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Prospects for phosphorus recovery from poultry litter

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ABSTRACT

Land disposal of poultry litter is an environmental concern often associated to excess phosphorus (P) in soils and potential water pollution in regions with intense poultry production. Although poultry litter can be moved off the farm and traded as fertilizer, its transportation becomes less economical with increasing distances from the farm. Thus, new litter management alternatives are needed to reduce the environmental impact of P litter application to land. This paper summarizes established and emerging alternative technologies in the U.S. that facilitate handling, concentration, and transporting of litter P. Furthermore, it examines the potential integration of technologies into poultry litter management systems that could reduce poultry litter volume and increase P content in litter byproducts. The adoption of alternative technologies may encourage new opportunities to produce bio-energy, fertilizer, and other valuable P byproducts from poultry litter while reducing environmental impact and promoting sustainable poultry production.

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1. Introduction

Poultry litter consists of bedding material mixed with manure, feathers, spilled water, and waste feed accumulated during the production cycle. Because of its high plant nutrient levels, it is a valuable organic fertilizer providing plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K). However, one of the main environmental risks of poultry production is the imbalance of N and P in poultry manure. These two nutrients in poultry litter are not in the same proportion as needed by crops (Edwards and Daniel, 1992; USDA-ERS, 2000). When poultry litter is spread on agricultural land based on N agronomic rates, excessive P is applied leading to P accumulation in soil (Sims et al., 2000). This P accumulation in soil has the potential to leave the farm's boundaries as soluble P via runoff and promote eutrophication of surface waters (Ribaudo et al., 2003; Sharpley et al., 2007). In order to reduce the environmental impact of poultry litter disposal, a substantial amount of P should be moved off farm by transporting poultry litter to agricultural lands with low P levels (USDA-ERS, 2000; Jones and D'Souza, 2001). As manure handling and transportation costs increase, the maximum distance of cost effective transport depends on P concentration of the manure (Keplinger and Hauck, 2006).

The aspect of P reuse is important for crop producers because of increasing demand and cost of inorganic fertilizers. The merging of food and fuel economies has increased the demand of mineral P fertilizer, and its price increased over 200% in 2007 (IFDC, 2008; Trostle, 2008). The increased P demand may stimulate new technologies and economic opportunities for P recovery from manure, specially using technologies that produce concentrated byproducts with nutrient values competitive with mineral fertilizers. Concurrently, recovered P reuse could minimize manure P losses into the environment and simultaneously promote long-term sustainability of poultry production.

The objectives of this paper were to: (1) summarize established and emerging alternative technologies to facilitate handling, concentration, and transporting of litter P; and (2) examine the potential of these technologies for integration into on-farm poultry litter management systems in the U.S.

2. Poultry litter recoverable phosphorus

Recoverable P is the quantity of the nutrient available for land application or utilization for other purposes (Kellogg et al., 2000). It is estimated as the mass of nutrient per ton of manure remaining after nutrient losses during manure collection, transfer, storage and treatment (Barker and Zublena, 1995). Recoverable P from poultry manure is about 39% of the total recoverable P from all animal manure in the U.S. because of its high P concentration with respect to other livestock manure (Gollehon et al., 2001). Close to 11 million metric tons of poultry litter is produced in the U.S. annually containing about 250 thousand metric tons of recoverable P (Gollehon et al., 2001; Kellogg et al., 2000). On the other hand, the annual consumption of mineral P for crop production in the U.S. is about 1680 thousand metric tons (PPI, 2002). Therefore, recoverable P from poultry litter could substitute about 15% of the total inorganic P consumption in the U.S.

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The reuse of recoverable P from poultry litter can be of interest to farmers and the fertilizer industry because it would provide high quality P fertilizer. The quality of mined P is already a concern largely due to high levels of trace element impurities in the mined phosphate sources (Smil, 2000). Excessive levels of trace elements, such as As, Cu, Cd, Cr, Mn, Ni, Pb, V, and Zn, in fertilizers may pose hazards to animal and human health (USEPA, 1999). Removing these trace elements from mined phosphate is costly because the removal process generates hazardous waste and may require high energy input (Smil, 2000). Although trace elements are also found in poultry litter (Kelley et al., 1996; Bolan and Adriano, 2003; Van Ryssen, 2008), they do not represent an environmental hazard in soils amended with poultry litter or its byproducts. For instance, Codling et al. (2002) found that trace element contents (As, Cu, Cd, Mn, Ni, Pb, and Zn) in soils amended with poultry litter ash were within the normal range of U.S. soils amended with traditional mineral fertilizer.

3. Technologies for recovery and reutilization of phosphorus in poultry litter

Given that poultry litter is a bulky material, transporting P becomes more cost effective by reducing its volume and mass. Technologies that could reduce volume or both volume and mass of poultry litter byproducts include densification, biological, thermochemical and chemical processes. These processes, associated technologies, and their byproducts with their respective P concentrations are summarized in Table 1.

3.1. Screening and densification

There have been several efforts to reduce the volume of poultry litter and increase its nutrient content by simple physical processes such as screening, pelletizing, and compaction (Table 1). For instance, Coloma (2005) reported a 12% increase in P content in screened litter with respect to untreated litter. But bulk density in both screened and unscreened fractions was not significantly different from untreated litter. Instead, pelletizing and compaction processes such as baling can reduce volume of poultry litter making it more economical for transport and suitable for application by commercial fertilizer equipment or use for bio-fuel production (Fasina et al., 2006). Using pelletizing, McMullen et al. (2005) increased the bulk density of poultry litter fourfold, from 200 to 790 kg/m^3 by extruding poultry litter mixed with 3% vegetable oil. Since pelletizing reduces empty volume but not mass, increase of total P concentration (g/kg) is minimal in pelletized materials. Hammac et al. (2007) reported a concentration of 23 g P/kg in untreated litter and 25 g P/kg in pelletized litter. Although higher P analysis can be obtained by adding inorganic P to the poultry litter pellets (Hamilton and Sims, 1995; Toor et al., 2007), the production of nutrient-enriched pellets has been done only in large centralized facilities because of the amount of energy and highly specialized equipment required for this process. On the other hand, compaction and baling of poultry litter may offer a competitive alternative to pelletizing because it uses less energy (Fasina et al., 2006).

3.2. Biological processes

Composting and anaerobic digestion are established technologies for biological treatment of organic wastes. Composting is the aerobic microbial breakdown and stabilization of organic matter. Although composting is a well-suited technology for on-farm agricultural waste management such as hygienic disposal of bird mortality (Blake, 2004; Mitchell and Tyson, 2001), composting of poultry litter alone (without mixing other organic residues) is not an environmentally sustainable technology (Moore, 2002). This is due to substantial N loss through ammonia volatilization during poultry litter compost production (Tiquia and Tam, 2000; Delaune et al., 2004). However, ammonia losses can be minimized using chemical amendments (Kithome et al., 1999; Moore et al., 1995) or, by co-composting poultry litter mixed with other residues to balance C/N ratio to values >14 (Nahm, 2005; NRCS, 2003). Sikora and Enkiri (2003) reported a P content of 16 g/kg and C/N = 18 in poultry litter composted with orchard grass hay. However, co-composting did not increased P concentration (6.4–16 g P/kg,

Table 1
Processes and technologies for poultry litter volume reduction and reutilization of phosphorus.

Process	Technology	Description	Phosphorus byproduct	Phosphorus content (g/kg)[a]	Reference
Densification					
	Screening	Screening of poultry litter in coarse and fine fractions	Fine screened fraction (<0.83 mm) used as fertilizer	14–15	Ndegwa et al. (1991); Kelley et al. (1996); Coloma (2005)
	Pelletizing	Extrusion and compaction at high temperature and pressure	Fertilizer, soil amendment, feed additive	25	Hammac et al. (2007)
	Compaction	Densification of poultry litter by pressure agglomeration (baling)	Fertilizer	–[b]	Fasina et al. (2006)
Biological					
	Composting	Aerobic microbial degradation of poultry litter and bird mortality	Fertilizer	16 6.4–12.2	Sikora and Enkiri (2003); Sharpley and Moyer (2000)
	Anaerobic digestion	Anaerobic microbial degradation and stabilization of organic material	Solid fertilizer Liquid fertilizer	13–20[c] 0.33	Liedl et al. (2006)
Thermochemical					
	Direct combustion	Single-stage chambers, fluidized bed or rotary kiln incinerator	Fertilizer, feed supplement	53–100	Codling et al. (2002); Zhu and Lee (2005); Blake et al. (2007)
	Pyrolysis	Carbonization	Bio-char	48–73	Lima and Marshall (2005); Lima et al. (2007)
	Gasification	Catalytic steam gasification	Fertilizer	62	Priyadarsan et al. (2004)
Chemical					
	Quick wash	Leaching followed by P precipitation	Fertilizer Washed litter	46–89	Szogi et al. (2008a,b)

[a] P content in untreated (raw) poultry litter is 8–26 g P per kg litter (Edwards and Daniel, 1992).
[b] Not reported.
[c] P concentration in solids on dry weight basis; P concentration in liquid in g per kg of liquid.

Table 1) with respect to raw litter (8–26 g P/kg) because of the addition of hay, wood chips, or corn cobs as C source.

Anaerobic digestion is a waste-to-energy technology that has a renewed interest because of its potential to produce renewable energy from poultry litter in the form of biogas and a fertilizer in the form of a nutrient-rich sludge. Anaerobic digestion can reduce both the volume and mass of the initial feed stock because about 60% of the volatile solids in poultry litter could be converted into biogas (Beddoes et al., 2007). Since poultry litter contains high levels of organic N, the concentration of ammonia during the digestion process may inhibit the fermentation process (Gungor-Demirci and Demirer, 2004). However, no inhibition problems were reported during four years of continuous operation of a thermophilic (56.6 °C) anaerobic digester fed solely with poultry litter (Espinosa-Solares et al., 2006) that produced a P-rich sludge with potential use as fertilizer (Liedl et al., 2006). Yet, the increase of P concentration is not obvious from the P contents shown in Table 1 for separated digested solids (13–20 g P/kg) because about 40% of the total P in the digested sludge remained in the liquid fraction.

3.3. Thermochemical conversion

Thermochemical conversion (TCC) processes employ high temperatures to break organic matter bonds and reform intermediate compounds into synthesis gas, hydrocarbons fuels, and/or a charcoal residual (Cantrell et al., 2008). Solid residues produced from these TCC processes are P-dense and amenable to be used as fertilizer. Poultry litter combustion has received major attention as a method to produce heat and electricity at large centralized facilities (Kelleher et al., 2002; Zering, 2006; Turnell et al., 2007; Fibrowatt, 2008). The byproduct of combusted poultry litter is ash with high P content (53–100 g P/kg) that can be used as fertilizer or P supplement in poultry feed (Codling et al., 2002; Blake et al., 2007). A limitation to the adoption of this technology is the high capital investment and public concern for potential emission of particulate matter, nitrogen oxides, carbon monoxide, and sulfur dioxide from large centralized combustion facilities burning poultry litter (Turnell et al., 2007).

Advances in gas cleanup and combustion system design may offer a cleaner way to ultimately treat poultry litter by TCC and remove the air quality concerns (Sheth and Turner, 2002). Other TCC technologies such as pyrolysis, gasification, and liquefaction are being researched or developed to provide small-scale systems that would allow on-farm waste-to-energy conversion of poultry litter (Table 1). Cantrell et al. (2007) reports on the advantages and obstacles to implement and adopt methods for TCC of livestock manure into energy. A potentially profitable TCC alternative for poultry litter treatment is pyrolysis. Pyrolysis converts the organic portion of poultry litter into a mixture of charcoal or bio-char and volatile gases. Lima and Marshall (2005) reported the use of pyrolysis to manufacture activated charcoal from both broiler and cake litter with P content in the range of 48–73 g/kg (Table 1). An alternative potential use of bio-char is as soil amendment to enhance soil quality and long-term C sequestration (Lehman, 2007; Laird, 2008). However, removal of P may be required before or after pyrolysis for the use of poultry litter bio-char to avoid the build up of high P concentration in soils (J. Novak, pers. comm.).

3.4. Chemical processes

A treatment process called "quick wash" was recently developed for extraction and recovery of P from poultry litter and animal manure solids (Szogi et al., 2008a,b). The quick wash process consists of three consecutive steps: (1) P extraction, (2) P recovery, and (3) P recovery enhancement. In step 1, organically bound P is converted to soluble-P by rapid hydrolysis reactions using mineral or organic acids such as citric, hydrochloric, or sulfuric. A large fraction (60–80%) of the initial total P in raw litter was extracted when the mixture of poultry litter and extracting solution reached a pH of <4.5. This step also releases P from insoluble inorganic phosphate complexes. The washed litter residue is subsequently separated from the liquid extract and dewatered; C and N transformation processes are inhibited by dewatering the residue. In step 2, P is precipitated by lime addition to the liquid extract forming a calcium-containing P product. In step 3, an organic poly-electrolyte is added to enhance the P grade of the product. For instance, the solid residue remaining after litter was washed with the acidic solution had a higher N:P ratio (5.8:1) than the control (1.8:1) washed with only water (Fig. 1). Therefore the washed litter would be more environmentally safe for land application and its N:P ratio better balanced for use by crops. In this particular example, the N:P ratio of washed litter is close to N:P ratio 6.2:1 of cotton (Table 2).

The quick wash approach has three salient characteristics: (1) the recovered P from the quick wash produces a concentrated product containing 46–89 g P/kg that can be reused as plant fertilizer (Szogi et al., 2008b,c); (2) compared to combustion and gasification processes, the residual organic matter is conserved for

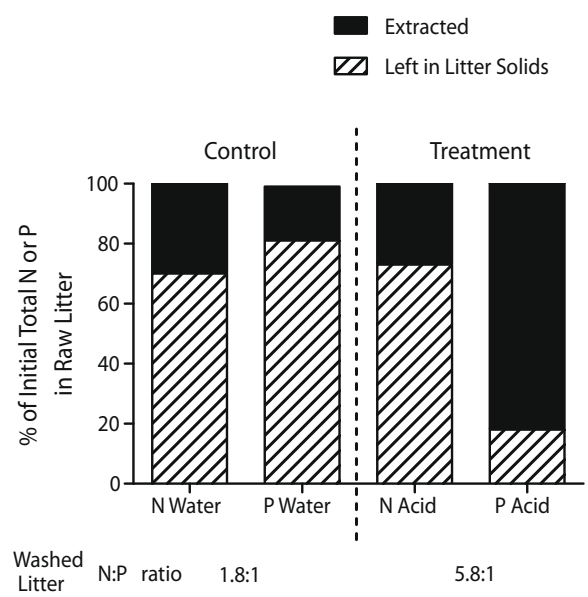

Fig. 1. Phosphorus (P) extraction with the quick wash process (step 1). The control treatment used litter mixed with only water (1:25 w/v) for the extraction (pH = 8.1). The quick wash treatment consisted of a litter–acidic solution mix (1:25 w/v) at pH = 4.5 using citric acid. Initial nitrogen (N) and phosphorus (P) in raw litter were 35.5 and 19.2 g/kg, respectively. The N:P ratio pertains to the washed poultry litter solids after control and quick wash extractions. Data adapted from Szogi et al. (2008c).

Table 2
Nitrogen to phosphorus ratio (N:P) in plant tissue of selected crops, untreated (raw), quick wash treated poultry litter and liquid effluent.

		N:P ratio
Crop[a]	Bermudagrass	13.4:1
	Tall fescue	11.9:1
	Corn	7.5:1
	Cotton	6.2:1
	Ryegrass	3.3:1
Poultry litter[b]	Raw	2.1:1 to 2.6:1
	Quick wash treated	4.0:1 to 10.0:1
	Quick wash effluent	6.2:1 to 8.4:1

[a] N:P ratio data for crops adapted from Edwards and Daniel (1992).
[b] N:P ratio data adapted from Szogi et al. (2008c).

additional soil benefit; and (3) manure P transport can be more effective since only about 15% of the initial volume would exit the farm containing the concentrated P product.

4. Integration of P recovery into poultry litter management systems

4.1. Potential scenarios

Technologies described in Table 1 have the potential of being integrated into poultry litter management systems. Three likely scenarios were considered for manure management systems that included P recovery using quick wash, bio-energy generation, and land application methods. Common to all three scenarios, poultry litter is treated using the quick wash approach to recover and concentrate P in a material to be moved off the farm.

Scenario 1: This scenario considers the land application of washed litter and effluent generated in steps one and three of the quick wash process, respectively. Both washed litter and effluent have a balanced N:P ratio and can be land applied on an N basis. The N:P ratio of the land-applied washed litter and effluent would match the N:P ratio of agronomic crops such as cotton and corn (Table 2).

Scenario 2: This scenario includes anaerobic digestion as an additional process. Both washed litter and liquid effluent from the quick wash process are used as feedstock for biogas production using an anaerobic digester. The feedstock composition (proportion of washed poultry litter solids to wash effluent volume) is adjusted to optimize process pH and methane production. The digested sludge containing a more balanced N:P ratio than unwashed litter could be land applied according to the farm's individual nutrient management plan.

Scenario 3: Pyrolysis was included in this scenario because, among other TCC technologies, it is a traditional method to produce charcoal in rural areas (Antal and Gronli, 2003). This scenario considers the TCC of washed litter by pyrolysis generating energy and producing bio-char on the farm. The bio-char produced with quick washed treated litter will have lower P content than the one produced with unwashed litter. Thus, this bio-char can be used for long-term soil C sequestration. Yet, the P-washed poultry litter may require conditioning such as further dewatering, drying, screening, and pelletizing prior to pyrolysis. This conditioning of the feedstock would use part of the energy produced by the TCC process. Similar to scenario 1, the liquid effluent of the quick wash could be applied to nearby cropland on an N basis.

4.2. Potential value of byproducts

The three selected scenarios may benefit farmers with manure byproducts more valuable than just selling raw poultry litter (e.g. US$3 to US$6 per ton of raw litter in South Carolina; Flora and Riahi-Nezhad, 2006). For scenario 1 byproducts, Szogi et al. (2008c) estimated an average recovery of about 14 kg P or 32 kg P_2O_5 per metric ton of poultry litter with a fertilizer value of $63.36 (US$1.98 per kg of P_2O_5) and a total chemical cost of US$44.07 per metric ton of treated poultry litter, representing a net benefit of US$19.29 per ton. It is expected that water quality credits will be an important benefit to farmers adopting new manure treatment technologies. For credit prices of US$11.11 per kg of P (Chesapeake Bay Watershed Nutrient Credit Exchange, 2007) and trading ratios for non-point sources of 2:1, the potential benefit from removing 14 kg P per ton of poultry litter is US$77.77. As an additional benefit, a total of about 30 kg of N (US$0.87 per kg of N) and 4 kg P remain on-farm (washed litter plus effluent) that can be used for soil quality improvement and crop fertilizer.

The value estimates for recovered P in scenario 1 apply for both scenarios 2 and 3 if P is extracted from poultry litter prior to anaerobic digestion or pyrolysis. In addition, scenarios 2 and 3 have the benefit of generating energy. In scenario 2, poultry litter could have an energy value equivalent to about 200 L of liquid gas propane (LPG) per metric ton of digested poultry litter (Flora and Riahi-Nezhad, 2006; Beddoes et al., 2007) with a potential benefit of U$56 (0.28 US$/L of LPG).

In scenario 3, pyrolysis of poultry litter could have an energy value equivalent to 352 L of LPG per ton of processed poultry litter (Reardon et al., 2001) with a potential benefit of about US$98. In addition, pyrolysis of the washed poultry litter could generate about 250 kg of bio-char C per ton (Lima and Marshall, 2005) with a benefit of US$ 1 to US$3 per ton of poultry litter (US$4–US$12/ton Ceq). Yet, a complete economic analysis of the selected three scenarios for on-farm recovery of P would need to consider annualized capital, energy use, and labor costs as well as other benefits such as reduction of land area required to dispose manure P, additional tipping or gate fees, and subsidies from government.

5. Conclusions

Land disposal of poultry litter is an environmental concern often associated to excess P in soils and potential water pollution. Raw poultry litter can be traded as fertilizer, but its transportation becomes less economical with increasing distances from the farm. With increasing fertilizer costs, integration of densification, biological, TCC and chemical technologies have the potential to provide on-farm recovery and concentration of P in valuable byproducts. Economic incentives such as government subsidies, environmental credits and tipping fees may be needed to promote wide adoption and integration of these alternative technologies into a poultry litter management plan.

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