell et al., 2012a; Havelin et al., 2005). A study by Schomberg et al. (2012) reported that soil parameter improvements greatly depended on biochar quality, temperature and speed of pyrolysis, and the soil. Laboratory incubations with various

biochar amendments were conducted in the long and short term to explore the effects of biochar on changes in soil pH, ammonia losses, and soil carbon effects. Biochar additions resulted in a reduction of NO_3^- leaching and large increases in mineralizable nitrogen were not observed, meaning most soil carbon in the biochar was not available to micro-organisms. The study suggested that development of standards and guidelines would allow better usage of biochar by matching the biochar to specific soils and land use situations (Schomberg et al., 2012).

A review by Kelleher et al. (2002) discussed the advances in poultry litter conversion technologies by analyzing the most common techniques: composting, anaerobic digestion, direct combustion, and pyrolysis. The goals of using these technologies are to make the products safer for land application, reduce the total volume, increase the nutrient density, and increase the value of the product.

The process of composting is an aerobic process that occurs relatively quickly (4-6 weeks) and produces a material that is odorless, fine-textured, and has low moisture content (Kelleher et al., 2002). Moisture content is an important factor in composting. The moisture should be between 40-60% to allow for evaporation during the metabolic heating process (Kelleher et al., 2002; Rynk et al., 1991). Higher moisture content will inhibit the composting process, resulting in higher ammonia volatilization rates; lower moisture rates will inhibit decomposition (Kelleher et al., 2002). At the end of the process, the composted material will be granular with moisture content of 20% or less (Elwell et al., 1998). The composted material will be pathogen free and easy to handle, but disadvantages include odor, the loss of nitrogen (47-62%), phosphorus not being reduced or concentrated, and a cost for equipment and labor inputs (Kelleher et al., 2002; Sweeten, 1988).

Anaerobic digestion is commonly used around the world as a way to dispose of numerous agricultural and industrial waste products. Anaerobic digestion has two basic stages. The first stage is acid fermentation, which breaks down the organic material into organic acids, alcohols, and bacterial cells. The second stage involves the conversion of the hydrolysis products to gases (carbon dioxide and methane) (Kelleher et al., 2002; Williams, 1999). The gas mixture (60% methane) produced by this process is collected and used in bioreactors, as fuel, as a natural gas alternative, or in generators to create electricity (Kelleher et al., 2002). Disadvantages to digestion include high equipment costs, added volume without concentrating phosphorus, the need for added nutrients to correct for the carbon-to-nitrogen ratio, and the need for nitrogen to drive microbial metabolism and reactions. Other added costs include measures taken to enhance digestion because poultry litter has a high pH and ammonia content, which inhibits methane production (Krylova et al., 1997; Kelleher et al., 2002).

Direct combustion, a high oxygen thermal conversion technique, is the most promising new technology available to farmers. Numerous studies showed that thermal conversion of poultry litter to a bio-fuel is possible through multiple techniques, including combustion (>1100ºC and high O_2), gasification (700-1000ºC and minimal O_2), liquefaction, and pyrolysis (350-650ºC and depleted O_2) (Mante and Agblevor, 2010; Çaglar and Demirbas, 2000; McKendry, 2002; Cantrell et al., 2007; Farm Manure-to-Energy Initiative,

2015). Direct combustion tends to be most feasible for the farm-scale conversion of poultry litter. Some models employ a technique called localized fluidized bed combustion units to gasify the poultry litter at 700-1000°C with moisture content at approximately 25% (Kelleher et al., 2002; Williams, 1999). The advantages of combustion are the concentration of nutrients to 6 or 7 times that of the original feedstock and an increase of 1.5 to 2.5 times the bulk density of the poultry litter (Bock, 2004). The main disadvantage of an ash product is the loss of nutrients during the combustion process; however, if the litter is combusted at a much lower temperature some losses can be avoided (Faridullah et al., 2009; Steiner et al., 2010). The majority of nutrients from the fresh poultry litter is released from the systems in the form of non-reactive nitrogen gas (N_2) but the reactive forms may also be released in the forms of nitrogen oxides (NO_x) and ammonia (NH_3) (Farm Manure-to-Energy Initiative, 2015). The emissions differ system to system, but the reactive emission typically range from less than 2 to less than 1 percent due to the presence of NH_3 and organic nitrogen in poultry litter. At higher temperatures they will react with NO_x to form the non-reactive N_2 gas and water vapor, minimizing the reactive nitrogen emissions (Farm Manure-to-Energy Initiative, 2015). It is generally known that the land application of fresh poultry litter results in much higher emissions of atmospheric nitrogen (approximately 50-90%), so the thermal conversion of poultry litter may actually reduce atmospheric emissions of reactive nitrogen (Farm Manure-to-Energy Initiative, 2015).

Pyrolysis is the thermal decomposition of biomass in a depleted oxygen environment that uses a fluidized bed reaction between 350-650°C (Farm Manure-to-Energy Initiative, 2015; Mante and Agblevor, 2010), but differs from direct combustion by using lower heat and lower oxygen concentrations. The lower temperature helps lower nitrogen losses, but a substantial amount is lost or converted to atmospheric nitrogen (Knicker, 2007). Pyrolysis also concentrates the amounts of nutrients from the original substrate, including phosphorus and potassium, while reducing the total mass by approximately 60%, which increases the nutrient density (Kim et al., 2009; Revell et al., 2012).

The majority of research for manure-based fertilizers has been related to nitrogen availability because nitrogen is typically the most yield-limiting nutrient in row crops (Slaton et al., 2013). The plant availability of nitrogen, phosphorus, and potassium are all vital to plant health and growth and interrelated in their respective cycles (Brady and Weil, 1996). A study by Sharpley and Sisak (1997) proposed that the bioavailability of phosphorus from manure sources may differ from traditional inorganic fertilizer and suggested that application recommendations be tailored to the unique fertilizer source. Studies have shown that the phosphorus in manure is generally found to be 60-100% of the availability of commercial fertilizers depending on the source over multiple years (Barbazan et al., 2009); the first-year bioavailability of phosphorus was similar to inorganic fertilizer (Sneller and Laboski, 2009), and most potassium is highly water soluble and plant available (Jackson et al., 1975).

Both organic and inorganic phosphorous is present in the solid phase of poultry litter and is normally present in the acid-soluble fraction. However, nutrient levels can vary widely due to husbandry and diet practices, such as the type of bedding material, number of birds in a flock, and number of flocks between clean-outs (Lynch et al., 2012). Soils tend

to strongly hold phosphorus due to clay, iron oxide, and aluminum oxide, so there is little to no risk of leaching in soils that test low for phosphorus (Sims et al., 1998; Brady and Weil, 1996). Phosphorous fixation occurs at both ends of the pH spectrum, in acidic low pH soils (<5.0) and basic, high pH soils (>8.0) (Brady and Weil, 1996). In the low ranges, phosphorus will react to aluminum, iron, and manganese oxides. In the high ranges, phosphorus will react with calcium, fixing the phosphorus into insoluble compounds (Brady and Weil, 1996). But under long-term applications of phosphorus, in excess of crop removal rates, the soil concentrations will rise (Maguire and Sims, 2002). When tested levels of phosphorus in the soil are high or excessive, an increased chance of nutrient leaching and agricultural runoff can be expected (Moore and Edwards, 2007; Maguire and Sims, 2002). Soil pH also affects the availability of phosphorus.

Traditionally in Virginia, the primary test for soil phosphorus has been Mehlich-I, which is also known as the dilute double acid method (Sims, 2000; Mehlich, 1953). Other methods discussed in literature pertaining to the Mid-Atlantic region are water extraction and dilute salt extraction at varying ratios of 1:10 and 1:100 (Aslyng, 1964; Olsen and Sommers, 1982; van Diest, 1963). Many phosphates in the soil have formed insoluble compounds that are no longer plant available (Brady and Weil, 1996). There is some criticism that the Mehlich acid-based extraction is too harsh and extracts more than the plant available phosphorus (Self-Davis and Moore, 2000), which leads to unreliable recommendations and leads many to recommend water or dilute salt extractions over the traditional Mehlich-I extraction (Self-Davis and Moore, 2000; Pote et al., 1996; Luscombe et al, 1979).

While there is no single recommended protocol for measuring water extractable phosphorus (WEP), there are some commonly recommended protocols (Self-Davis and Moore, 2000; Kleinman et al., 2007). The dilute salt (0.1M $CaCl_2$) and water extractions (1:10 and 1:100) are tests that extract the readily available portions of the nutrients that will be available for plant uptake. These tests produce lower concentrations of nutrients as compared to acid extractions and are used in the industry to make recommendations for phosphorus management systems on farms (Self-Davis and Moore, 2000). The dilute salt extraction is used in place of water to obtain a clearer filtrate, but the amount of soluble phosphorus will be smaller due to Ca^{2+} ions enhancing phosphorus sorption in the soil (Aslyng, 1964). Water extraction ratios have been discussed in the literature since the mid-1980s. A study by Kleinman et al. (2007) looked at WEP extraction ratios with help from 10 laboratories across the country. They compared extracts at 3 different ratios (soil: extractant): 1:10, 1:100, and 1:200. They found the 1:10 level was the most problematic out of the 3 ratios of soil to extractant. At the 1:10 ratio, the results were inconsistent, they had trouble obtaining sufficient extract for analysis, and the extracts were relatively dark in color causing many problems for colorimetric analysis, including the clogging of instrumentation tubing (Kleinman et al., 2007). They also found a consistent trend, with greater quantities of WEP being recovered as the extraction ratio increased. However, due to the experimental variability no proportional relationship could be determined between the ratios. The study recommended the usage of the 1:100 ratio as the middle ground

because it offered the most reasonable balance of precision and practicality (Kleinman et al., 2007).

This project evaluated removing excess phosphorus from nutrient-dense areas by repurposing ash and biochar co-products of the poultry industry into a marketable fertilizer that can be exported out of the watershed and used by farmers in the phosphorus-deficient areas of the country or within the watershed where fresh poultry litter is not an option. The objective of this project was to characterize and analyze the composition of poultry litter co-products in comparison to traditional inorganic fertilizers and fresh poultry litter.

2. Characterization of Poultry Litter Ash Co-Products

2.1 Materials and Methods

This study was initiated to evaluate the chemical characteristics of poultry litter co-products (ash and biochar) (Table 2.1) compared to triple super phosphate and muriate of potash. The fertilizers were arranged in a randomized complete block design (RCBD) with 4 replications.

2.1.1 Elemental Analysis

Fertilizer samples (0.5 g) were digested in nitric acid and hydrogen peroxide using method 3050B (USEPA, 1996), and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011). Using dilute salt and water extraction testing protocols for 0.1M $CaCl_2$ (Aslyng, 1964), 1:10 water (Olsen and Sommers, 1982), and 1:100 (van Diest, 1963) the correct ratio of sample to solution was placed in 60 ml straight-walled plastic extracting beakers. The samples were shaken for 1 hour on a reciprocating shaker (Eppindorf, Enfield, CT, 06082) set at 200 oscillations per minute. The extracts were filtered through Whatman no. 2 filter paper into plastic vials and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011). A total nitrogen, carbon, and sulfur combustion procedure was conducted for the samples using the Dumas method with a Vario EL Cube (elementar Americas, Mt. Laurel, NJ, USA) (Bremner, 1996).

2.1.2 Balance Comparison

Balance comparisons of the poultry litter going in and ash coming out of poultry litter burners took place as litter burners began running at the farm locations. Each thermal system was unique to the farm, including its physical construction, operating conditions, residence time, and initial feedstock (Table 2.2); individual system sampling methods are listed below. Samples were tested for percent moisture (Wolf and Haskins, 2003), calcium carbonate equivalent (Wolf and Haskins, 2003), and elemental concentration using the EPA method 3050B. Densification was calculated by taking the ash nutrient concentration percentage and dividing by the corresponding nutrient concentration percentage in the poultry litter feedstock (times concentrated = ash nutrient percentage/ poultry litter nutrient percentage)

- Wayne Combustion Global Refuel: ASH3 and ASH6

  Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter going in, the main bulk ash auger, and the fly ash auger from the side at the heat exchanger. The residence time was observed to be 30 minutes from the start to the main bulk ash auger and the fly ash auger. The time and temperature of the combustion chamber was recorded for each sampling.

- Total Energy Blue Flame Stoker: ASH4

  Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter entering the system, the main ash auger, and the end ash auger. The residence time was observed to be 60 minutes from start to the main bulk ash auger and 70 minutes from start to the end auger with the bulk ash and fly ash mixture. The time, stack temperature, and water heating set point was recorded for every sample. The combustion temperature was not available on this system.

- Enginuity Energy: Energy Ecoremedy Gasifier: ASH7

  Samples were taken at two sampling locations in accordance to the residence time of the systems: fresh poultry litter entering the system and the bulk ash auger at the end of the system. The residence time was observed to be 157 minutes from the start to the end of the system. The time and chamber temperature was recorded at two locations within the system at a residence time of 55 minutes (gas burner #1) and 147 minutes (gas burner #2). The water boiler set temperature was also recorded for each sample.

2.1.3 Total Carbon Content

Total carbon content of the ash co-products were determined using a total nitrogen, carbon, and sufur dry combustion procedure was conducted for the samples using the Dumas method with a Vario EL Cube (elementar Americas, Mt. Laurel, NJ, USA) (Bremner, 1996).

2.1.4 Statistical Analysis

Statistical analysis was conducted using analysis of variance (ANOVA), SAS PROC MIXED procedures and Fisher's LSD with an alpha level of 0.10 using SAS 10.1 statistical software (SAS Institute, 2007).

2.2 Results and Discussion

2.2.1 Elemental Analysis

Acid Digestion

The nitric acid/hydrogen peroxide digestion is a complete elemental digestion that quantified the total concentrations of elements (Table 2.3a; Table 2.3b). The industry standard triple super phosphate (TSP) had the highest phosphorus concentration (201.81 g kg^{-1}) and a significant concentration of Ca (168.22 g kg^{-1}). Muriate of potash (KCl) had the highest potassium concentration (493.11 g kg^{-1}) as expected. When comparing the ash co-products to each other, ASH3 was the superior fertilizer because it had the highest concentrations of nutrients across the board, which was followed by ASH4 as a close second (Table 2.3a). BIOCHAR3 had the worst concentration of micro-nutrients; meaning that, although it has a significant concentration of macro elements (phosphorus, potassium,

sulfur), it was lacking in the micro, which would make it the least complete fertilizer (Table 2.3a). The biochar co-products had the lowest concentrations of nutrients across the board. The ASH5 fertilizer was superior for potassium, but low as a complete fertilizer (Table 2.3a).

When compared to the industry fertilizer standards no co-product was similar to TSP for phosphorus concentration (Table 2.3a, 2.4, 2.5, 2.6). For potassium concentration, no co-products were similar to KCl, but all co-products had concentrations greater than or similar to the fresh poultry litter standard (Table 2.3a, 2.6). In the dilute salt extraction and the 1:10 water extraction, BIOCHAR1 had a concentration less than both KCl and poultry litter (Table 2.4, 2.5). Poultry litter had the greatest sulfurS concentration, and all co-products had significant less sulfur but were similar to each other (Table 2.3a)

Micro-nutrients or trace elements were present in all of the co-product samples (Table 2.3a; Table 2.3b). With the exception of ASH5, all of these concentrations were below the level of environmental concern according to the fertilizer law (USDA-NRCS, 2015). Micro-nutrients such as boron, manganese, copper, and inc are vital to growth in plants. In highly managed and high-yielding farming systems, farmers are looking to supplement these nutrients to crops. By using a poultry litter co-product, these farmers will get the extra benefit of these nutrients not normally found in inorganic fertilizers. ASH5 had the highest concentration of trace elements (Table 2.3b) and was over the threshold to be applied as a commercial fertilizer due to its arsenic levels. This is most likely due to being created from poultry litter that was more than 10 years old. Since, there have been many regulation and pharmaceutical changes that have significantly reduced the trace elements in poultry litter. The biggest change has been in residual arsenic concentration, which was prevalent with the usage of the pharmaceutical known as Roxersone. Roxersone was used in poultry production to help prevent coccidiosis, a parasitic disease that infects the intestinal tracts in poultry and can lead to death in poultry (US-FDA, 2015). After a FDA study in 2009 found significant concentrations of arsenic in poultry meat, the industry voluntarily shifted away from the use of Roxersone (US-FDA, 2015).

Dilute Salt and Water Extractions

While there is no single recommended protocol for measuring WEP, we analyzed our sources using three of the most recommended protocols (Kleinman et al., 2007). The dilute salt extraction is used in place of water to obtain a clearer filtrate, but the amount of soluble phosphorus will be smaller due to Ca^{2+} ions enhancing phosphorus sorption in the soil (Aslyng, 1964). Our results found known significant differences between the three extractions for phosphorus concentration. There was a significant difference for potassium concentration; the 1:100 water extractions produced higher concentrations than the others. Trends show that although no significant differences were produced from our data the 1:10 $CaCl_2$ extraction concentrations (Table 2.4) were tended to be slightly less than the 1:10 water extract concentrations (Table 2.5).

The results from the WEP testing reaffirmed our results from the complete acid extractions in terms of which system produced superior fertilizer products, although it showed they were potentially less plant available. The ash co-products were all similar in

their nutrient concentrations (Table 2.4, 2.5, 2.6). ASH5, the only fly ash tested, had the highest potassium and sulfur concentrations. Potassium and sulfur are likely to volatilize and exit the system through the exhaust stack (Kelleher et al., 2002) and would therefore likely be present in the fly ash. BIOCHAR1 had the lowest nutrient concentration, and BIOCHAR2 was similar.

2.2.2   Balance Comparison

The characterization of poultry litter from four different farms showed many differences in moisture, calcium carbonate equivalent (CCE), and elemental concentrations (Table 2.6), which was expected. The composition of poultry litter varies greatly from location to location depending on the practices of the individual poultry producer (Bolan et al., 2010; Kelley et al., 1996; Tasistro et al., 2004). Thus, the resulting ash from the different thermal combustion systems is influenced by not only the unit, but by the starting material (Table 2.7). The ASH7 system had much higher moisture concentrations than the other locations, and thus produced an incomplete burn (Table 2.8). The incomplete burn of the ASH7 system resulted in the lowest densification of nutrients (Table 2.9). The ASH4 location had the highest concentration of nutrients from the densification across the board; this system had the superior mix of burn temperature (1000ºC), oxygen levels, and feedstock moisture content (25.24%). This is supported by the literature, which stated that the ideal conditions for combustion are at 700-1000°C with a moisture content of approximately 25% (Kelleher et al., 2002; Williams, 1999). The literature also states that the typical concentration factor is 6 or 7 times that of the original feedstock nutrients (phosphorus, potassium, and sulfur) of the poultry litter (Bock, 2004). Our study found that this varied between systems based on moisture, but falls well within our range of 4-10 times concentration for phosphorus (Table 2.9). The systems tested in our balance comparison trials were not equipped with cyclones or bagging units, so the majority of potassium and sulfur escaped the systems through the exhaust (Kelleher et al., 2002) and resulted in lower concentrations (2.5-5) for potassium (Table 2.9), and for sulfur (2-3) (Table 2.9).

2.2.3   Ash Co-Product Carbon Content

The carbon content of poultry litter co-products also varies greatly based on the thermal conversion system and the initial poultry litter feedstock. ASH7 had the highest carbon content, followed by ASH3 and ASH4 (Table 2.10). The feedstock of ASH7 had the highest moisture content and thus the most incomplete burn, having less carbon removed from the system.

2.3   Conclusion

Overall, our data has determined that nutrient concentrations of poultry litter co-products are highly dependent on the conditions of their feedstock. The thermal combustion system is the greatest variable; this includes the temperature of combustion, the fuel-to-oxygen ratio for combustion, the residence time of the poultry litter, and whether or not the system has an exhaust scrubbing system to catch fly ash. Another major

factor is the poultry litter from which the co-product is formed; the initial concentration of nutrients, bedding material, and moisture content of the litter impact the co-product.

Our study found that nutrient densification varied between systems: phosphorus concentration fell within a range of 4-10 times concentrated, potassium concentration was 2.5-5 times concentrated, and sulfur was 2-3 times concentrated. Our comparisons between total nutrient digestions and water soluble extractions found that the ash products were significantly less plant available than the standard fertilizers, which means that a greater amount of the co-products will have to be applied to meet the same nutrient availability of the standards. Overall, if all ideal combustion criteria are met (700-1000ºC; 25% moisture), then poultry litter co-products are a feasible form of fertilizer. However, the co-products will need to be individually analyzed for nutrient content before application recommendations can be made.

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2.5 Tables

Table 2.1   Descriptions of poultry litter co-product sources used in all studies

Source	Co-Product Type	Farm Name	Thermal Conversion System
Ash1	Bulk Ash	BHSL	Gasification
Ash2	Bulk Ash	MOO	Gasification
Ash3	Bulk Ash	RHO	Combustion
Ash4	Bulk Ash	ZIM	Combustion
Ash5	Fly Ash	MOK	Combustion
Ash6	Bulk Ash	ROR	Combustion
Ash7	Bulk Ash	HEL	Gasification
Ash8	Bulk Ash	WVR	Combustion
Biochar1	Biochar	NCB	Pyrolysis
Biochar2	Biochar	JFB	Pyrolysis
Biochar3	Biochar/Ash	FPPC	Combustion

Table 2.2 Source information and background information for poultry litter co-product thermal conversion systems

Source	Location	System	Burn Temp	Residence Time	Mode of Energy Dispersal	Poultry Litter Type	Co-Product Type
ASH1	Limerick, Ireland	Bhsl-Ireland Fluidized bed system	85ºC water set temp	N/A†	Hot Water	Broiler	Ash
ASH2	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	157 min	Forced Air	Broiler	Ash
ASH3§	Port Republic, VA	Wayne Combustion Global Refuel	593ºC in chamber	30 min	Forced Air	Turkey	Ash
ASH4§	Lancaster County, PA	Total Energy Blue Flame Stoker	82ºC water set temp 171ºC exhaust temp	60 min	Hot Water	Organic Broiler¶	Ash
ASH5	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	167 min	Forced Air	Broiler	Fly Ash
ASH6§	Lancaster County, PA	Wayne Combustion Global Refuel	593ºC in chamber	30 min	Forced Air	Broiler	Ash
ASH7§	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	157 min	Forced Air	Organic Broiler	Ash
ASH8	Pendleton County, WV	Wayne Combustion Global Refuel	593ºC in chamber	30 min	Forced Air	Broiler	Ash
BIOCHAR1	North Carolina State University	Coaltec Unit	400ºC in chamber	5 min	Forced Air	Broiler	Biochar
BIOCHAR2	Hardy County, WV	Westfiber by PHG Energy	450ºC	360 min	Forced Air	Broiler	Biochar
BIOCHAR3‡	Cheraw, SC	BGP	871ºC in chamber	60 min	Forced Air	Broiler	Biochar/Ash

†N/A. Information not available at this time.

‡When the system capacity is overload with feedstock, unit will produce biochar (our sample) but is designed to produce ash.

§Thermal conversion systems used in the balance comparison study.

¶Organic broiler operations clean the litter out the poultry house with every flock, meaning fewer nutrients will be present in the poultry litter feedstock.

Table 2.3a   Total elemental concentration of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	S	Ca	Mg	Mn	Na	Fe	Al	B	Zn	Cu
	--g kg^{-1}--									--------------------mg kg^{-1}-----------------		
ASH1	81.89d†	114.30e	24.33b	138.42c	37.19b	3.12b	31.55b	9.56cde	10.56c	249.19c	2670.55b	1222.61d
ASH2	52.72f	71.27f	13.59b	77.33d	27.48d	2.16e	33.74a	9.11de	9.52d	139.41e	1510.43d	1089.3e
ASH3	104.90b	129.77d	28.42b	162.58a	36.59b	4.60a	25.24c	16.88b	2.15f	220.56d	2888.41a	3429.68a
ASH4	90.22c	145.78c	16.95b	131.82c	46.42a	2.94c	23.57d	14.98b	17.94b	383.45b	2515.92b	1861.01c
ASH5	9.40i	202.35b	41.49b	51.86e	8.93f	0.86g	13.98g	70.95a	2.53ef	98.10f	2879.72a	809.23f
ASH8	77.21e	116.57e	34.20b	133.04c	34.26c	2.45d	31.36b	13.24bc	19.82a	242.27c	1793.99c	3252.34b
BIOCHAR1	34.37g	32.03g	9.20b	147.19b	10.18f	0.86g	6.56i	6.01ef	9.31d	38.21g	948.90e	84.10hi
BIOCHAR2	30.81h	67.15f	13.64b	45.80e	14.92e	1.19f	17.22f	10.28cd	8.85d	108.81f	1081.55e	1848.22c
BIOCHAR3	37.08g	66.30f	9.06b	47.82e	7.36g	0.58h	21.81e	4.81f	2.82ef	45.39g	39.35g	155.80h
KCl	0.03j	493.11a	0.25b	0.72g	0.88i	NDi‡	15.01g	0.22g	0.07h	0.73h	0.15g	0.16j
Poultry Litter	12.51i	29.06g	370.92a	23.64f	174.73g	1.39h	9.38h	0.04g	1.02g	43.66g	588.35f	519.43g
TSP	201.81a	1.70h	247.95a	168.22a	4.54h	0.11i	3.03j	2.55fg	3.08e	643.96a	425.41f	22.56ij
LSD$_{0.10}$	3.44	9.62	166.85	8.44	1.84	0.14	1.13	3.96	0.77	16.84	173.78	79.84

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.3b   Total elemental concentration of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	As	Be	Cd	Co	Cr	Hg	Mo	Ni	Pb	Sb	Se	Si
	--mg kg^{-1}--											
ASH1	2.87ef†	0.92c	NDc	9.21d	41.96cd	ND‡	37.08c	37.60def	9.48b	1.21d	2.77c	44.09bc
ASH2	15.07c	0.34e	NDc	12.00c	169.69ab	ND	25.51d	108.86ab	7.18c	1.87c	1.88cd	29.59cde
ASH3	13.51c	0.12h	NDc	8.97d	15.45d	ND	48.84a	50.00cde	5.58d	1.07de	4.59b	35.04bc
ASH4	4.48de	1.37b	NDc	19.68b	33.11d	ND	25.14d	67.17cd	5.14d	1.60cd	2.51c	56.51ab
ASH5	51.87a	0.17g	4.91b	27.05a	237.07a	ND	36.32c	146.33a	56.89a	4.26a	20.29a	24.15cdef
ASH8	3.79de	0.44d	NDc	6.98f	31.09d	ND	42.20b	60.82cde	5.88d	0.35f	1.33de	32.63bcd
BIOCHAR1	0.87fg	0.45d	NDc	7.59ef	13.33d	ND	4.52g	7.47f	5.14d	0.22f	NDf	22.68cdef
BIOCHAR2	19.46b	0.31f	NDc	6.37f	12.86d	ND	21.37e	22.72ef	6.21d	0.38f	2.03cd	8.77def
BIOCHAR3	1.83efg	0.35e	NDc	3.46g	104.11bc	ND	13.90f	86.38bc	2.54e	0.54ef	NDf	4.07ef
KCl	0.27fg	NDi	NDc	0.04i	0.05d	ND	NDh	0.24f	NDf	NDf	NDf	19.64cdef
Poultry Litter	NDg	0.14gh	NDc	1.25hi	4.83d	ND	1.19h	3.35f	2.02e	NDf	0.67ef	NDf
TSP	5.99d	1.59a	8.28a	1.71h	159.13b	ND	4.57g	26.58ef	3.08e	2.53b	NDf	81.92a
LSD$_{0.10}$	2.81	0.03	0.67	1.50	69.94	---------	1.59	38.17	1.25	0.65	0.92	25.59

† A different letter within the column designates significance at the 0.10 level.

‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.4   Weak Salt (0.1 M CaCl$_2$) Extraction of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	S	Mg	Mn	Zn	B
	--------------------g kg^{-1}--------------------			--------------------------------mg kg^{-1}--------------------------------			
ASH1	0.054b†	60.29e	28.94c	679.47de	0.02c	ND‡c	29.65c
ASH2	0.06b	48.25f	27.45d	1865.64b	0.22c	0.32c	10.75fg
ASH3	0.08b	72.81d	30.06c	646.97e	0.17c	NDc	21.10e
ASH4	0.02b	60.15e	19.95e	4.42g	NDc	NDc	50.13a
ASH5	0.01b	211.95b	50.35a	1287.03c	0.73c	1.35c	10.06g
ASH8	0.01b	88.64c	39.21b	218.03fg	0.05c	NDc	26.13d
BIOCHAR1	0.14b	13.25i	2.44i	259.99f	0.73c	0.30c	4.39h
BIOCHAR2	0.26b	42.32g	10.14h	927.81d	7.05c	12.01c	13.82f
BIOCHAR3	11.64b	74.74d	11.71g	5.17g	NDc	NDc	1.73hi
KCl	0.28b	483.89a	0.27j	563.96e	0.28c	NDc	0.90i
Poultry Litter	0.82b	26.07h	13.11f	567.07e	21.43b	79.93b	25.00d
TSP	219.57a	1.64j	3.09i	5138.78a	112.70a	443.26a	38.74b
LSD$_{0.10}$	16.56	3.89	1.13	250.89	8.07	20.65	3.29

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.5   Water Extraction (1:10) of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	Ca	S	Mg	Mn	Zn	B
	----------------------------g kg^{-1}------------------------				--------------------------------mg kg^{-1}-----------------------------			
ASH1	0.13c†	62.60e	0.12c	25.53c	150.16e	0.02d	ND‡d	30.63c
ASH2	0.10c	48.06f	0.19c	23.21d	1293.29b	0.95d	1.35d	11.12g
ASH3	0.27c	70.31d	0.12c	25.23c	167.43e	0.29d	0.05d	20.85e
ASH4	0.11c	63.95e	0.05c	17.48e	8.81f	NDd	NDd	42.86a
ASH5	0.03c	194.39b	6.72b	44.25a	1243.33b	0.56d	0.91d	8.54h
ASH8	0.06c	89.54c	0.34c	33.16b	136.86e	NDd	NDd	23.45d
BIOCHAR1	0.59c	11.39i	0.08c	1.98i	90.92ef	0.37d	0.76d	3.86i
BIOCHAR2	0.40c	37.85g	0.18c	8.47g	436.85cd	5.72c	16.14c	13.53f
BIOCHAR3	11.82b	67.90de	0.02c	9.83f	6.17f	NDd	NDd	1.42j
KCl	0.02c	516.14a	0.30c	0.23j	503.46c	0.03d	NDd	1.49j
Poultry Litter	0.82c	22.52h	0.48c	10.94f	346.69d	16.78b	77.39b	23.50d
TSP	209.68a	1.80j	132.40a	3.37h	4158.25a	108.80a	294.95a	38.96b
LSD$_{0.10}$	5.23	5.40	3.40	1.24	109.58	4.41	3.90	1.17

† A different letter within the column designates significance at the 0.10 level.

‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.6   Water Extraction (1:100) of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	Ca	S	Mg	Mn	Zn	B
	--g kg^{-1}----------------------------------				--mg kg^{-1}----------------------------------			
ASH1	1.95d†	72.52def	0.23c	27.04c	1189.50c	0.32e	ND‡e	31.49c
ASH2	1.43de	57.15fg	0.50c	24.43c	2080.35b	2.42de	2.42e	14.28f
ASH3	1.97d	86.56cd	0.35c	28.40bc	1063.69c	2.94de	NDe	25.26d
ASH4	0.77def	70.02ef	0.21c	18.48d	603.55de	NDe	NDe	48.88a
ASH5	0.21ef	265.59b	18.31b	65.73a	1871.13b	5.44d	32.93c	17.77ef
ASH8	0.26ef	92.93c	1.03c	32.03b	487.48e	0.15e	NDe	26.19d
BIOCHAR1	1.36de	28.80hi	0.37c	5.21f	535.72c	5.45d	9.59de	8.49g
BIOCHAR2	1.52d	44.93gh	0.63c	8.35ef	893.33cd	11.66c	18.68d	14.31f
BIOCHAR3	12.61b	77.70cde	0.08c	10.60e	134.29f	0.04e	NDe	NDh
KCl	0.06f	479.70a	0.41c	0.23g	571.76de	0.67e	0.28e	1.06h
Poultry Litter	3.55c	27.23i	0.85c	11.44e	990.78c	25.93b	74.21b	22.08de
TSP	190.42a	1.54j	133.86a	12.01e	4571.50a	118.17a	359.51a	43.20b
LSD$_{0.10}$	1.25	16.53	3.40	4.27	344.82	4.40	13.28	5.09

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.7 Characterization of fresh poultry litter samples from four different thermal conversion systems in the Mid-Atlantic

	Moisture	CCE[†]	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	K_2O[‡]	P_2O_5[‡]
	--%--								--mg kg^{-1}----------------------------------							----------%--------	
ASH3	22.56d§	0.29d	4.58b	1.70a	2.19c	0.88a	0.59b	2.64b	5696c	678	116c	749a	616a	620b	57c	2.02c	3.04
ASH4	25.24c	1.78c	3.91d	0.76d	2.26c	0.38c	0.53b	1.65b	3769d	231	308b	420d	175c	565c	52c	2.03c	3.61
ASH6	28.9b	2.36b	4.04c	1.20c	3.00b	0.81b	0.64b	2.02b	6220a	665	603a	540c	226b	423d	706a	2.57b	1.97
ASH7	40.35a	3.46a	5.54a	1.41b	5.14a	0.86a	2.09a	5.14a	6018b	808	312b	663b	146d	909a	636b	3.67a	1.93
LSD$_{0.10}$	1.25	0.66	0.17	0.13	0.30	0.03	0.60	1.47	176	NS	72	37	23	36	24	0.20	NS

† CCE = calcium carbonate equivalent.
‡Available fertilizer equivalent.
§A different letter within the column designates significance at the 0.10 level.

Table 2.8 Characterization of poultry litter ash samples from three different thermal conversion systems in the Mid-Atlantic

	Moisture	CCE[†]	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	K_2O[‡]	P_2O_5[‡]
	--%--								--mg kg^{-1}----------------------------------							--------%---------	
ASH3	0.20b§	22.54c	0.30b	10.70a	11.04b	2.32a	3.83	17.68a	33980a	10320b	1806d	4102a	3262a	2170b	261c	13.26	24.50a
ASH4	0.09b	31.13a	0.15c	7.20b	11.52b	1.24c	3.93	11.77b	20211c	12600a	18622a	2751b	1115b	2099b	316c	13.83	16.50b
ASH6	0.50b	28.90b	0.35b	6.09c	11.30b	2.30a	3.11	9.76c	28000b	9780b	13200b	2330c	1060c	1620c	2590a	13.40	13.90c
ASH7	17.76a	12.71d	2.36a	5.46d	12.47a	1.85b	5.96	7.29d	17400d	5336c	4036c	2177c	396d	2496a	1770b	12.33	10.27d
LSD$_{0.10}$	1.28	1.96	0.20	0.40	0.63	0.11	NS	1.22	1518	610	617	220	52	143	87	NS	0.80

† CCE = calcium carbonate equivalent.
‡Available fertilizer equivalent.
§A different letter within the column designates significance at the 0.10 level.

Table 2.9   Concentrations of nutrients from the densification of poultry litter entering the thermal conversion unit and poultry litter ash exiting the unit from four different units in the Mid-Atlantic

	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	K_2O	P_2O_5
	--Times Concentrated[†]--														
ASH3	0.07b‡	6.41b	5.04a	2.63b	6.62b	6.93b	5.98a	22.93b	15.71c	5.54b	5.36b	3.52b	4.61b	6.55b	8.26b
ASH4	0.04c	10.22a	5.12a	3.26a	7.49a	7.25a	5.41b	55.54a	65.44a	6.63a	6.48a	3.79a	6.05a	6.83a	11.36a
ASH6	0.09b	5.08c	3.77b	2.84b	4.86c	4.83c	4.50c	14.71c	21.89b	4.31c	4.69c	3.83a	3.67c	5.21c	7.06b
ASH7	0.43a	4.07c	2.48c	2.15c	3.12d	2.44d	2.90d	14.53c	16.58c	3.30d	2.80d	2.74c	2.77d	3.41d	5.54c
LSD$_{0.10}$	0.04	1.22	0.21	0.21	0.51	0.76	0.41	5.39	7.09	0.48	0.46	0.28	0.28	0.25	1.78

†Times Concentrated = ash nutrient concentration percentage/feedstock poultry litter nutrient concentration percentage).
‡A different letter within the column designates significance at the 0.10 level.

Table 2.10   Differences in carbon content of poultry litter ash and fresh poultry litter by thermal conversion system

	Bulk Poultry Litter Ash	Fresh Poultry Litter
	-----------------------------C-----------------------------	
	-----------------------------%-----------------------------	
ASH3	5.30b†	37.95b
ASH4	2.31c	38.43a
ASH7	13.03a	36.98c
LSD$_{0.10}$	1.11	0.39

†A different letter within the column designates significance at the 0.10 level.

3. Incubation of Poultry Litter Co-Products for Phosphorous and Potassium Availability

3.1 Abstract

Phosphorus and nitrogen are nutrients of concern in the Chesapeake Bay watershed due to nutrient imbalances in areas with confined animal feeding operations. By converting poultry litter to an ash or biochar, nutrients are concentrated into a form that can be economically shipped out of nutrient-dense areas to nutrient deficient regions, such as the corn belt. In nutrient deficient regions, these poultry litter co-products have potential use as fertilizer with less impact on water quality.

A non-leached aerobic incubation study was conducted on a Bojac sandy loam soil to test phosphorus and potassium availability from poultry litter ash. Four poultry litter ash products, derived from different sources using different combustion techniques, and 2 biochar products were surface broadcast applied at a rate of 85 mg P kg^{-1} and the corresponding potassium rate was recorded. Poultry litter co-products were compared to a no-fertilizer control and inorganic phosphorus (TSP) fertilizers at similar rates. A dilute salt extraction (phosphorus and potassium) was used to analyze the characteristics and availabilities of the poultry litter co-products under a controlled soil incubation environment to determine how they compare to the current industry standards in terms of potential bioavailability.

Overall, standard fertilizers (TSP and poultry litter) had the greatest initial availability for phosphorus (55.50% TSP; 9.13% poultry litter) and K (97.99% poultry litter) respectively. The poultry litter co-products varied in availabilities based on thermal conversion system from 1.60- 8.63% for phosphorus to 8.14- 88.10% for potassium. One ash co-product (ASH4) produced similar availabilities to the industry standard fertilizers after 56 days.

In conclusion, co-products from combustion thermal conversion systems were found to be superior to gasification and pyrolysis systems when the desire was to produce co-products with the most plant available phosphorus and potassium. As new thermal conversion systems are designed, the ash co-products will need further evaluation as temperature and oxygen during the combustion process significantly alters water-soluble nutrient availability.

3.2   Materials and Methods

The objective of this study was to analyze the characteristics and availabilities of the poultry litter co-products under a controlled soil incubation environment to determine how they compare to the current industry standards in terms of potential bioavailability.

3.3   Experimental Design

A non-leached aerobic incubation study was conducted with a Bojac sandy loam soil (Table 3.1) (Coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) (USDA-NRCS, 2012) with a bulk density of 1.14 g cm^{-3} (Table 3.2) to evaluate the phosphorus and potassium mineralization characteristics of poultry litter co-products. To evaluate the phosphorus and potassium mineralization of 4 ash co-products (ASH1, ASH2, ASH3, and ASH4) and 2 biochar co-products (BIOCHAR1 and BIOCHAR2) (Table 3.3) compared to TSP and KCl applied at a rate of 85 mg P kg^{-1} and the amount of potassium applied per co-product was recorded. The fertilizers were arranged in a randomized complete block design with 4 replications and incubated for 0, 3, 7, 14, 28, 56, 84, 112, and 140 days as described by (Reiter et al., 2014). The fertilizers were mixed in 50 g of air-dried soil in 500 ml plastic bottles. Bottles were then raised to approximately 60% water-filled pore space (0.15 g water g soil^{-1}; Schomberg et al., 2011) with double de-ionized water. Final weights were taken so the water content could be adjusted on an as-needed basis. Uncapped bottles were placed into incubation chambers at 80% humidity and 25°C.

3.3.1   Sample Analysis

At each sampling day, 4 replications were extracted per treatment source. For extraction, each bottle was filled with 500 mL of 0.01 M CaCl$_2$ solution (Aslyng, 1964) and shook for 1 hour at 200 opm (Kuo, 1996). The suspension settled for an hour and the supernatant was decanted and filtered through Whatman 42 filter paper into 25 mL scintillation vials and stored at 4°C until analyzed. Samples were analyzed for phosphorus and potassium concentrations using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire, R. O. and S. E. Henkendorn, 2011). The phosphorus and potassium concentrations of the untreated control soil samples were averaged and subtracted out. The percent remaining in the sample was calculated by the concentration of the sample divided by the original amount of fertilizer added and multiplied by 100.

$$\left(\frac{\text{Sample Concentation}}{\text{Original Amount Added}} \times 100 = \% \text{ remaining}\right)$$

3.3.2   Statistical Analysis

Statistical analysis was conducted using analysis of variance (ANOVA), SAS PROC MIXED procedures and Fisher's LSD with an alpha level of 0.10 using SAS 10.1 statistical software (SAS Institute, 2007).

3.4   Results and Discussion

Overall availability of soil phosphorus from fertilizer sources was low due to the acidic nature of the soil. Water pH readings from the incubation soil averaged 5.4 (Table 3.2), which would decrease overall recoverable phosphorus. Phosphorous fixation occurs rapidly in the acidic pH ranges reacting with Al, Fe, and Mn ions and oxides to form insoluble compounds that are not plant available (Brady and Weil, 1996). When comparing the percentage phosphorus recovered/ phosphorus fertilizer applied over time for each fertilizer source (Figure 3.1), a significant phosphorus interaction was observed between fertilizer source and incubation sampling day (Table 3.5). As expected, the standard fertilizer TSP was initially the most available and water soluble at 0 d (55.50%), followed by fresh poultry litter (9.13%). Triple super phosphate became less available over time as Fe-oxides and Al-oxides in the soil absorbed phosphorus (Sims et al., 1998; Brady and Weil, 1996). Fresh poultry litter decreased in availability until day 28 (4.35%) and began significantly increasing in availability, 56 d (6.36), until peak availability at 112 d (7.19%). The increase in availability over time is likely from microbial activity, as the fresh material releases the phosphorus from poultry litter organic matter (Sharpley et al., 2007). Fresh poultry litter was found to be far less available (9.13%) than the 60-100% bioavailability range the literature field studies suggested (Slaton et al., 2013; Barbazan et al., 2009; Sneller and Laboski, 2009).

In comparing ash co-products, ASH4 has the highest water-soluble phosphorus (5.84 % at 0 d) and experienced a similar increase in availability to poultry litter at 14 d (5.95%) and 56 d (8.63%). The remaining co-products remained at a consistent solubility across time and had a range of approximately 2-4% available phosphorus, which was lower than the TSP and fresh poultry litter standards. Trends showed that ASH2 and the biochars had the least phosphorus availability.

The characteristics and solubility of the ash co-products vary due to the differences in their formation. All of the sources were derived from different thermal conversion systems and were combusted at different temperatures and had varying oxygen rates (Table 2.2). It seems that the ASH4 system had the optimal ratio of temperature to oxygen for soluble phosphorus availability in a growing season, and the ASH2 system would lead to the lowest solubility. The ASH2 system was gasified at higher temperatures for a longer period of time than the ASH4 system. The biochars were found to have a lower phosphorus availability rate, which was expected as biochars are formed in low heat with the intention of creating a slow-release product from which the full nutrient release may not be seen for years (Maguire and Agblevor, 2010).

When comparing the percentage of potassium recovered/ potassium fertilizer applied over time by each of the sources (Figure 3.2), a significant potassium interaction was observed between fertilizer source and incubation sampling day (Table 3.6). Fresh poultry litter had the greatest initial potassium availability at 0 d (97.99%). Our results for potassium availability were closer to the estimated availability in the literature, which stated that potassium should be highly soluble and should be 100% plant available (Jackson et al., 1975; Slaton et al., 2013). At 56 d, the potassium availability of ASH4

(88.19%) became similar to poultry litter (88.19%) and remained consistent until then end of the study. Also at 56 d, there was a significant increase in potassium availability for 4 of the co-products: ASH1 (46.37%), BIOCHAR2 (78.65%), ASH3 (54.54%), and ASH4 (81.04%). Out of all the co-products, ASH2 had the least water-soluble potassium at 0 d (10.89%).

Fresh poultry litter was by far the highest supplier of water-soluble potassium, which was expected as the standard unprocessed material, but over time ASH4 produced similar potassium availabilities after 56 d. Similar to the phosphorus release, ASH2 had the lowest nutrient availability; it did not change over time and remained within a range of 8.14-12.63%. The difference in these sources can once again be explained by differences in initial feedstock and system of thermal conversion (temperature and oxygen ratios). The potassium availability results further reiterate the ASH4 system's optimal conditions for creating a nutrient-dense and plant-available fertilizer.

3.5 Conclusion

The industry inorganic phosphorus fertilizer (TSP) and fresh poultry litter had the greatest initial availability for phosphorus and potassium. Over time, some of the ash co-products reached similar availabilities comparable to the industry standards but differed due to the variability in their systems of formation. The ASH4 thermal conversion system produced an ash co-product that was the most similar to the standards and provided an ideal fertilizer that was both nutrient dense and plant available. The ASH2 system converted the feedstock at higher temperatures and had longer residence times, creating a nutrient-dense product that was not readily water soluble. The biochar co-products were among the least available of the fertilizers in the study; this was expected because the biochars are formed with a slow-release product in mind to strongly hold and remove nutrients and carbon from the soil system for many years. Further ash research will be needed for each thermal conversion system and feedstock as the burning process significantly alters the overall nutrient water solubility over time.

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3.7 Tables

Table 3.1   Mehlich-I background analysis of nutrients of the Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) used in the incubation studies

	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
	-------------------------kg ha^{-1}-----------------------				----------------------------------mg kg^{-1}--------------------------------				
Soil	194	146	832	95	1.4	25.4	1.3	25.0	0.2

Table 3.2   Chemical and physical properties of the Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) used in the incubation studies

	pH	Buffer Index	Estimated CEC†	Bulk Density	Acidity	Base Saturation
			---meq 100 g^{-1}---	g cm^{-3}	---------------------%-------------------	
Soil	5.4	6.14	3.9	1.136	39.5	60.6

†CEC = Cation exchange capacity

Table 3.3   Nutrient content of poultry litter co-products, fresh poultry litter, and standard fertilizer (TSP) for phosphorus and potassium incubation study

Source	N	P	K	S
	--%--			
ASH1†	0.256	1.08	12.77	2.98
ASH2†	0.542	6.07	33.13	3.18
ASH3†	0.280	10.39	11.25	2.29
ASH4†	0.141	6.38	8.40	1.45
BIOCHAR1‡	1.44	2.29	1.71	0.40
BIOCHAR2‡	2.51	2.59	4.87	1.25
Poultry Litter	3.55	1.08	1.91	1.10
TSP	0.00	20.09	0.00	0.00

Table 3.4   Phosphorus (P) availability as a percentage of total P recovered or total P applied over a 140 d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products, fresh poultry litter, and standard phosphorus fertilizer (TSP)

	0	3	7	14	28	56	84	112	140
	--Incubation Day--								
	---% P Recovered---								
ASH1	3.69†	4.43	3.89	3.30	4.13	3.48	3.89	3.85	4.33
ASH2	1.89	2.58	2.32	1.78	2.71	2.29	2.78	2.29	2.20
ASH3	2.44	3.40	3.24	2.72	2.72	3.12	3.75	3.95	3.45
ASH4	5.84	6.74	5.99	5.95	6.45	8.01	8.63	7.75	7.51
BIOCHAR1	1.60	2.19	2.04	1.76	2.69	1.74	2.25	2.11	2.11
BIOCHAR2	3.28	3.34	3.23	2.75	3.70	3.50	3.17	3.51	3.95
Poultry Litter	9.13	4.50	5.21	4.64	4.35	6.36	6.65	7.19	5.25
TSP	55.50	15.12	12.32	11.31	11.36	7.43	6.68	5.25	5.88

† Phosphorus source x incubation time interaction $LSD_{0.10}$=1.99%.

Table 3.5   Potassium (K) availability as a percentage of total K recovered or total K applied over a 140-d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products and fresh poultry litter

	\-Incubation Day\-							
	0	3	7	14	56	84	112	140
	\-% K Recovered\-							
ASH1	36.00†	43.12	40.36	33.70	46.37	45.60	47.74	43.44
ASH2	10.89	11.39	12.10	8.14	12.63	12.15	10.81	10.42
ASH3	41.29	53.59	51.17	39.48	54.54	62.74	61.77	57.59
ASH4	58.76	66.91	67.41	60.44	81.04	88.10	76.73	81.95
BIOCHAR1	63.58	72.23	73.92	49.53	71.54	76.31	66.80	59.64
BIOCHAR2	64.19	69.55	67.83	59.61	78.65	82.18	80.68	74.20
Poultry Litter	97.99	88.58	88.36	87.94	88.19	93.24	92.75	87.73

†Potassium source x incubation time interaction $LSD_{0.10}$=8.99%.

3.8 Figures

Figure 3.1   Phosphorus (P) availability as a percentage of total P recovered or total P applied over a 140 d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products, fresh poultry litter, and standard phosphorus fertilizer
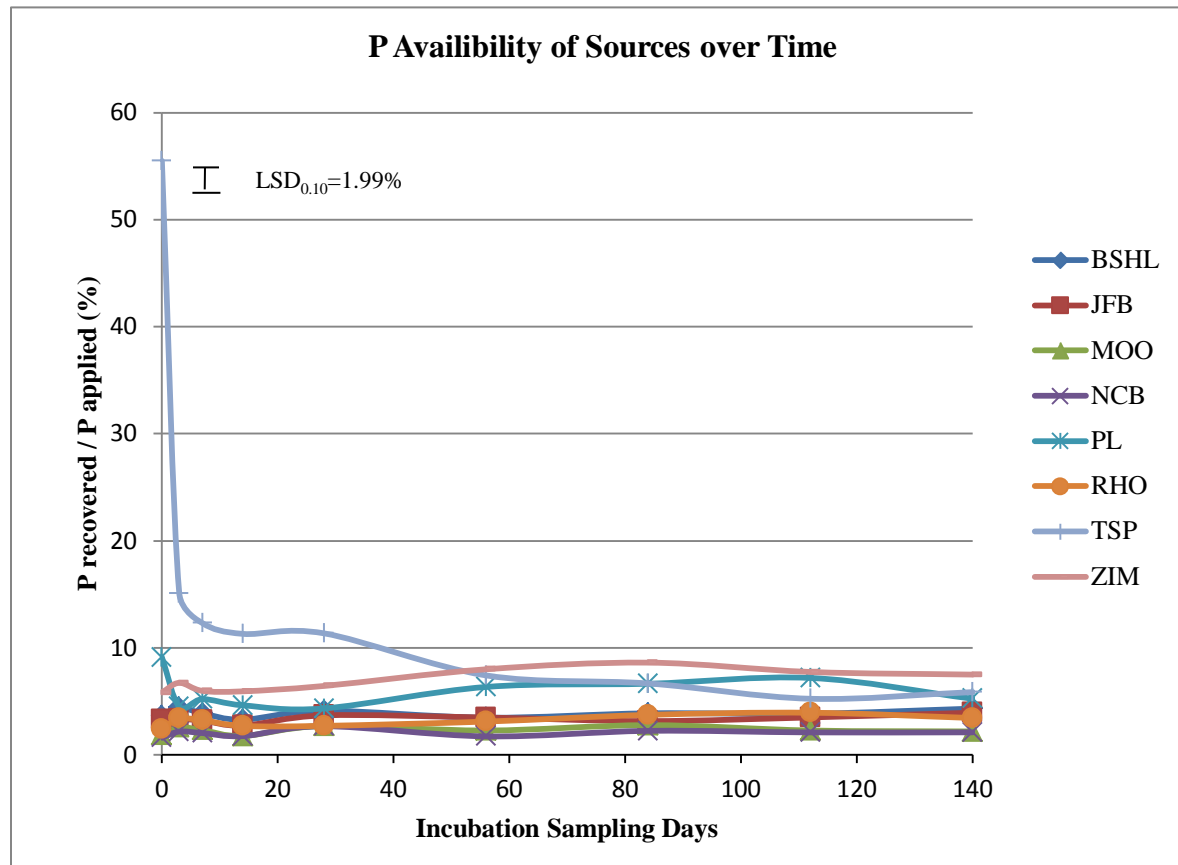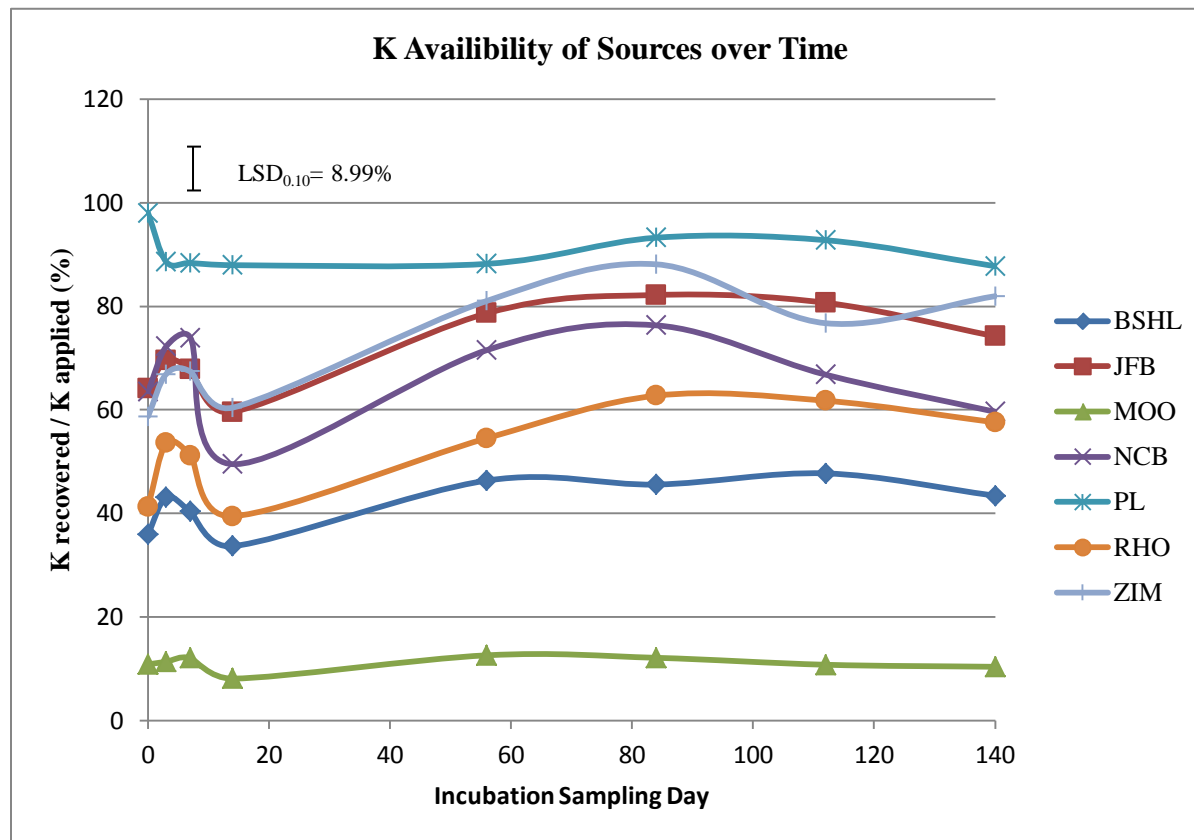
Figure 3.2   Potassium (K) availability as a percentage of total K recovered or total K applied over a 140 d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products and fresh poultry litter

4. Nutrient Availability of Poultry Litter Co-Products in Field Trial Applications

4.1 Abstract

Phosphorus is a nutrient of concern in the Chesapeake Bay watershed due to nutrient imbalances in areas with confined animal feeding operations. By converting poultry litter to an ash or biochar, nutrients are concentrated into a form that can be economically shipped out of nutrient-dense areas to nutrient deficient regions, such as the corn belt. In nutrient deficient regions, these poultry litter co-products have potential use as fertilizer with less impact on water quality.

We initiated field studies (corn [*Zea mays* (L.)], soybean [*Glycine max* (L.)], and wheat [*Triticum aestivim* (L.)]) on sandy loam soils to test phosphorus and potassium availability from poultry litter ash. Four ash co-products, derived from different sources using different combustion techniques, and 2 biochar products were surface broadcast applied at varying phosphorus and potassium rates. Poultry litter co-products were compared to a no-fertilizer control and industry standard inorganic phosphorus (TSP) and inorganic potassium (KCl) fertilizer at similar rates. Yield, Mehlich-I extractable soil nutrients, plant tissue and grain samples, and organic matter content were used to compare treatments. In general, poultry litter was the superior fertilizer source. Poultry litter ash co-products were highly variable due to the variations in thermal conversion systems and feedstock of formation. However, when applied at the proper rate, the poultry litter co-products appear to be comparable to standard fertilizers in corn, soybeans, and wheat field studies.

4.2 Materials and Methods

4.2.1 Experimental Design

We initiated a study on sandy loam soils (Table 4.1) to test phosphorus and potassium availability from poultry litter ash on corn, soybean, and wheat. Overall, three corn phosphorus studies, two full-season soybean potassium studies, three double-crop soybean potassium studies, three wheat potassium studies, and three wheat potassium studies were conducted.

Corn studies were conducted at the Virginia Tech Eastern Shore Agriculture Research and Extension Center (AREC) in Painter, Virginia (2013, 2014) and at the Virginia Tech Tidewater AREC in Suffolk, Virginia (2014). Studies consisted of 4 replications and 25 total fertilizer treatments arranged in a randomized complete block design (RCBD). Four ash co-products (ASH1, ASH2, ASH3, and ASH4), derived from different sources using different combustion techniques, and 2 biochar products (BIOCHAR1 and BIOCHAR2) (Table 4.2) were surface broadcast applied at 3 phosphorus rates (22, 44, and 88 kg P_2O_5 ha^{-1}). Potassium was applied with a

balanced application using KCl to ensure all plants had identical total potassium rates. Poultry litter co-products were compared to a no-fertilizer control and inorganic phosphorus (TSP) fertilizer at similar rates.

Full-season soybean studies were conducted at the Virginia Ag Expo location in the Land of Promise, Virginia (2013) and Lottsburg, Virginia (2014) (Table 4.1). Double-crop soybean studies were conducted on the Eastern Shore of Virginia at 2 sites in Accomack County (2014) (Table 4.1). The studies consisted of 4 replications and 10 total fertilizer treatments arranged in a RCBD. Five ash co-products (ASH1, ASH2, ASH3, ASH4 and ASH5), derived from different sources using different combustion techniques, and 2 biochar products (BIOCHAR1 and BIOCHAR2) (Table 4.2) were surface broadcast applied at one potassium rate (67 kg K_2O ha^{-1}) and phosphorus was applied with a balanced application using TSP. Poultry litter co-products were compared to a no-fertilizer control and potassium (KCl) fertilizer at similar rates.

Phosphorus wheat studies were conducted at three locations on the Eastern Shore of Virginia in Accomack County (2014) (Table 4.1). The studies consisted of 4 replications and 13 total fertilizer treatments arranged in a RCBD. One ash co-product (ASH3) (Table 4.2) was surface broadcast applied at 4 phosphorus rates (34, 67, 101, and 134 kg P_2O_5 ha^{-1}) and potassium was applied with a balanced application using KCl. Poultry litter co-product was compared to a no-fertilizer control and inorganic phosphorus (TSP) fertilizer at similar rates.

Potassium wheat studies were conducted at three locations on the Eastern Shore of Virginia in Accomack County (2014) (Table 4.1). The studies consisted of 4 replications and 13 total fertilizer treatments arranged in a RCBD. One ash co-product (ASH3) (Table 4.2) was surface broadcast applied at 4 potassium rates (34, 67, 101, and 134 kg K_2O ha^{-1}) and phosphorus was applied with a balanced application using TSP. Poultry litter co-product was compared to a no-fertilizer control and inorganic potassium (KCl) fertilizer at similar rates.

4.2.2   Sample Analysis

Yield, grain moisture, and grain test weight were collected at the time of harvest. Grain weight was captured in field by the combine's software (ALMACO Seed Spector LRX, Nevada, IA). Sample moisture and grain test weight was collected using a GAC® 2100 Agri DICKEY John Moisture Tester (Churchill Industries, Minneapolis, MO). Yield was corrected for percent moisture to industry bushel standards: 25.4 kg (56 lbs) per bushel for corn at 15.5% moisture, 27.2 kg (60 lbs) per bushel for soybeans at 13% moisture, and 27.2 kg (60 lbs) per bushel for wheat at 13.5% moisture (Murphy, 1993).

Plant tissue samples were dried until a constant weight at 55°C. Samples (corn ear leaf, corn grain, soybean tissue at V3 and V5, soybean whole plant at R2, soybean grain, wheat whole plant prior to bloom, and wheat grain) were coarse ground to pass a 2 mm sieve. Ground samples (0.5 g) were digested in nitric acid and hydrogen

peroxide using method 3050B (USEPA, 1996) and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011) for phosphorus and potassium.

Mehlich-I extractable nutrients were analyzed with ICP-OES (Mehlich, 1953). Soil samples were taken pre-fertilization at 3 depths: 0-15 cm, 15-30 cm, and 30-60 cm and at harvest at the 0-15 cm depth. Soils were air-dried and ground using a hammer mill to pass through a 2 mm screen. Using the Mehlich-I soil testing protocols, 8 grams of soil were extracted with 40 ml of Mehlich I solution (1:5 soil to extractant ratio) in 60 ml straight-walled plastic extracting beakers. The samples were shaken for 5 minutes on a reciprocating shaker set at 180 opm. Extracts were filtered through Whatman no. 2 filter paper into plastic vials and was then analyzed by ICP-OES for nutrient concentration.

To estimate phosphorus currently available in soil solution, 4 grams of soil were extracted with 40 ml of 0.01 $CaCl_2$ solution (1:10 soil to extractant ratio) in 60 ml straight-walled plastic extracting beakers (Aslyng, 1964; Olsen and Sommers, 1982). The samples were shaken for 1 hour on a reciprocating shaker set at 200 opm. Extracts were filtered through Whatman no. 2 filter paper into plastic vials. The solution was analyzed by ICP-OES for nutrients.

Soil organic matter samples were determined using the Loss-On-Ignition (LOI) Method as described by Ben-Dor and Banin (1989). The sample was air-dried at 105°C for 24 hours, cooled in a desiccator and weighed. The sample was then placed in a muffle furnace and ignited at 400°C for 16 hours, cooled in a desiccator and weighed. Organic matter is assumed to equal the % LOI. The LOI was determined by the equation % LOI = (Weight$_{105}$ - Weight$_{400}$ / Weight$_{105}$) x 100 (Ben-Dor and Banin, 1989).

4.2.3   Statistical Analysis

Statistical analysis was conducted using analysis of variance (ANOVA), SAS PROC MIXED procedures and Fisher's LSD with an alpha level of 0.10 using SAS 10.1 statistical software (SAS Institute, 2007).

4.3   Results and Discussion

4.3.1   Corn

There were significant differences between site year, so data is presented separately and the phosphorus source x phosphorus rate interaction was not significant. For the phosphorus rate main effect, yield increased in a linear relationship with phosphorus rate in the first year (Painter 2013) (Figure 4.1), averaged across phosphorus fertilizer sources. Phosphorus was limited in this experiment because a plateau was not reached due to the initial low phosphorus testing soil (9 mg kg^{-1}). Yield increased linearly in the second year (Suffolk 2014), until it reached a plateau at 22 kg ha^{-1} (Figure 4.1). After this point, no further

benefit to phosphorus fertilizer was realized due to high initial soil phosphorus concentrations (29 mg kg^{-1}). Yield data from Painter 2014 was omitted due to significant deer damage across all replications.

Overall, for phosphorus source, Suffolk 2014 data indicated that poultry litter was significantly the highest yielding source (7891 kg ha^{-1}), averaged over phosphorus rate. We speculate that heavy rains during the early growing season leached or denitrified significant amounts of nitrogen fertilizer, and the slow-release nitrogen from poultry litter was available to the corn crop and gave a significant yield advantage. The ash co-products were similar to TSP but higher than the no-phosphorus fertilizer control (Table 4.3). Overall, our data agrees with Slaton et al. (2013) who, found that poultry litter provided an additional yield benefit above that of commercial fertilizer at one of their eight responsive sites and similar yields at the other sites. The cause of the yield benefit was unknown and could not be attributed to another essential nutrient present in the poultry litter but not in the commercial fertilizer (Slaton et al., 2013). The Painter 2013 site was not significant and the average yield was 4565 kg ha^{-1}.

When averaged by site year and phosphorus fertilizer source, corn grain moisture had a significant linear response to phosphorus rate. Moisture increased with phosphorus rate at Suffolk 2014 (y= 0.0049x + 13.5; p=0.0640) and the no-fertilizer control had the lowest grain moisture (15.85%). No-fertilizer plots matured more quickly with lower yields and lower available nutrient concentrations, resulting in lower grain moisture concentrations at harvest.

Corn grain test weight varied with location and phosphorus source. Test weight by phosphorus source, averaged over phosphorus rate, was significantly different with one biochar co-product, BIOCHAR1 (673.0 kg m^{-3}), having lower corn grain test weight than all the other treatments (Table 4.4). The lower test weight could be explained by the biochar removing nutrients from the soil system and preventing them from being immediately available to plants (Maguire and Agblevor, 2010) as BIOCHAR1 had lower grain test weight than the no-fertilizer control.

There were no observed significant differences of phosphorus concentration in the corn ear leaf. The ear leaf concentrations averaged (2.2 g kg^{-1}) across all treatments and site years; which is below the optimal range of 2.5-.5.0 g kg^{-1} for tissue P (Bryson et al., 2013).

Averaged across site year, grain phosphorus concentrations varied with phosphorus rate and phosphorus source. For phosphorus rate, the highest rate (88 kg ha^{-1}) had the greatest concentration, which increased linearly (y= 1.589x + 2129; p= 0.0578). For phosphorus source, TSP (2.33 g kg^{-1}) had the highest grain phosphorus concentration and was significantly similar to ASH4 (2.29 g kg^{-1}) (Table 4.4). ASH4 was also comparable to TSP in yield, moisture, test weight, and grain phosphorus concentration indicating similar phosphorus availability. BIOCHAR2 tended to have the lowest yield, moisture, test weight, and grain phosphorus

concentration, indicating that the biochar co-product had the least available in the first growing season following application as a phosphorus fertilizer source.

4.3.2   Soybeans

Full Season Soybeans

Full season soybean yield, moisture, and test weight varied only with location and potassium fertilizer source was not significant. The Promise 2013 (2858 kg ha^{-1}) location had a statistically lower yielding crop than Lottsburg 2014 (5115 kg ha^{-1}).

The Lottsburg 2014 had statistically higher moisture concentrations (15.8%) than Promise 2013 (13.1%). The Lottsburg 2014 grain test weight (1839 kg m^{-3}) was statistically denser than Promise 2013 (709 kg m^{-3}). Therefore, the ash co-products were tested under variable growing conditions around Virginia, but source did not matter. Similar data and results were seen in other Virginia studies conducted during these same years at the same locations, as ample growing conditions did not necessitate additional potassium fertility (Stewart, 2015).

All V3 tissue concentrations averaged across all treatments and site years (27.0 g kg^{-1}) were above or within the optimal range of 17.0-25.0 g kg^{-1} for tissue potassium (Bryson et al., 2013). Tissue potassium concentration of V5 and R2 tissue varied with location. Lottsburg 2014 (21.0 g kg^{-1} and 25.0 g kg^{-1} for V5 and R2, respectively) had statistically higher concentrations than Promise 2013 (19.0 g kg^{-1} and 14.0 g kg^{-1}, respectively). All V5 and R2 tissue concentrations were within the optimal range of 18.0-25.0 g kg^{-1} for V5 tissue potassium and 15.0-22.5 g kg^{-1} for R2 tissue potassium (Bryson et al., 2013). The only significant result from potassium fertilizer source occurred at the Promise 2013 site location for grain potassium concentration. All ash co-products were statistically similar to the fresh poultry litter and TSP standards with the exception of ASH4 (17.5 g kg^{-1}), which had lower grain potassium concentrations.

Double Crop Soybeans

The Willis Wharf A site location had significant differences between potassium sources. The fly ash co-product ASH5 (1824 kg ha^{-1}) underperformed fresh poultry litter, KCl and most ash co-products, averaged across potassium rate. Interestingly, the fly ash has the highest potassium concentration (202.4 g kg^{-1}) of all ash co-products (Table 2.3a) tested. The fly ash is a fine particulate that exhausts from the thermal conversion units as they burn poultry litter, but appears to have lower water solubility than the bulk ash from the same systems and poultry litter as those treatments yielded 2435 kg ha^{-1} (ASH2). The ASH5 fly ash yields were actually lower than the no-fertilizer control plots (2222 kg ha^{-1}). Similarly, BIOCHAR1 was also lower yielding than the standard fertilizer treatments and several ash sources (Table 4.5).

For grain moisture, averaged over location, BIOCHAR1 and BIOCHAR2 were statistically similar to fresh poultry litter and KCl; the rest of the co-products were significantly drier than the standards, with ASH4 being the driest (Table 4.6). For test weight averaged over site year, there was a significant difference between potassium sources. BIOCHAR1, ASH3, ASH4, and ASH5 were similar to applying no fertilizer at all (Table 4.6). Low test weight results were similar to yield, and potassium availability may not be available from the biochar and fly ash co-products compared to other technologies that produce more soluble ash sources.

For the R2 tissue concentration of potassium averaged across location, Willis Wharf B site had significant differences between potassium sources. Poultry litter had the highest tissue potassium concentration at R2 (28.0 g kg^{-1}) than other co-products. All other co-products were similar to the no-fertilizer control. However, all R2 tissue concentrations were within the optimal range of 15.0-22.5 g kg^{-1} for R2 tissue (Bryson et al., 2013). Muriate of potash (18.4 g kg^{-1}) had the highest grain potassium concentrations.

4.3.3   Wheat Phosphorus

Overall, there were no major differences between ash co-products for wheat yield. Average yield by location for Gospel Temple was 4133 kg ha^{-1}, Cheriton was 3722 kg ha^{-1}, and Quinby was 3360 kg ha^{-1}. Grain moisture was only significant at the Cheriton site in phosphorus rate main effect, averaged over phosphorus source. Grain moisture content increased linearly with phosphorus addition (y= 0.0025x +13.8; *p*= 0.0100). Similarly, grain test weight decreased linearly with the addition of P (y= -0.0712x + 766; *p*= 0.0351).

For tissue phosphorus concentration averaged across phosphorus rate, the Gospel Temple site had a significant phosphorus source effect. ASH3 (2.5 g kg^{-1}) was statistically similar to TSP (2.8 g kg^{-1}), but had lower concentrations than poultry litter (3.0 g kg^{-1}). However, all tissue phosphorus samples were within the range of 2.0-5.0 g kg^{-1} (Bryson et al., 2013). Codling et al. (2002) found that poultry litter ash treatments produced higher tissue phosphorus concentrations than the standard, although their concentrations were below the optimum range due to initial low soil phosphorus concentrations. Overall, there were no major differences between ash co-products grain phosphorus concentration and averaged 3.9 g kg^{-1} for Quinby, 3,8 g kg^{-1} for Gospel Temple, and 3.7 g kg^{-1} for Cheriton.

4.3.4   Wheat Potassium

Averaged across location and potassium fertilizer rate, poultry litter was statistically the highest yielding (3744 kg ha^{-1}). Muriate of potash and ASH3 were similar to the no-fertilizer control treatments (3398 kg ha^{-1}) (Table 4.7). Therefore, the poultry litter provided additional yield benefit just as in a soybean study by Slaton et al. (2013), although the source of the additional benefit was unknown. Moisture exhibited similar results to yield when averaged over potassium rate, as

poultry litter (13.8%) was statistically the driest source and KCl and ASH3 were statistically similar to each other and drier than the control plot (14.3%) (Table 4.7).

The tissue potassium concentration increased linearly with increasing fertilizer rate ($y = 21.29x + 13051$; $p = 0.0017$) (Figure 4.2), which is indicative of potassium availability and plant uptake from the fertilizer sources. Averaged across location and potassium rate, tissue potassium concentration from fresh poultry litter (16.2 g kg^{-1}) was statistically higher than KCl and ASH3 (Table 4.6). Only the poultry litter source had tissue potassium concentrations within the optimal range of 15.0-30.0 g kg^{-1} for tissue potassium (Bryson et al., 2013). Quinby had a significant difference between potassium fertilizer sources, averaged across potassium rates. ASH3 (4.3 g kg^{-1}) was statistically similar to poultry litter (4.3 g kg^{-1}) and had higher grain potassium concentrations than KCl (4.1 g kg^{-1}) and the control plot (4.1 g kg^{-1}) Therefore, the co-product was equally plant available compared to the standard sources.

4.3.5   Soil Mehlich-I and Soil Organic Matter

Following harvest, the phosphorus and potassium concentrations in the soil increased linearly with rate of fertilizer application, averaged over fertilizer source. Soil phosphorus concentrations increased linearly with the addition of fertilizer at the Painter 2014 corn location ($y = 0.0549x + 3.8$; $p = 0.0115$) (Figure 4.3) and soil potassium concentration for the wheat potassium locations ($y = 0.1873x + 81.7$; $p = 0.0088$) (Figure 4.4).

For the Gospel Temple site year phosphorus source main effect, poultry litter (32.5 mg P kg^{-1}) had higher phosphorus concentrations than the TSP standard (29.7 mg P kg^{-1}); this was most likely due to its greater residual phosphorus, although not significantly different than ASH3 (29.7 mg P kg^{-1}) or the no-fertilizer control (27.7 mg P kg^{-1}). At the Painter 2014 corn location, BIOCHAR2 (87.8 mg K kg^{-1}) had the greatest concentration of potassium in the soil while, the other sources were statistically similar (Table 4.8). This supports the yield data that the biochar sources are less plant available and will remain in the soil for future years (Maguire and Agblevor, 2010).

The vast majority of micro-elements increased linearly with increasing rate of fertilizer application and was observed with Al, Ca, Cu, B, Mg, and Zn. The overall Fe concentration in the soil made it difficult to see an Fe response from the application of the fertilizers. Overall, Zn tended to be less concentrated in the soil fertilized by ash co-products leading us to believe that Zn is more plant available in the ash form. Soil B concentration trended to be higher following poultry litter applications. Soil Cu concentrations tended to be higher following poultry litter and ash, as Cu is typically absent from inorganic fertilizers. None of the soil-applied elements exceeded concentrations that would cause environmental concern based on comparison of background concentrations in US soils according to the elemental limit recommendation charts from the USDA-NRCS (2015).

No significant differences were found for organic matter content after a single year application of ash and biochar. No significant difference was expected because at our greatest rate (88 kg ha^{-1}) we applied biochar at a rate of 1.7 Mg ha^{-1}and a study by Revell et al. (2012) found that after two years of applying biochar at a rate of 9 Mg ha^{-1}, 3 field sites showed significant increases in soil C (0.51, 0.39, and 0.36%; respectively). More research is need for multi-year usage to know when a change in organic matter will present.

4.4 Conclusion

Overall, poultry litter ash and biochar sources are suitable and comparable phosphorus and potassium fertilizers for crops on sandy loam soils in the Mid-Atlantic.

Poultry litter co-products vary greatly based on thermal conversion system and initial feedstock. If all ideal combustion criteria are met, then poultry litter co-products are feasible fertilizers, but need to be individually analyzed for nutrient content before making application recommendations. In our study, we found that the combustion systems seemed to have those ideal conditions and produced co-products that were highly plant available. However, a greater amount of the co-products will have to be applied to meet the same nutrient availability of the standards due to their lower plant availability. Fresh poultry litter tends to be the better fertilizer due to its added nitrogen content, which is lost in thermal conversion systems and would have to be supplemented with the ash co-products. Biochars tend to be less plant available than their ash counter parts. More research using the water-soluble availabilities instead of the total concentration nutrients of the co-products are needed to be able to identify stronger relationships with standard fertilizers.

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4.6 Tables

Table 4.1 Locations, soil types, and soil characterization for all field trial site locations

Year	Location	Crop	Texture	Classification	CEC†	pH	P	K	Ca	Mg
					--meq 100 g^{-1}--		------------mg kg^{-1}----------			
2013	Painter, VA	C‡	SL§	Typic Hapludults	5.6	5.7	9	71	641	92
2014	Painter, VA	C	SL	Typic Hapludults	5.4	6.1	5	60	686	95
2014	Cheriton, VA	W	FSL	Typic Hapludults	4.2	6.3	37	87	460	117
2014	Quinby, VA	W	SL	Typic Hapludults	4.8	5.6	36	109	473	71
2014	Willis Wharf, VA	SB/W	SL	Typic Hapludults	6.0	5.3	86	128	646	49
2014	Gospel Temple, VA	W	SL	Typic Hapludults	5.3	5.7	31	143	592	63
2014	Keller, VA	SB	LS	Typic Hapludults	4.2	6.0	14	102	569	55
2013	Land of Promise, VA	SB	L	Typic Hapludults	8.6	5.8	48	54	958	145
2014	Suffolk, VA	C	LS	Typic Hapludults	2.8	5.0	29	94	247	51
2014	Lottsburg, VA	SB	FSL	Aquic Hapludults	5.9	6.6	84	108	783	207

† CEC = cation exchange capacity
‡ C = corn, W = wheat, SB = soybean
§SL= sandy loam, L = loam, FSL= fine sandy loam, LS = loamy sand

Table 4.2   Nutrient content of ash and biochar treatment sources for field studies

Source	N	P	K	S
	----------------------------%----------------------------			
ASH1†	0.256	1.08	12.77	2.98
ASH2†	0.542	6.07	33.13	3.18
ASH3‡	0.280	10.39	11.25	2.29
ASH4‡	0.141	6.38	8.40	1.45
ASH5†		0.66	37.10	
BIOCHAR1§	1.44	2.29	1.71	0.40
BIOCHAR2§	2.51	2.59	4.87	1.25
Poultry Litter	3.55	1.08	1.91	1.10
TSP	0.00	20.09	0.00	0.00
KCl	0.00	0.00	53.57	0.00

† Gasification
‡ Combustion
§ Pyrolysis

Table 4.3   Corn yield at the Suffolk 2014 site year comparing poultry
litter co-product fertilizers to industry standard fertilizers (TSP)

Source	Suffolk 2014
	-------------------kg ha^{-1}-------------------
ASH1	6862b
ASH2	7083b
ASH3	6476b
ASH4	6978b
BIOCHAR1	6773b
BIOCHAR2	7062b
Poultry Litter	7891a
TSP	6871b
Control	5566c
LSD$_{0.10}$	834†

† A different letter within the column designates significance at the 0.10 level.

Table 4.4   Average corn grain test weight and grain phosphorus concentration across 3 site locations comparing poultry litter co-products, fresh poultry litter, and standard fertilizers (TSP)

Source	Test Weight	Grain P Concentration
	---------------kg m^{-3}-------------	-----------------g kg^{-1}------------------
ASH1	689.4a	2.22b
ASH2	682.5a	2.25b
ASH3	686.1a	2.16c
ASH4	685.5a	2.29a
BIOCHAR1	673.0b	2.02d
BIOCHAR2	685.3a	2.07d
Poultry Litter	688.3a	2.26b
TSP	690.9a	2.32a
Control	688.9a	2.16c
LSD$_{0.10}$	8.5	0.06

†A different letter within the column designates significance at the 0.10 level.

Table 4.5   Double crop soybean yield response to potassium source for WWA site location comparing poultry litter co-products, fresh poultry litter, and standard fertilizers (KCl)

Source	Yield
	----------------kg ha^{-1}---------------
ASH1	2435a
ASH2	2435a
ASH3	2397a
ASH4	2133abc
ASH5	1824c
BIOCHAR1	2020bc
BIOCHAR2	2237ab
Poultry Litter	2414a
KCl	2195ab
Control	2222ab
LSD$_{0.10}$	321

†A different letter within the column designates significance at the 0.10 level.

Table 4.6   Double crop soybean moisture, test weight, and grain potassium concentration by source over 3 site locations comparing poultry litter co-products, fresh poultry litter, and standard fertilizers (KCl)

Source	Grain Moisture	Test Weight	Grain K Concentration
	------------------%----------------	--------------kg m^{-3}-------------	---------------g kg^{-1}------------
ASH1	12.9bcd	715.4abc	17.5cd
ASH2	12.9bcd	718.6abc	17.4cd
ASH3	12.9cd	714.7cd	17.3d
ASH4	12.8d	715.1bcd	17.6cd
ASH5	12.9bcd	712.8d	17.4cd
BIOCHAR1	12.9abc	713.7d	17.7bc
BIOCHAR2	13.0ab	718.7ab	17.8bc
Poultry Litter	13.1a	718.1abc	18.0b
KCl	13.0a	721.4a	18.4a
Control	13.0a	713.8d	17.9bc
LSD$_{0.10}$	0.1	3.9	0.4

†A different letter within the column designates significance at the 0.10 level.

Table 4.7   Wheat yield, grain moisture, and tissue potassium (K) concentration response to K source across 3 site locations comparing ash co-product, fresh poultry litter, and standard fertilizers (KCl)

Source	Yield	Grain Moisture	Tissue K Concentration
	----------------kg ha^{-1}------------	----------------%---------------	-------------g kg^{-1}-------------
ASH3	3214b	14.0b	14.1b
Poultry Litter	3744a	13.8c	16.2a
KCl	3319b	14.0b	14.2b
Control	3397b	14.3a	12.8c
LSD$_{0.10}$	222	0.1	0.7

†A different letter within the column designates significance at the 0.10 level.

Table 4.8   Soil potassium concentration by fertilizer source for the Painter 2014 corn site location

Source	Painter 2014
	---------------------------- Potassium --------------------------
	--------------------------------mg kg^{-1}----------------------------
ASH1	71.8bc
ASH2	76.5bc
ASH3	77.0b
ASH4	73.3bc
BIOCHAR1	66.8c
BIOCHAR2	87.8a
Poultry Litter	74.9bc
TSP	69.4bc
Control	74.4bc
LSD$_{0.10}$	10.0

†A different letter within the column designates significance at the 0.10 level.

4.7 Figures

Figure 4.1   Corn yield by phosphorus (P) rate for 2 corn site locations
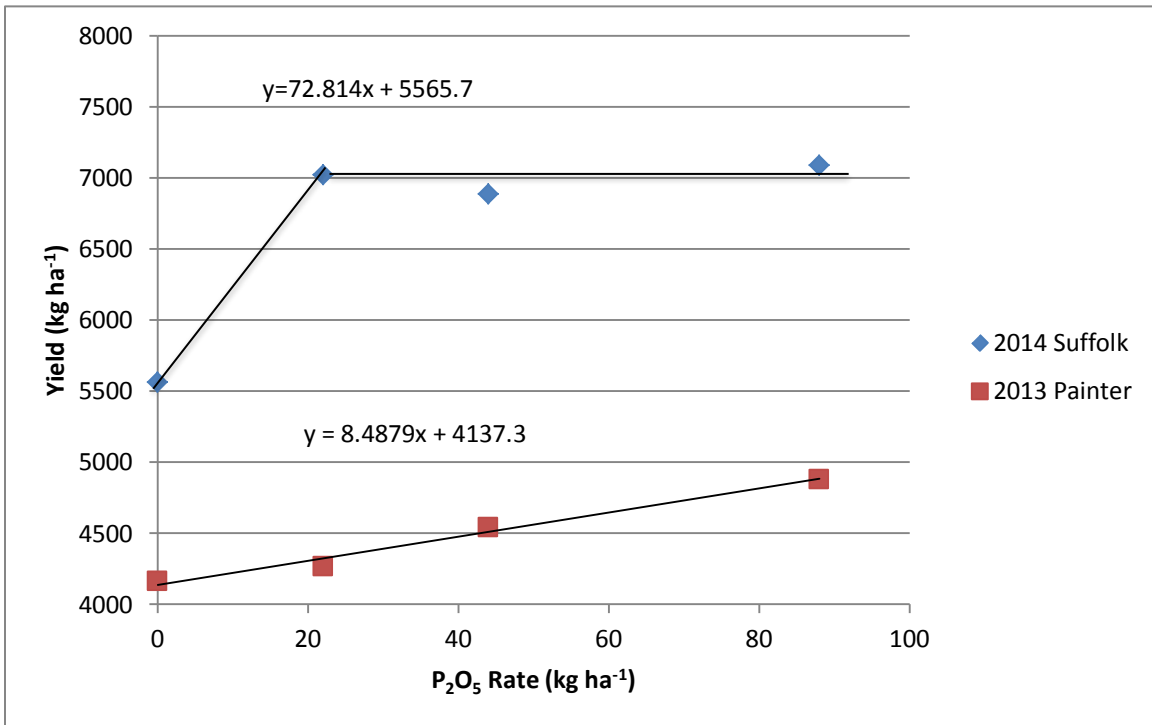
Figure 4.2   Wheat potassium (K) tissue K concentration response to rate of K across 3 site locations
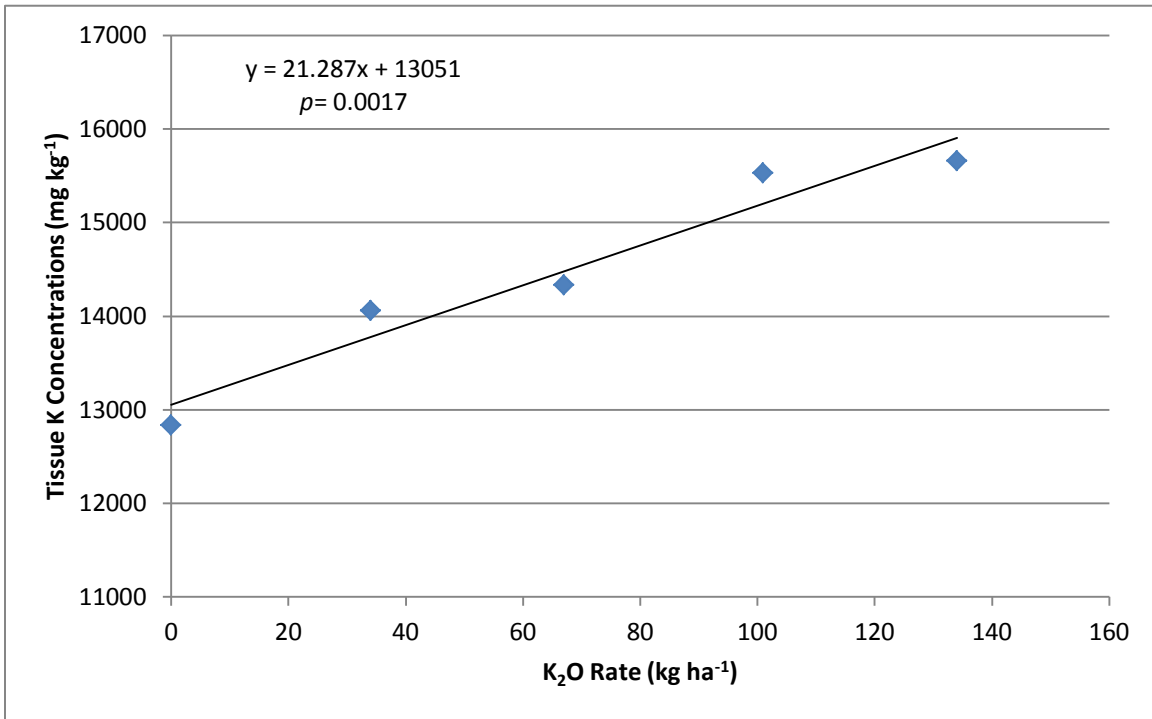
Figure 4.3 Soil phosphorus (P) concentration by treatment rate for the Painter 2014 site location

$y = 0.0549x + 3.8256$
$p = 0.0115$

Soil P concentration (mg kg^{-1}) vs. P$_2$O$_5$ Rate (kg ha^{-1})
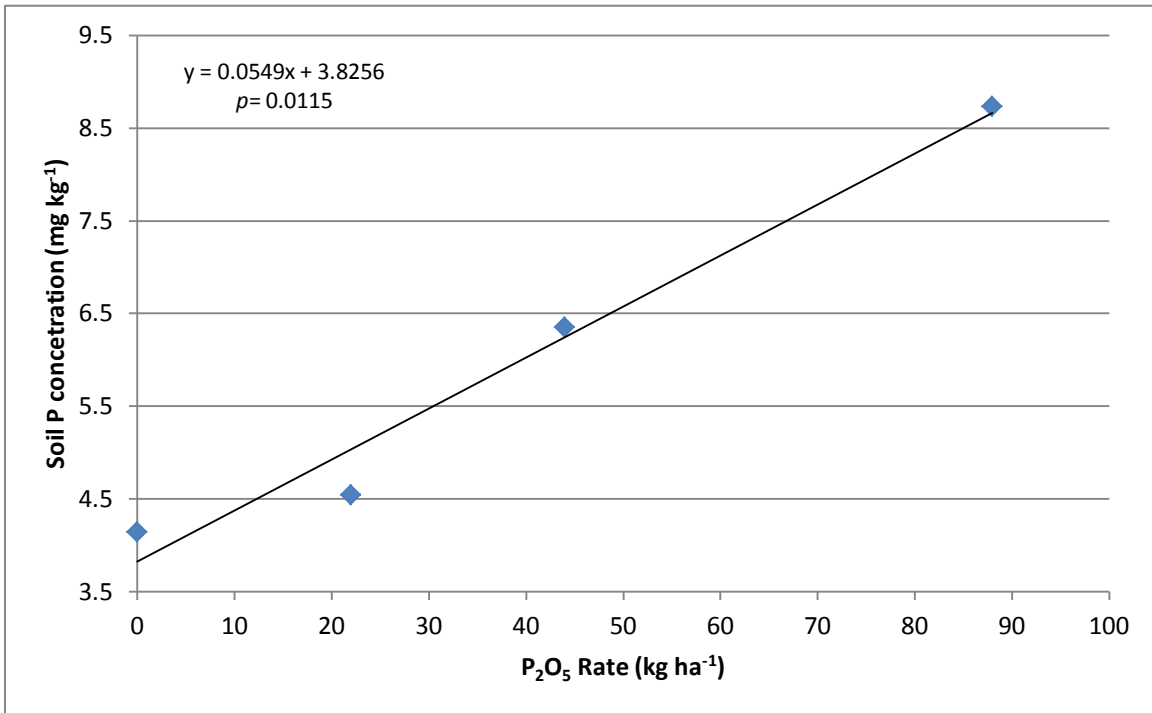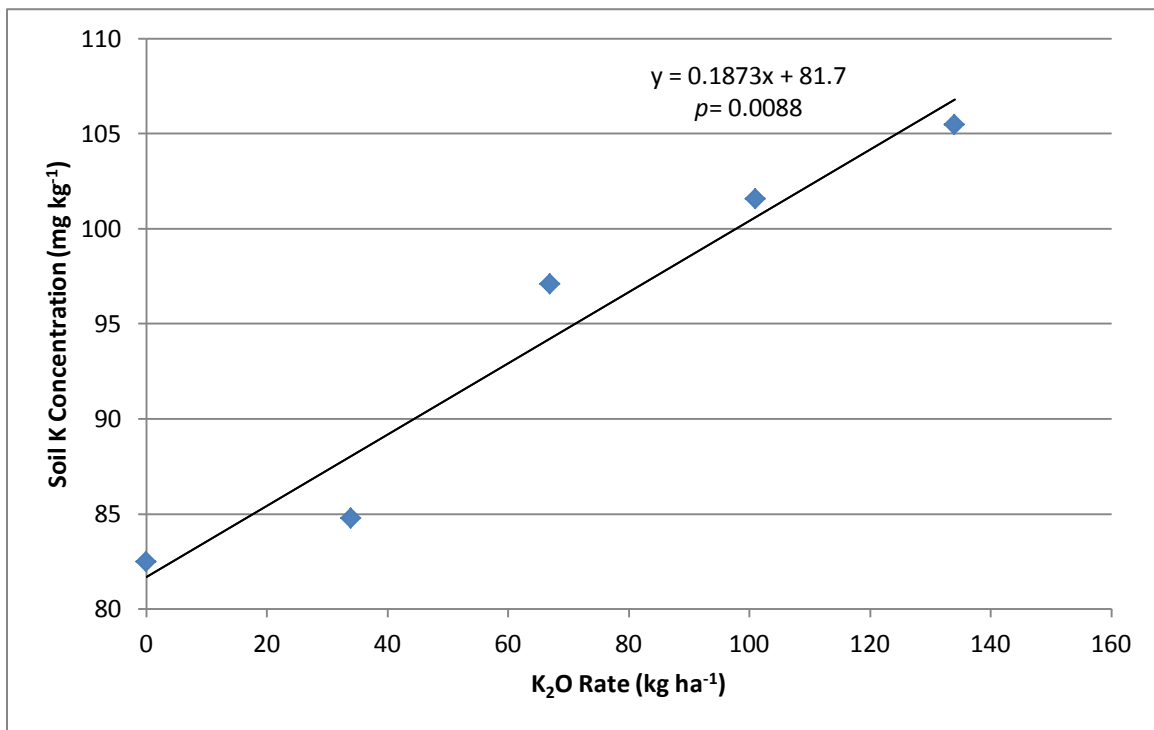
Figure 4.4   Soil potassium (K) concentration by treatment rate for Wheat K site locations

5. Comparison of Poultry Litter Input versus Ash Output During Emissions Testing

5.1 Abstract

Creating ash co-products from the thermal conversion of poultry litter concentrates nutrients in the ash and also releases nutrients to the atmosphere. We initiated a sampling study to compare poultry litter going into thermal conversion units to poultry litter ash that corresponded to air quality emissions testing. Three different systems were tested with varying scales of heat production and poultry litter feed rates. Overall, the macro-nutrients nitrogen and sulfur were significantly reduced in the resulting ash and were likely lost via the stack during gasification and combustion. Potassium in the bulk ash was reduced in gasification system bulk ash, but not impacted in the combustion systems. Stable nutrients, such as phosphorus, were concentrated 4.5 to 12.2 times when calculated on an "as-is" basis. This concentration effect would allow phosphorus to be shipped greater distances from the fresh poultry litter source, based on the nutrient value. In conclusion, elemental data from poultry litter and poultry litter ash can be combined with air emissions data to establish a complete nutrient mass balance for manure-to-energy projects.

5.2 Materials and Methods

5.2.1 Balance Comparison Sampling

Each thermal conversion system was unique to the farm location in its physical construction, operating conditions, residence time, and initial poultry litter feedstock (Tables 5.1 and 5.2); individual system sampling methods are listed below. Samples were tested for percent moisture (Wolf and Haskins, 2003), calcium carbonate equivalent (Wolf and Haskins, 2003), and elemental concentration using the EPA method 3050B. Air emissions testing occurred during each of these sampling times.

- Enginuity Energy: Energy Ecoremedy Gasifier: ASH7 and ASH9

  Samples were taken at two sampling locations in accordance to the residence time of the systems: fresh poultry litter entering the system and the bulk ash auger at the end of the system. Fly wash was collected at the bottom of the cyclone. Residence time was observed to be 299 minutes from the start to the end of the system. The time and chamber temperature was recorded at two locations within the system at a residence time of 134 minutes (Gas burner #1) and 239 minutes (Gas burner #2). The water boiler set temperature was also recorded for each sample.

- Total Energy Blue Flame Stoker Version 2.0: ASH10 and ASH11

  Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter entering the system, the main ash auger, and the end ash auger. The residence time was observed to be 120 minutes from

start to the main bulk ash auger, and 100 minutes from start to the end auger with the bulk ash and fly ash mixture. The time, stack temperature, and boiler temperature were recorded for every sample.

- LEI Bio-Burner: ASH12 and ASH13

    Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter entering the system, the main ash auger, and the bottom of the stack. The residence time was observed to be 15 minutes from start to the main bulk ash auger. The fly ash was sampled at the end of the day as the unit had to be opened. The time, stack temperature, poultry litter feed rate, and boiler temperature were recorded for every sample.

5.2.2   Elemental Analysis

Fresh poultry litter and ash samples (0.5 g) were digested in nitric acid and hydrogen peroxide using method 3050B (USEPA, 1996), and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011).

5.3   Results and Discussion

5.3.1   Elemental Analysis

The nitric acid/hydrogen peroxide digestion is an elemental digestion that quantified the total elemental concentration expected to be plant available; this is typically a complete digestion with fresh poultry litter (Tables 5.3a and 5.3b). Total nitrogen, phosphorus, and potassium fertilizer ratios for each poultry litter feedstock used was 2.8-1.8-5.5, 2.4-1.8-1.8, and 2.8-2.6-2.1 as $\%N-\%P_2O_5-\%K_2O$ (Table 5.3a); this is in the range of typical feedstocks found in the Mid-Atlantic region. Moisture ranges were from 23.2 to 25.7%, which is on the dryer side of fresh poultry litter sources. All micro-nutrient concentrations were within range of expected values (Table 5.3b). Typically, poultry litter composition varies greatly from location to location depending on the practices of the individual poultry producer (Bolan et al., 2010; Kelley et al., 1996; Tasistro et al., 2004).

5.3.2   Nutrient Concentration

The nutrient concentration impact varied widely across the study locations; it was calculated by the ash nutrient concentration being divided by the feedstock poultry litter nutrient concentration on an "as-is" basis. On average, total nutrients were concentrated 5.2, 7.3, and 12.1 for ASH12, ASH7, and ASH10, respectively (Table 5.4). Literature stated that the typical concentration factor is 6 or 7 times that of the original feedstock nutrients (phosphorus, potassium, and sulfur) for fresh poultry litter (Bock, 2004). Our study found that concentrations varied between systems based on moisture, but also varied for each specific nutrient source. For instance, the most stable nutrient, phosphorus, demonstrated a concentration effect of 4.5 to 12.2 (Table 5.4). Phosphorus is typically easily digested using the methodology used and is not typically lost via stack emissions. Other nutrients,

such as nitrogen and sulfur, were greatly reduced after combustion due to stack emissions. Potassium reacted differently based on energy system being used. For instance, the gasification system had significant potassium loss via the stack, as potassium was only 3.2 times concentrated versus the 10.0 concentration of phosphorus (Table 5.4). However, the two combustion systems had nearly identical concentration effects for phosphorus and potassium (12.2 vs. 12.9 and 4.5 versus 4.9 for ASH10 and ASH12, respectively). Conversely, the ASH9 fly ash had nearly 4 times the amount of potassium than the two combustion sources (662.0 vs. 157.0 and 124.0 g K kg^{-1}, respectively) (Table 5.3a). Micro-nutrients, such as Fe and Al demonstrated a much higher concentration as they are more difficult to extract via the US-EPA 3050B digestion and were made significantly more available and extractable after being heated in the manure-to-energy systems.

5.4 Conclusion

Our study found that nutrient densification varied between systems and poultry litter feedstocks, with an average densification between 5.2 to 12.1 when averaged across all micro- and macro-nutrients. Densification varied between each nutrient as each nutrient reacted differently to the heating process and/or was lost from the system via air emissions. For instance, the unit producing ASH10 lost 100% of its nitrogen, but concentrated and increased aluminum availability up to 29.4 times. The gasification system that produced ASH7 lost more potassium via the stack than the combustion systems that produced ASH10 and ASH12. Regardless of the system, phosphorus was concentrated significantly (4.5 to 12.2 times) and would allow greater movement of phosphorus manure sources from the fresh poultry litter due to nutrient value alone; this would help move excess phosphorus out of watersheds. Overall, elemental data from poultry litter samples going into the energy system can be used alongside poultry litter ash elemental concentration and air emissions data to establish a complete manure-to-energy nutrient mass balance.

5.5 References

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5.6 Tables

Table 5.1   Descriptions of poultry litter co-product sources used for input/output comparisons

Source	Co-Product Type	Farm Name	Thermal Conversion System
ASH7	Bulk Ash	HEL	Gasification
ASH9	Fly Ash	HEL	Gasification
ASH10	Bulk Ash	CUR	Combustion
ASH11	Fly Ash	CUR	Combustion
ASH12	Bulk Ash	RHO	Combustion
ASH13	Fly Ash	RHO	Combustion

Table 5.2   Source information and background information for poultry litter co-product thermal conversion systems

Source	Location	System	Burn Temp	Residence Time	Mode of Energy Dispersal	Poultry Litter Type	Co-Product Type
ASH7 & ASH9	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	299 min	Hot Water	Organic Broiler	Ash
ASH10 & ASH11	Snyder County, PA	Total Energy Blue Flame Stoker V2.0	82ºC water set temp 171ºC exhaust temp	120 min	Hot Water	Organic Turkey	Ash
ASH12 § ASH13	Port Republic, VA	LEI Bio-Burner	884ºC	15 min	Hot Water	Organic Turkey	Ash

Table 5.3a   Total elemental concentration of ash co-products and corresponding fresh poultry litter on an "as-is" basis

Source	Product	Moisture	CCE†	N	NH$_4$-N	NO$_3$-N	P	K	S	Mg	Ca
					---------g kg^{-1}---------						
ASH7 & ASH9	Fresh Poultry Litter	257	41	27.9	7.1	0.384	7.9	46.0	8.0	6.3	20.4
ASH7	Bulk Ash	4	300	6.0	0.0	0.004	79.7	146.3	22.9	34.5	103.4
ASH9	Fly Ash	93	126	9.7	10.7	0.000	53.9	662.0	65.7	22.9	68.8
ASH10 & ASH11	Fresh Poultry Litter	232	16	23.9	4.6	0.047	7.8	14.8	3.2	3.6	13.5
ASH10	Bulk Ash	5	350	0.8	0.0	0.011	95.1	190.3	15.5	48.6	157.0
ASH11	Fly Ash	13	290	1.8	0.0	0.007	66.9	157.0	26.5	39.7	111.0
ASH12 & ASH13	Fresh Poultry Litter	246	20	28.4	7.5	0.108	11.2	17.9	6.1	10.3	38.9
ASH12	Bulk Ash	16	210	11.0	0.0	0.000	50.6	87.2	9.6	17.0	100.6
ASH13	Fly Ash	4	273	0.2	0.0	0.002	109.1	124.0	23.0	46.3	175.0

†Calcium carbonate equivalent.

Table 5.3b   Total elemental concentration of ash co-products and corresponding fresh poultry litter on an "as-is" basis

Source	Product	Na	Fe	Al	Mn	Cu	Zn	B
		--g kg^{-1}--						
ASH7 & ASH9	Fresh Poultry Litter	4597	415	557	498	125	614	790
ASH7	Bulk Ash	26900	10667	10320	2387	566	2540	3253
ASH9	Fly Ash	19800	8030	4500	1690	598	5120	3490
ASH10 & ASH11	Fresh Poultry Litter	3357	651	451	294	298	291	39
ASH10	Bulk Ash	43100	9457	13267	3607	3520	1333	302
ASH11	Fly Ash	39700	7630	12700	2800	2390	2960	301
ASH12 & ASH13	Fresh Poultry Litter	3867	333	467	359	567	337	49
ASH12	Bulk Ash	13267	5680	6333	1363	1927	755	135
ASH13	Fly Ash	36767	10957	8067	3757	4880	1870	621

Table 5.4   Concentrations of nutrients from the densification of poultry litter entering the thermal conversion unit and poultry litter ash exiting the unit from three different units in the Mid-Atlantic

	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	CCE	Average‡
	--Times Concentrated†---														
ASH7	0.2	10.0	3.2	2.9	5.5	5.1	5.9	25.7	18.5	4.8	4.5	4.1	4.1	7.3	7.3
ASH10	0.0	12.2	12.9	4.8	13.5	11.6	12.8	14.5	29.4	12.3	11.8	4.6	7.7	21.4	12.1
ASH12	0.4	4.5	4.9	1.6	1.7	2.6	3.4	17.0	13.6	3.8	3.4	2.2	2.7	10.4	5.2

†Times Concentrated = (ash nutrient concentration % / feedstock poultry litter nutrient concentration %) on an "as-is" basis.

‡Average is mean value of all nutrients and is not weight balanced.

6. Summary and Conclusions

Several factors impact the overall nutrient concentrations of poultry litter co-products and their resulting availability. The thermal combustion system is one variable, which includes the temperature of combustion, fuel-to-oxygen ratio, residence time of the poultry litter feedstock, and whether or not the system has an exhaust scrubbing system to catch fly ash. Another major factor is the poultry litter from which the co-product is formed; the initial concentration of nutrients, bedding material, and moisture content of the poultry litter impact the co-product.

Our study found that nutrient densification varied between systems: phosphorus was concentrated between 4-12 times its original density, potassium was concentrated between 3-13 times its original density, and sulfur was concentrated between 2-5 times its original density. Our comparisons between total nutrient digestions and water-soluble extractions found that the ash co-products were significantly less plant available than the standard inorganic fertilizers (TSP and KCl). A greater amount of the co-products will have to be applied to meet the same nutrient availability of the standards. Overall, if all ideal combustion criteria are met, poultry litter co-products are feasible fertilizers; however, they will need to be individually analyzed for nutrient content before making application recommendations. More research into balance comparisons are needed to be able to identify stronger relationships within the nutrients.

TSP and fresh poultry litter had the greatest initial availability for phosphorus and potassium. Over time, some of the ash co-products reached similar availabilities comparable to the standards but differed due to the variability in their systems of formation. The system that produced ASH4 generated the co-product that was most similar to the standards and provided an ideal fertilizer that was both nutrient dense and plant available. The ASH2 system converted the feedstock at higher temperatures and had longer residence times, creating a nutrient-dense product that was not readily water soluble. The biochar co-products were among the least available of the fertilizers in the study; this was expected because biochars are formed with a slow-release product in mind to strongly hold and remove nutrients and carbon from the soil system for many years. Further ash research will be needed for each thermal conversion system and feedstock, as the burning process significantly alters the overall nutrient water solubility over time.