



Fertilizer Effectiveness of Phosphorus Recovered from Broiler Litter

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ABSTRACT

Phosphorus can be recovered from broiler litter using a new process (“quick wash”). However, limited information is available on the beneficial use of this P product as plant fertilizer. The objective of this study was to determine the agronomic effectiveness of this P material. A greenhouse study was conducted with annual ryegrass (*Lolium multiflorum* Lam.) to compare the recovered phosphorus (RP) to both commercial triple superphosphate (TSP) and raw broiler litter (BL) as a P source. The study consisted of a 7-wk experiment that was repeated three times. Fertilizer rates were 0, 22, 44, 88, and 176 mg P kg⁻¹ soil. Three harvests of the ryegrass were made at 2-wk intervals. On average, biomass production was higher than the control with no P for plants fertilized with RP, BL, or TSP. Total P uptake increased linearly with application rate for all three fertilizer materials. At the highest application rate, total P uptake was 36.1 mg pot⁻¹ for TSP, 21.3 mg pot⁻¹ for the BL, and 17.3 mg pot⁻¹ for the RP. Chemical analysis of the RP material revealed that more than 90% of the total P in the RP material was mostly as citrate-soluble. Mehlich-3 extractable soil P at the end of the experiment indicated that less RP material dissolved than TSP during this short study. The RP material appears to have potential as a P fertilizer.

AS A RESULT of frequent land application of poultry litter, soil P can accumulate to elevated levels in regions with intense poultry production. In turn, soil P surplus has the likelihood to pollute water resources by means of field runoff and soil leaching (Johnson et al., 2004; Kaiser et al., 2009; Schroeder et al., 2004). This environmental concern has stimulated interest into cleaner options to dispose and reuse poultry litter (Kelleher et al., 2002; Szogi and Vanotti, 2009). Since mineral P is a nonrenewable resource, the aspect of P reuse is important for crop production because of increasing global demand and soaring fertilizer costs (Cordell et al., 2009; Trostle, 2008). Therefore, P recovery from poultry litter has the potential to promote sustainable poultry production by both reducing P losses into the environment and recycling P in the form of a valuable fertilizer byproduct.

To solve soil P accumulation problems, a substantial amount of poultry litter can be transported to lands low in P for its use as plant fertilizer through manure transfer programs (NRCS, 2003; Sharpley et al., 2007). Given that raw poultry litter is a bulky material, a more effective P transfer can be achieved by

creating poultry litter byproducts with less volume than raw litter (McMullen et al., 2005). A few poultry litter byproducts such as poultry litter compost, broiler litter pellets and poultry litter ash have been tested for their use as plant fertilizer sources by comparing their effectiveness to inorganic P fertilizers. Sikora and Enkiri (2005) reported that poultry manure compost was equal to TSP in providing P to fescue (*Festuca arundinacea* Schreb.) grown in a P-deficient soil with no yield differences between both P sources. In a greenhouse experiment, Hammac et al. (2007) found similar yields for both ryegrass and sudangrass [*Sorghum bicolor* (L.) Moench] using either pelletized poultry litter as P source or calcium phosphate (CaHPO₄). In another study, Codling et al. (2002) evaluated the effectiveness of poultry litter ash and potassium phosphate as a P source for wheat (*Triticum aestivum* L.). Their results showed that wheat dry matter yield with poultry litter ash treatments were equal to that of potassium phosphate in limed soils. All these studies indicate the potential of poultry litter byproducts to substitute commercial inorganic P fertilizer.

Recently, a new poultry litter P byproduct was produced using a new process called quick wash (Szogi et al., 2008b). The quick wash process was conceived to recover P from solid manure in a concentrated solid form. The P content (46–89 g P kg⁻¹) of this poultry litter byproduct suggests it likely has utility as a fertilizer source (Szogi et al., 2008a, 2008c). The objective of this study was to evaluate the agronomic effectiveness of this P material recovered from broiler litter.

MATERIALS AND METHODS

Phosphorus Recovery from Poultry Litter

The RP material in this study was obtained at the USDA-ARS Coastal Plains Soil, Water and Plant Research Center, Florence, SC, from a pilot-scale study to recover manure P

Abbreviations: BL, broiler litter; ICP–AES, inductively coupled plasma–atomic emission spectrometer; RP, recovered phosphorus; SSP, single superphosphate; TSP, triple superphosphate.

USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, 2611 W. Lucas St., Florence, SC 29501-1242. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply approval of a product to the exclusion of others that may be suitable. Received 14 Sept. 2009. *Corresponding author (Ariel.Szogi@ars.usda.gov).

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using the quick wash process. The quick wash process consists of three consecutive steps: (i) P extraction, (ii) P recovery, and (iii) P recovery enhancement (Szogi et al., 2008b). In step 1, organically bound P is converted to soluble-P by rapid reaction with selected mineral or organic acids (e.g., citric or hydrochloric acid). This step also releases P from insoluble inorganic phosphate complexes. The washed litter residue is subsequently separated from the liquid extract and dewatered. In step 2, P is recovered by addition of lime $[\text{Ca}(\text{OH})_2]$ to the liquid extract to form a Ca-containing P precipitate. In step 3, an organic poly-electrolyte is added to enhance the P concentration of the precipitate. The P precipitate was recovered by filtration using a polypropylene filter material (Szogi et al., 2006). Further details of the quick wash process are described in Szogi et al. (2008c).

Greenhouse Study

The study was conducted under greenhouse conditions with annual ryegrass comparing the RP material to commercial TSP and raw broiler litter. The study consisted of a 7-wk experiment that was repeated three times. Temperature inside the greenhouse was monitored with a HOBO (Onset Computer, Bourne, MA) temperature data logger. Average daily temperature [(maximum temperature + minimum temperature)/2] was 26.3°C (range 20.2–34.4°C) for the first experiment, 28.4°C (range 25.3–32.0°C) for the second experiment, and 28.6°C (range 24.4–32.0°C) for the third experiment. Artificial lighting was not used.

A sandy-textured soil, Uchee sand (loamy, kaolinitic, thermic Arenic Kanhapludult), was used in all three experiments of this study. The soil was collected from a wooded area known to be very low in P at the Pee Dee Research and Extension Center, Clemson University, Florence, SC. The soil was passed through a 6.35-mm screen to remove large particles and roots. Two 100-g samples of the soil were air dried on a greenhouse bench, ground, and then chemically analyzed at Clemson University's Agricultural Service Laboratory. Results from this analysis showed that the soil had, on average, a cation exchange capacity of 2.0 cmol kg^{-1} , exchangeable acidity of 2.0 cmol kg^{-1} , pH of 4.9 units, and P content of 1.7 mg kg^{-1} . Based on the pH and acidity results, the sieved soil was mixed with $\text{Ca}(\text{OH})_2$ to raise the pH to 6.5 using a small cement mixer to blend the two materials. The soil was then pasteurized (FAMCO, Inc., Model 14 Soil Pasteurizer, Medina, OH) and stored in large plastic containers until it was used.

Treatments were three fertilizer sources (TSP, RP, and BL) and five fertilizer rates (0, 22, 44, 88, and 176 mg P kg^{-1} soil). Triple superphosphate 0–45–0 (N–P₂O₅–K₂O) was obtained from a local fertilizer distributor. Particle sizes of the TSP were about 85% between 2.0 and 4.0 mm, and 15% between 1.0 and 2.0 mm. Before applying to soil, the RP material was ground with a Dynacrush mill (Custom Laboratory Equipment Inc., Orange City, FL) and passed through 1.0-mm sieve but retained on a 0.5-mm sieve to simulate commercial fertilizers with small particles (Bauer et al., 2007). Broiler litter was collected from a 21,000-bird broiler house in Lee County, SC. A 15-kg composite sample of BL (11.5 g P kg^{-1}) was passed through a 5.8-mm sieve and placed in cold storage (–6.5°C) until used in the greenhouse experiments. The broiler litter had a granular distribution within the following size classes: <0.1 mm (11%), 0.1–1.0 mm (43%), 1.0–2.0 mm (30%), and 2.0–5.8 mm (16%) (Szogi et al., 2008c).

The fertilizer treatments were thoroughly mixed into 15-cm diam. pots containing 1.36 kg soil, 2 g of 15–0–15 (N–P₂O₅–K₂O) fertilizer, and 0.12 g of technical grade $(\text{NH}_4)_2\text{SO}_4$. Pots were then placed on greenhouse benches and kept moist by watering them to 100 g water kg^{-1} soil using a scale. Three weeks after applying the fertilizer, 1.11 g of annual ryegrass seed was planted in each pot. The soil surface in each pot was kept moist by adding water as needed. At about 5 wk after planting, each pot received 1.00 g of NH_4NO_3 .

Three harvests of plant shoot tissues were made in each of the three experiments. Harvests were made by cutting plants ~2.5 cm above the soil surface. In the first experiment, shoot tissue was collected at 20, 33, and 52 d after planting. In the second experiment, shoot tissue was collected at 19, 34, and 47 d after planting. In the third experiment, shoot tissue was collected at 21, 35, and 50 d after planting. Plant tissue samples were dried at 60°C for 3 d and then weighed and ground. After the last cutting in each experiment, three 2.5-cm soil cores were collected from each pot and dried on a greenhouse bench. The soil samples were ground for P extraction after removing large roots.

Chemical Analyses

Duplicate samples of the RP material were ground, sieved (no. 40 mesh, <0.475 mm) and analyzed for total P, water-soluble P, citrate-insoluble P, and available P (citrate-soluble) according to AOAC Official Methods 958.01, 977.01, 963.03 B(a) (AOAC International, 2000) at Thornton Laboratories Inc. (Tampa, FL).

Total C and N contents were determined by dry combustion with a LECO C/N analyzer (LECO Corporation, St. Joseph, MI). Total elemental analysis of the TSP, RP and BL materials was determined with an inductively coupled plasma–atomic emission spectrometer (ICP–AES, Varian Instruments, Walnut Creek, CA) after automated digestion (AutoBlock, Environmental Express, Mt. Pleasant, SC) with nitric acid and hydrogen peroxide (Peters et al., 2003). To further compare the three fertilizer materials, duplicate samples of TSP, BL, and RP were subjected without grinding to a deionized water extraction following a slightly modified procedure described by Sharpley and Moyer (2000). A 1.00-g sample of air-dried material was combined with 250 mL of deionized water and shaken end-over-end for 1 h. Following centrifugation and 0.45- μm filtration, the sample extracts were acidified and analyzed for P using ICP–AES.

Ryegrass shoot tissues were digested with concentrated sulfuric acid (Gallaher et al., 1976) and P concentration determined in the digest by automated ascorbic method adapted to digested extracts (Szogi and Vanotti, 2008). Total P in the plant tissues at each harvest was calculated by multiplying P concentration by biomass, and total P recovery for the experiment was determined by summing the total P from each harvest. Soil extractable P was determined in soil samples collected at the end of the experiment using the Mehlich-3 procedure (Tucker, 1992); P content was determined in the extract using automated colorimetric analysis.

Statistical Analysis

Experimental design was a randomized complete block, and there were four replications in each experiment. For the biomass, P concentration, and P content data the three cuttings of each experiment were summed and analysis was conducted on the

summed data. Biomass data were analyzed over the three experiments of the study using a mixed model analysis with the GLIMMIX procedure of SAS (SAS Institute, Cary, NC). Experiments and replicates were considered random and treatments were considered fixed. Biomass least square means were compared using the pdiff option and means were considered different when the probability of greater t values were ≤ 0.05 . The P concentration, total P uptake, and soil extractable P data were analyzed without the control treatment in a factorial design using a mixed model with the GLIMMIX procedure. Experiments and replicates were considered random and fertilizer materials and rates were considered fixed. Responses to application rate for P concentration in plant tissues, total P uptake, and soil extractable P for each fertilizer material were determined using linear regression analysis. Homogeneity of slopes were evaluated with t tests and slopes were considered different when P values were ≤ 0.05 .

RESULTS AND DISCUSSION

Recovered Phosphorus Material

On average, the RP material contained large amounts of Ca, P, and C relative to the amounts of N, Mg, K, and Na (Table 1). As a result of the quick wash process, Ca and P in the RP were 9- and fourfold more concentrated than in BL, respectively. However, the C concentration remained similar in both RP and BL because small fragments of bedding material (wood shavings) settled with the RP precipitates. According to Turner and Leytem (2004) acid extractable P in raw broiler litter is dominated by inorganic (35–41%) and organic P forms (58–65%). Inorganic phosphate species in poultry manure include dibasic calcium phosphate, amorphous calcium phosphate and weakly bound water-soluble phosphates (Sato et al., 2005), while organic P in poultry litter is largely in the form of phytic acid salts (Turner and Leytem, 2004). Since the RP was obtained from broiler litter with quick wash process, it had about half of its total P content in inorganic form and half in organic form (Szogi et al., 2008c). Additional analysis of RP material samples by thermo-gravimetry showed a weight loss peak within 310 to 320°C range, which was similar to the temperature range for the maximum weight loss of a phytic acid salt standard; further weight loss within 350 to 500°C accounted for other organic C forms (Cantrell et al., 2009). The high Ca concentration in the RP material was related to the use of $\text{Ca}(\text{OH})_2$ to selectively precipitate and recover the extracted P both in inorganic and organic Ca phosphate forms during the quick wash process (Szogi et al., 2008b).

The potential use of RP as a fertilizer source relies on its total P content and the fraction of P available for plant growth. Phosphorus availability of fertilizing materials is usually determined using the AOAC “available P” test (AOAC International, 2000). The water extraction represents the water soluble P fraction. The analysis of the filtrate obtained from the remaining water-insoluble material after extraction with neutral ammonium citrate is the citrate-soluble P fraction. What is called “plant available P” is the sum of water-soluble P plus neutral citrate-soluble P (Havlin et al., 1999). The RP material used in our study had a total P content of 46 g kg^{-1} (10.5 g P_2O_5 per 100 g material, Table 2). This value is close to the P content of other manure byproducts such as poultry litter ash (53 g P kg^{-1}) (Codling et al., 2002) or calcium phosphate recovered from swine (*Sus scrofa*) lagoon effluents (50 g P kg^{-1}) (Szogi and Vanotti, 2009). Although total

Table 1. Selected elemental analysis of the broiler litter (BL) and recovered phosphorus material from broiler litter (RP).

Element	Composition†	
	BL	RP
	g kg^{-1}	
Ca	13	119
Total P	12	46
Total C	356	389
Mg	3	7
K	24	9
Total N	26	36
Total S	4	6
Na	5	3
Fe	1	2
Al	1	4
Mn	0.2	1
Zn	0.2	5
Cu	0.2	0.3

† Mean of duplicate samples.

P content of RP is lower than commercial single superphosphate (SSP) (70–96 g P kg^{-1}) or TSP (192–231 g P kg^{-1}), the fraction of plant available P in the RP material was about 92% with respect to total P and close to values of 97 to 100% reported for both SSP and TSP (Tisdale et al., 1985). Important to notice is that the plant available P in the RP material is mostly based on the citrate-soluble form (91%) with very little P in the water-soluble form (1%), which indicates that RP has low solubility in water.

Agronomic Effectiveness

Differences in biomass production of the ryegrass were significant among treatment combinations in this study. On average, biomass production was higher for plants fertilized with RP, BL, or TSP at all four P rates than the control with no P (Table 3). At increasing P application rates, differences in biomass production were not significant for all three P sources except at the rate of 176 mg P pot^{-1} . At this high rate, TSP had significantly higher ryegrass biomass than both RP and BL. Although biomass production did not change appreciably, P concentrations in plant tissue increased steadily with increasing P applications (Fig. 1). Similar concentrations of P in plant tissues were found for RP and BL at the same treatment P rates. On the other hand, much higher P concentrations in plant tissue occurred with TSP than with RP or BL treatments. At the highest application rate, P concentrations in plant tissues were 7.4 g kg^{-1} for TSP and about 4.4 g kg^{-1} for both RP and BL.

Fertilizer material and application rates and their interaction (Material \times Rate) had a significant effect on both plant uptake

Table 2. Water-soluble, water-insoluble P, and total P content of the recovered phosphate material.

Component	Composition†	Fraction of total P‡
	g P kg^{-1} material	%
Water-soluble	0.5	1.1
Citrate-soluble	41.9	91.3
Citrate-insoluble	3.5	7.6
Total P§	45.9	100.0

† Mean of duplicate samples.

‡ Plant available = water-soluble + citrate-soluble fractions (92.4%).

§ Total P as % P_2O_5 = 10.5 g P_2O_5 per 100 g of material.

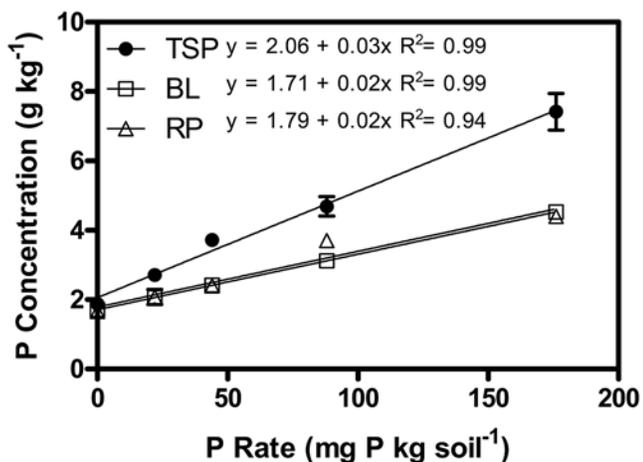


Fig. 1. Phosphorus concentration of ryegrass plant tissues as affected by fertilizer material and application rate. Data are the average of three experiments. Standard error bars are shown when their size was larger than that of the symbol.

and soil P. The relative effect of materials and application rate on plant uptake is indicated by the slope of the linear regression lines in Fig. 2. For TSP, plant uptake increased 0.17 mg pot⁻¹ for each mg kg⁻¹ increase in applied P and it was significantly higher than the slopes for RP and BL ($P \leq 0.05$). Phosphorus uptake with the BL increased 0.09 mg pot⁻¹ for each mg kg⁻¹ increase in applied P while P uptake in pots containing RP increased only 0.07 mg pot⁻¹ per each mg kg⁻¹ increase in applied P. However, the P plant uptake slopes for BL and RP were not significantly different ($P \geq 0.05$). At the highest application rate, total P uptake was 36.1 mg pot⁻¹ for TSP, 17.3 mg pot⁻¹ for RP, and 21.3 mg pot⁻¹ for BL.

Mehlich-3 extractable soil P at the end of the experiment is shown in Fig. 3. The highest response of TSP to Mehlich-3 extractable P (0.40 mg extractable P kg⁻¹ per each mg P kg⁻¹ applied) explains the high P concentrations found in plant tissue and P uptake (Fig. 1 and 2). The soil response slope of TSP to applied P was significantly higher than the slopes for both RP and BL ($P \leq 0.05$, Fig. 3). In turn, the slopes for BL

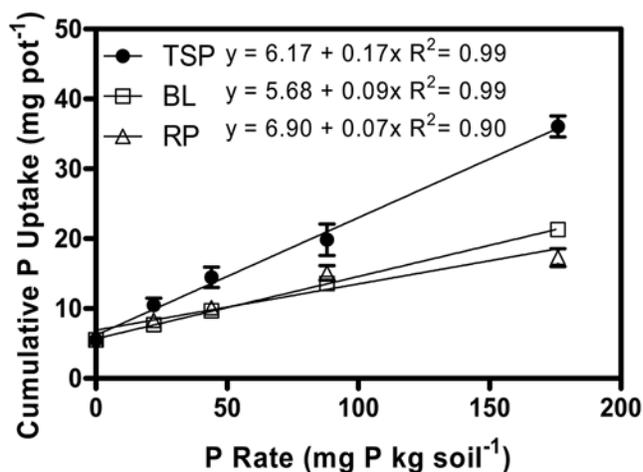


Fig. 2. Phosphorus uptake by ryegrass as affected by fertilizer material and application rate. Data are the average of three experiments. Standard error bars are shown when their size was larger than the symbol.

(0.22 mg extractable P kg⁻¹ per each mg P kg⁻¹ applied) and RP (0.24 mg extractable P kg⁻¹ per each mg P kg⁻¹ applied) were not significantly different ($P \geq 0.05$).

The higher soil availability and plant uptake response to TSP vs. the lower response to both RP and BL is due to the influence of chemical properties of the soil and P fertilizer materials on both P solubility and adsorption in soils. Given that P solubility and adsorption is controlled by pH, in our study the soil pH was corrected to about 6.5 units to favor P dissolution and availability to plants (Adams et al., 1982). Since TSP is highly soluble in water, it first dissolves rapidly in moist soil and subsequently reacts with soil and becomes available to plants at a favorable pH. If soil available P increases, plant uptake will increase and induce a higher P concentrations in plant tissue (Black, 1992). In our study, an initial large release of P into soil solution by applying TSP may explain why the Mehlich-3 extractable P rate (0.40 mg P kg⁻¹) and P plant uptake rate (0.17 mg pot⁻¹) were almost twofold the extractable P and plant uptake rates of either RP or BL (Fig. 2 and 3). Although TSP had a larger particle size (2–4 mm) than BL (mostly <2 mm) or RP (0.5–1 mm), its water-extractable P was about 20- and 100-fold (46 g P kg⁻¹) larger than the water extractable P of BL (2.2 g P kg⁻¹) and RP (0.5 g P kg⁻¹), respectively (Table 4). The low water-soluble P of RP suggests that it may be suited for use as a slow release P fertilizer. The water-extractable P fraction of RP (1%) is similar to the low water-soluble fraction P of 0.6% that was reported for calcium phosphate recovered from liquid swine manure (Szogi et al., 2006; Bauer et al., 2007). However, further research under field conditions is needed with more soil types, other crops and different particle sizes of the RP material for fertilizer application recommendations.

Table 3. Effect of fertilizer material and rate on ryegrass biomass.

Material	Rate	Biomass
	mg P kg soil ⁻¹	
Control	0	3.2 a†
RP‡	22	4.2 b
	44	4.4 b
	88	4.3 b
	176	4.1 b
BL	22	4.1 b
	44	4.4 b
	88	4.4 b
	176	4.3 b
TSP‡	22	4.1 b
	44	4.1 b
	88	4.2 b
	176	5.2 c

† Least square-means followed by the same letter are not significantly different by the pdiff option ($P \leq 0.05$) in GLIMMIX procedure.

‡ RP, recovered phosphorus; BL, broiler litter; TSP, triple superphosphate.

Table 4. Water-extractable P of source materials.

Source	Total P	Water-extractable P	Water-soluble
	g P kg ⁻¹		%†
RP‡	46	0.5	1
BL	12	2.2	18
TSP	201	46	23

† Fraction of water-extractable P with respect to total P.

‡ RP, recovered phosphorus; BL, broiler litter; TSP, triple superphosphate.

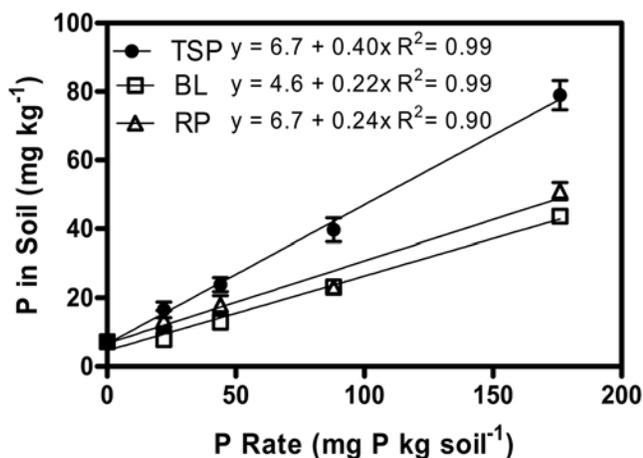


Fig. 3. Mehlich-3 extractable P concentration remaining in the soil after 7 wk of ryegrass growth as affected by fertilizer material and application rates. Data are the average of three experiments. Standard error bars are shown when their size was larger than the symbol.

CONCLUSIONS

Chemical analysis of the RP material revealed that more than 90% of the total P was mostly plant available P as citrate-soluble. Plants fertilized with RP had P uptake responses lower than TSP but as good as raw broiler litter application. Also, soil extractable P at the end of the study was not very much different from soil P concentrations when BL was used as the fertilizer source. The lower soil response to RP is consistent with the P uptake result and suggested a less readily available source than TSP. Although further research is needed under field conditions, diverse soil types, and crops for fertilizer application recommendations, the recovered P material from poultry litter has the potential as a fertilizer source without further chemical processing into other P materials, such as those typically used to process rock phosphate for fertilizer use. The use of recovered P could minimize manure P losses into the environment, promote long-term sustainability of poultry production, and provide a P fertilizer source for crop production.

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REFERENCES

Adams, J.F., F. Adams, and J.F. Odom. 1982. Interaction of phosphorus rates and soil pH on soybean yield and soil solution composition of two phosphorus-sufficient Ultisols. *Soil Sci. Soc. Am. J.* 46:323–328.

AOAC International. 2000. Official methods of analysis. 17th ed. AOAC Int., Gaithersburg, MD.

Bauer, P.J., A.A. Szogi, and M.B. Vanotti. 2007. Agronomic effectiveness of calcium phosphate recovered from liquid swine manure. *Agron. J.* 99:1352–1356.

Black, C.A. 1992. Soil fertility evaluation and control. Lewis Publ., Boca Raton, FL.

Cantrell, K.B., A.A. Szogi, P.G. Hunt, M.B. Vanotti, K.S. Ro, and P.J. Bauer. 2009. Plant nutrients and bioenergy production via a new quick wash procedure for livestock manures. p. 1238–1244. *In* Proc. 2009 Beltwide Cotton Conf., San Antonio, TX. 5–8 Jan. 2009. Natl. Cotton Council, Cordova, TN.

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

Cordell, D., J. Drangert, and W. Stuart. 2009. The story of phosphorus: Global food security and food for thought. *Glob. Environ. Change* 19:292–305.

Gallaher, R.N., C.O. Weldon, and F.C. Boswell. 1976. A semiautomated procedure for total nitrogen in plant and soil samples. *Soil Sci. Soc. Am. J.* 40:887–889.

Hammac, W.A., C.W. Wood, B.H. Wood, O.O. Fasina, Y. Feng, and J.N. Shaw. 2007. Determination of bioavailable nitrogen and phosphorus from pelletized broiler litter. *Sci. Res. Essay* 2:89–94.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 1999. Soil fertility and fertilizers. An introduction to nutrient management. 6th ed. Prentice Hall, Upper Saddle River, NJ.

Johnson, A.F., D.M. Victor, F.M. Rouquette, Jr., and V.A. Harby. 2004. Fate of phosphorus in dairy wastewater and poultry litter applied on grassland. *J. Environ. Qual.* 33:735–739.

Kaiser, D.E., A.P. Mallarino, and M.U. Haq. 2009. Runoff phosphorus loss immediately after poultry manure application as influenced by the application rate and tillage. *J. Environ. Qual.* 38:299–308.

Kelleher, B.P., J.J. Leahy, A.M. Henihan, T.F. O'Dwyer, D. Sutton, and M.J. Leahy. 2002. Advances in poultry litter disposal technology—A review. *Bioresour. Technol.* 83:27–36.

McMullen, J., O.O. Fasina, C.W. Wood, and Y. Feng. 2005. Storage and handling properties of pellets from poultry litter. *Appl. Eng. Agric.* 21:645–651.

NRCS. 2003. Manure transfer. National Conservation Practice Standard-NHCP Code 634. Available at <http://efotg.nrcs.usda.gov/references/public/WI/634.pdf> (verified 22 Jan. 2010). USDA-NRCS, Washington, DC.

Peters, J., S.M. Combs, B. Hoskins, J. Jarman, J.L. Kovar, M.E. Watson, A.M. Wolf, and N. Wolf. 2003. Recommended methods of manure analysis. Univ. of Wisconsin-Ext. Publ. A3769. Univ. of Wisconsin, Madison.

Sato, S., D. Solomon, C. Hyland, Q.M. Ketterings, and J. Lehmann. 2005. Phosphorus speciation in manure and manure-amended soils using XANES spectroscopy. *Environ. Sci. Technol.* 39:7485–7491.

Schroeder, P.D., D.E. Radcliffe, and M.L. Cabrera. 2004. Rainfall timing and poultry litter application rate effects on phosphorus loss in surface runoff. *J. Environ. Qual.* 33:2201–2209.

Sharpley, A.N., S. Herron, and T. Daniel. 2007. Overcoming the challenges of phosphorus-based management challenges in poultry farming. *J. Soil Water Conserv.* 58:30–38.

Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. *J. Environ. Qual.* 29:1462–1469.

Sikora, L.J., and N.K. Enkiri. 2005. Comparison of phosphorus uptake from poultry litter compost with triple superphosphate in Codorus soil. *Agron. J.* 97:668–673.

Szogi, A.A., P.J. Bauer, and M.B. Vanotti. 2008a. Agronomic effectiveness of phosphorus materials recovered from manure. p. 52–56. *In* V. Koutev (ed.) 13th Ramiran Int. Conf., Ambrosia NT Ltd., Bulgaria.

Szogi, A.A., and M.B. Vanotti. 2008. Removal of phosphorus from livestock effluents. *J. Environ. Qual.* 38:576–586.

Szogi, A.A., and M.B. Vanotti. 2009. Prospects for the recovery of phosphorus from poultry litter. *Bioresour. Technol.* 100:5461–5465.

Szogi, A.A., M.B. Vanotti, and P.G. Hunt. 2006. Dewatering of phosphorus extracted from liquid swine waste. *Bioresour. Technol.* 97:183–190.

Szogi, A.A., M.B. Vanotti, and P.G. Hunt. 2008b. Process for removing and recovering phosphorus from animal waste. Patent Application Serial no. 20090193863. U.S. Patent Office, Washington, DC.

Szogi, A.A., M.B. Vanotti, and P.G. Hunt. 2008c. Phosphorus recovery from poultry litter. *Trans. ASABE* 51:1727–1734.

Tisdale, S.M., W.L. Nelson, and J.D. Beaton. 1985. Soil fertility and fertilizers. 4th ed. Macmillan, New York.

Trostle, R. 2008. Global agricultural supply and demand: Factors contributing to the recent increase in food commodity prices. Outlook WRS-0801. USDA–Economic Res. Serv., Washington, DC.

Tucker, M.R. 1992. Determination of phosphorus by Mehlich 3 extractant. p. 6–8. *In* S.J. Donohue (ed.) Reference soil and media diagnostic for the southern region of the United States. Southern Coop. Series Bull. 374. Virginia Agric. Exp. Stn., Blacksburg.

Turner, B.L., and A.B. Leytem. 2004. Phosphorus compounds in sequential extracts of animal manures: Chemical speciation and novel fractionation procedure. *Environ. Sci. Technol.* 38:6101–6108.