

# Use of Aluminum- and Iron-Rich Residues to Immobilize Phosphorus in Poultry Litter and Litter-Amended Soils

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## ABSTRACT

Poultry production is concentrated on Maryland's eastern shore on areas with sandy soils low in sesquioxides. Water quality has been affected by runoff and leaching of phosphorus from poultry litter-amended fields. Phosphorus movement is of major concern because P is a limiting nutrient for eutrophication in surface water. The objectives of this study were to (i) evaluate the ability of Al-rich drinking water treatment residue (DWTR) and iron-rich residue (IRR) to reduce water-soluble P and Bray and Kurtz no. 1-extractable phosphorus (BK-1 P) in poultry litter and three long-term litter-amended soils and (ii) determine the effects of these residues on pH and electrical conductivity (EC) in the amended litter and soils. Poultry litter and soils were treated with four rates of DWTR and IRR and incubated for 7 wk at 25°C. Litter and soils were sampled at 2, 4, and 7 wk. Both residue materials increased the pH of the litter and the soils. The DWTR was more effective in reducing both water-soluble P and BK-1 P in litter at all rates. At the 25 and 50 g kg<sup>-1</sup> rates, reductions in water-soluble P with IRR were comparable with that of DWTR, but DWTR was twice as effective as IRR in reducing BK-1 P concentration. The results showed that water-soluble P and BK-1 P in poultry litter and long-term litter-amended soils can be substantially reduced by incorporating residues rich in Al and Fe; these residues may be useful for reducing P runoff and leaching from poultry litter and litter-amended fields.

THE high demand for poultry products in the USA in recent years has caused a dramatic increase in the growth of the poultry industry (USDA Agricultural Research Service, 1997, p. 26–54). Increased poultry production has, in turn, resulted in a corresponding increase in the amount of poultry litter (manure mixed with straw, wood chips, sawdust, or peanut hulls) that must be disposed of. Maryland, a state with a long history of poultry production, currently ranks seventh in the nation in broiler production. Maryland produced 636 million kg of broilers (live weight) in 1996 that generated approximately 400 million kg of litter (Maryland Agricultural Statistics Service, 1996). Poultry litter typically contains 8 to 25.8 g P kg<sup>-1</sup> dry weight, with about 4.9 g P kg<sup>-1</sup> being water-soluble reactive P, because P is added to chicken (*Gallus gallus*) diets to ensure rapid growth (Edwards and Daniel, 1992). Most of the poultry litter produced in Maryland has been applied to relatively small areas of cropland in close proximity to the chicken houses (Sims and Wolf, 1994). Many of the soils in the poultry production areas of Maryland are coarse textured, low in clay and sesquioxides, which are important in immobilizing P, and have shallow water tables (Mozaffari and Sims, 1994). Re-

peated land applications of litter on these soils have increased the potential for P loss through surface runoff and leaching to the ground water (Wadman et al., 1987; Kingery et al., 1994).

Phosphorus movement through runoff from poultry litter-amended soils has become a major concern as a nonpoint nutrient source in the Chesapeake Bay watershed (Sharpley and Menzel, 1987). High phosphorus levels in these soils comprise a risk to eutrophication of streams and rivers (Cooke et al., 1986; Federico et al., 1981; Schindler, 1997). Several studies have demonstrated that P movement through runoff from fields receiving poultry litter increased with litter application rate, frequency of application, and rainfall intensity (Edwards and Daniel, 1993; McLeod and Hegg, 1984; Westerman et al., 1983). Several methods are under consideration for lowering soluble P levels in long-term litter-amended soils. The present study addresses the lowering of soluble P in three soils and litter via chemical fixation (precipitation with metals and/or adsorption onto metal oxides or hydroxides) using an IRR and a DWTR.

Several studies have found that soluble P is readily adsorbed and precipitated in soils that contain Al, Fe, and Ca (Hsu, 1975; Tisdale et al., 1985; Lindsay, 1979). Application of reagent grade calcium oxide, alum, iron sulfate, and iron chloride to poultry litter reduced water-soluble P from >2000 mg P kg<sup>-1</sup> to <1 mg P kg<sup>-1</sup> (Moore and Miller, 1994). An 85% reduction in water-soluble P was also observed when alum [Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>·14H<sub>2</sub>O] was used as an amendment to poultry litter (Shreve et al., 1995). Less expensive industrial and municipal residues that contain high levels of Al and Fe have been used in reducing available P in high-P soils. Peters and Basta (1996) observed a reduction in water-soluble and Mehlich 3-extractable P concentration when Al-rich solids from water treatment facilities and an iron-rich bauxite mixed with gypsum were used. However, no work has been reported in which iron-rich by-products were used to reduce soluble P in poultry litter. An IRR has been investigated as a soil amendment to improve physical properties of potting soil (Goyette, 1992). The IRR material used in the present study is a by-product of an industrial process that generates TiO<sub>2</sub> pigments. About 50 million kg of IRR (on a dry weight basis) are produced annually in the Mid-Atlantic region of the United States and are stored in unlined slurry ponds or stockpiled (Salingar et al., 1994a; Goyette, 1992). The residue contains large amounts of iron oxides that may be effective in fixing soluble P in

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**Abbreviations:** BK-1 P, Bray and Kurtz no. 1-extractable phosphorus; DWTR, drinking water treatment residue; EC, electrical conductivity; IRR, iron-rich residue.

poultry litter and in litter-amended soils. However, IRR also contains high levels of chloride, chromium, and manganese compared with average soils. Potential adverse effects of chloride and Cr in IRR have been considered regarding both crop growth and environmental pollution. Salinger et al. (1994a) found in a column leaching study that 92% of the Cl in IRR was removed with the first pore volume, and that other electrolytes were removed with the removal of the salts. Their work also showed that Cr in IRR was Cr(III) in chemically inert forms. Although oxidation of Cr(III) has been reported from laboratory studies with soluble salts, high-Cr serpentine soils and soils amended with Cr-rich leather by-products have not supported Cr oxidation (Chaney et al., 1997). Farmers in the poultry producing areas of Maryland's eastern shores generally maintain their fields at pH 5.5 to 6.5 for soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.) production, and oxidation of Cr<sup>3+</sup> to Cr<sup>6+</sup> is extremely unlikely if IRR should be used to reduce the solubility of P. Further, Salinger et al. (1994b) found in both column and stirred-flow studies that only a small proportion of total Mn and Cr in IRR is soluble.

The other P-fixing material used in this study is a DWTR that results from the use of alum [Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>·4H<sub>2</sub>O] plus calcium hydroxide [Ca(OH)<sub>2</sub>] to precipitate impurities during the purification of city water obtained from wells. About 18 000 gallons (68 040 L) (2% solids) of this residue are produced annually at a facility within 5 mi (~8.0 km) of the poultry production area. At present, this waste product is discharged directly to a city sewage treatment plant where the Al(OH)<sub>3</sub> in the residue aids in flocculating solids in the primary sewage treatment.

These two residues would appear to have chemical properties that will increase the precipitation or adsorption of labile P in high-P soils and poultry litter. The objectives of this study were to (i) evaluate the ability of IRR and DWTR to reduce water-soluble reactive P and BK-1 P in poultry litter and in long-term litter-amended soils and (ii) determine the effects of these residues on pH and EC of the treated litter and amended soils. This incubation study was conducted in advance of field studies planned for three locations on long-term poultry litter-amended soils on the eastern shore of Maryland.

## MATERIALS AND METHODS

### Characterization of Residues

Residue materials used in the present study were Al-rich DWTR and IRR. The DWTR was obtained from a water treatment facility that used well water. The facility was located in Rock Hall, on the eastern shore of Maryland. Alum and calcium hydroxide were added to the well water to adjust pH and precipitate metals and impurities. Iron-rich residue, a by-product of TiO<sub>2</sub> production, was obtained from Du Pont (Wilmington, DE). These materials were air-dried, crushed, and sieved to <250 microns. The residues were analyzed for pH and total metal content. The pH values were determined in 1:2 (residue to deionized water, by volume) mixtures using a glass electrode (McLean, 1982). Electrical conductivity values

**Table 1. Electrical conductivity, pH, Bray and Kurtz no. 1-extractable P, water-soluble P, and total elemental composition of poultry litter, drinking water treatment residue (DWTR), and iron-rich residue (IRR).**

Parameters	Poultry litter	IRR	DWTR
pH (1:2 residue to water)	6.8	7.7	8.0
Electrical conductivity, mS cm <sup>-1</sup>	20.3	36.7	0.43
Water-soluble P, g kg <sup>-1</sup>	3.87	<0.05	<0.05
Bray and Kurtz no. 1-extractable P, g kg <sup>-1</sup>	7.59	<0.05	<0.05
Total P, g kg <sup>-1</sup>	16.0	<0.03	11.6
Al, g kg <sup>-1</sup>	0.16	13.0	62
Cu, mg kg <sup>-1</sup>	332	42.0	1.0
Cr, mg kg <sup>-1</sup>	NA†	1924	5.0
Fe, g kg <sup>-1</sup>	1.6	238	204
Mn, g kg <sup>-1</sup>	0.22	13.4	2.1
Ni, mg kg <sup>-1</sup>	NA	52.0	0.69
Pb, mg kg <sup>-1</sup>	NA	212	<1
Zn, mg kg <sup>-1</sup>	350	237	19
Ca, mg kg <sup>-1</sup>	8.9	50.0	9.0
Mg, g kg <sup>-1</sup>	1.62	2.11	0.40
Na, mg kg <sup>-1</sup>	NA	74.0	121
K, g kg <sup>-1</sup>	31.05	0.11	0.14
Cl, g kg <sup>-1</sup>	NA	62.7	0.31

† No data available.

were determined using an Orion (Beverly, MA) Model 160 conductivity meter on a 1:2 (residue to deionized water, by volume) mixture after 1 h. Total elemental concentration (Table 1) was determined by digesting samples of the materials with aqua regia (Olsen and Sommers, 1982) and analyzing the filtrate using flame atomic absorption spectrometry with deuterium background correction as appropriate (McGrath and Cunliffe, 1985). Chloride concentration in the residues was determined by shaking a 1:5 (residue to deionized water) mixture for 1 h and analyzing the filtrate using a Dionex (Sunnyvale, CA) 120 ion chromatograph (Table 1).

### Poultry Litter Characterization

Multiple poultry litter samples were obtained from litter stockpiled in a covered manure storage structure on a poultry farm on the eastern shore of Maryland. The litter samples were composited, air-dried, crushed to <2 mm, mixed, and stored in plastic containers until use. Litter pH was measured in a 1:3 (litter to deionized water, by volume) solution after 1 h. Electrical conductivity values were determined using an Orion Model 160 conductivity meter with a 1:3 (litter to deionized water, by volume) mixture after 1 h. Water-soluble P was determined using a soil method in which 2 g litter was shaken with 20 mL deionized water for 1 h and filtered through a Whatman #42 filter paper (Sparks, 1996). The BK-1 P was determined by using a modified soil method for extraction in which 2 g litter was extracted with 40 mL of (0.03 M NH<sub>4</sub>F + 0.025 M HCl) and reactive P measured using the ascorbic acid method of color development (Sparks, 1996). Absorbance was determined on a Shimadzu (Kyoto, Japan) UV-120 spectrophotometer at a wavelength of 882 nm for both water-soluble and BK-1 P. Metal contents, Ca, Mg, and K were extracted using aqua regia (Olsen and Sommers, 1982) and then analyzed by flame atomic absorption spectrometry using lanthanum at 1 g L<sup>-1</sup> to prevent interferences (McGrath and Cunliffe, 1985) (Table 1).

### Soil Sampling and Characterization

The three soils used in the incubation study were Evesboro sand (mesic, coated Typic Quartzipsamments), Matapeake silt loam (fine silty, mixed, mesic Typic Hapludults), and Woodstown fine sandy loam (fine-loamy, mixed, mesic Aquic Haplu-

**Table 2. Chemical properties and characteristics of long-term poultry-litter amended soils from the eastern shore of Maryland.**

Parameters	Soils		
	Matapeake	Woodstown	Evesboro
Soil texture	silt loam	sandy loam	sand
Water-soluble P, mg kg <sup>-1</sup>	41	54	84
Bray and Kurtz no. 1-extractable P, g kg <sup>-1</sup>	1.26	1.09	0.96
pH (1:1 soil to water)	4.6	5.7	5.6
Electrical conductivity, mS cm <sup>-1</sup>	2.0	0.8	0.6
Cu, mg kg <sup>-1</sup> †	8.4	13.4	5.6
Zn, mg kg <sup>-1</sup> †	6.6	9.0	9.9
Mn, mg kg <sup>-1</sup> †	14.7	5.1	7.9
Ca, g kg <sup>-1</sup> ‡	1401	1487	2038
Mg, mg kg <sup>-1</sup> ‡	135	171	272
K, mg kg <sup>-1</sup> ‡	601	292	535
Organic carbon, g kg <sup>-1</sup>	18	19	29

† DTPA extraction.

‡ Mehlich I extraction.

dults). The soils were collected from agricultural fields near Ocean City, MD that had received poultry litter applications annually for more than 30 yr. Bulk soils were collected from the surface (0–15 cm), air-dried, sieved to <2 mm, and stored in plastic containers until use. Soil texture was determined using the hydrometer method (Gee and Bauder, 1986) (Table 2). Soil pH was measured in 1:1 (soil to water, by volume) suspensions after 1 h. Electrical conductivity was determined in 1:2 (soil to water) filtrates after 1 h. Water-soluble P was determined by shaking 2 g soil in 20 mL deionized water for 1 h and filtering through Whatman #42 filter paper (Sparks, 1996). The BK-1 P was determined by using a modified method in which 2 g soil were extracted with 40 mL of a mixture containing 0.03 M NH<sub>4</sub>F + 0.025 M HCl (Sparks, 1996). Samples were shaken at 200 rpm on a platform oscillating shaker for 5 min then filtered using Whatman #42 filter paper. The ascorbic acid method was used for color development and absorbance determined as described above. The DTPA-extractable Cu, Mn, and Zn levels were determined using the Lindsay and Norvell (1978) method and analyzed using flame atomic absorption spectrometry. Calcium, Mg, and K were extracted using the Mehlich I method (Sparks, 1996) described above.

### Residue Applications and Treatment Assessment

The two residue materials (DWTR and IRR) were each added to litter at rates of 0, 25, 50, and 100 g kg<sup>-1</sup> (dry weight), and to the three soils at rates of 0, 10, 25, and 50 g kg<sup>-1</sup>, separately in three replications per treatment. The amendments were mixed and moisture content was adjusted to 20% followed by incubation in plastic bags at 25°C for 7 wk. Litter and soil subsamples were taken at 2, 4, and 7 wk after the start of incubation and analyzed for pH, EC (at the 2-wk sampling) and water-soluble P and BK-1 P using the methods described above. The results were subjected to statistical analysis using SAS procedures (SAS Institute, 1996). Treatment means were separated using Duncan's multiple range test at  $p < 0.05$  (Steel and Torrie, 1980).

## RESULTS AND DISCUSSION

### Poultry Litter Treated with Drinking Water Treatment Residue and Iron-Rich Residue

After 2 wk of incubation, the DWTR-treated litter exhibited a progressive increase in pH with application

rates (Table 3); however, there were no significant differences between the control and the low rate (25 g kg<sup>-1</sup>) for the DWTR-treated litter. Throughout the incubation study, the pH of IRR-treated litter did not change significantly (Table 3).

Electrical conductivity was determined only for the samples taken at 2 wk of incubation because it was assumed that reaction would be essentially completed within 2 wk. The EC values for the litter at the 100 g kg<sup>-1</sup> rate of DWTR and IRR treatment were 17.2 and 16.9 mS cm<sup>-1</sup>, respectively, and were not significantly different from the control value of 16.7 mS cm<sup>-1</sup> (Table 3). This lack of significant change in litter EC with DWTR and IRR addition may be due to the initially high EC of the litter.

Water-soluble P in the untreated litter increased from Weeks 4 to 7 (Table 3), probably due to mineralization of organic P. Water-soluble P in litter treated with DWTR progressively decreased with increasing rate, with the greatest reductions occurring at the fourth week of incubation (Table 3). At Week 4, water-soluble P levels had been reduced 25, 63, and 87%, compared with the control, for the 25, 50, and 100 g kg<sup>-1</sup> rates, respectively. Similar reductions were observed by Moore and Miller (1994) when alum buffered by CaCO<sub>3</sub> was mixed with litter. The reductions in water-soluble P concentrations with increased rates of DWTR (Table 3) were probably caused by adsorption or precipitation of soluble P by metals such as Fe and Al present in the residue (Table 1) (Cooke et al., 1986). For example, Hsu (1976) reported that Al was most effective in lowering the soluble P content at pH values ranging from 5.5 to 8.0.

The IRR treatments also reduced water-soluble P levels in the litter compared with control but there was no significant difference when the application rate increased from 25 and 50 g kg<sup>-1</sup> at 4 and 7 wk (Table 3). Water-soluble P levels were reduced by 43, 42, and 62% at the 100 g kg<sup>-1</sup> rate of IRR at Weeks 2, 4, and 7, respectively (Table 4). These findings agree with observations reported by Moore and Miller (1994), who found that adding water-soluble Fe salts [Fe<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>·2H<sub>2</sub>O or FeCl<sub>3</sub>] to poultry litter effectively reduced water-soluble P levels.

The BK-1 P in the control litter was significantly higher at Week 7 compared with Week 2. This increase again may be due to the mineralization of organic P in the litter over time (Table 3). The BK-1 P in litter was progressively reduced as the application rates of DWTR were increased, with the general patterns over time appearing similar to those noted for water-soluble P. Likewise, IRR was not as effective in reducing BK-1 P as was observed for the DWTR material (Table 3), with reduction in P levels for the 100 g kg<sup>-1</sup> DWTR rate of 81, 84, and 82% compared with 30, 45, and 44% for the IRR-treated litter for 2, 4, and 7 wk of incubation, respectively (Table 4). The larger reductions in water-soluble P and BK-1 P with the addition of DWTR compared with IRR may have been related to the high

**Table 3. Poultry litter pH, electrical conductivity (EC), water-soluble P, and Bray and Kurtz no. 1-extractable P at 2, 4, and 7 wk after incubation with drinking water treatment residue (DWTR) and iron-rich residue (IRR).**

Residue	Application rates	Incubation Time			Electrical conductivity
		Week 2	Week 4	Week 7	
	$\text{g kg}^{-1}$	pH			$\text{mS cm}^{-1}\ddagger$
Control	0	6.88cd‡	6.97bcd	6.86cd	16.7abc
DWTR	25	7.00bcd	6.84cd	6.86cd	15.7c
	50	7.34b	8.02a	8.18a	16.5abc
	100	7.94a	8.33a	8.35a	17.2a
IRR	25	6.92cd	6.91cd	7.12bc	15.8bc
	50	6.94cd	6.70d	6.93cd	16.9ab
	100	6.96bcd	6.87cd	7.22bc	16.9ab
		Water-soluble P, $\text{g kg}^{-1}$			
Control	0	5.23a	4.30bc	5.89a	
DWTR	25	3.88cd	3.22efg	3.04fg	
	50	2.16ij	1.57k	1.67jk	
	100	2.17ij	0.56l	0.71l	
IRR	25	4.53b	3.69de	3.60de	
	50	3.96cd	3.88cd	3.50def	
	100	2.97gh	2.51hi	2.25i	
		Bray and Kurtz no. 1-extractable P, $\text{g kg}^{-1}$			
Control	0	7.60b	7.29bc	8.38a	
DWTR	25	5.79e	4.80f	5.21ef	
	50	3.72hi	2.93j	3.33ij	
	100	1.46k	1.19k	1.54k	
IRR	25	7.37bc	5.81e	6.81cd	
	50	6.59d	5.55e	6.57d	
	100	5.35ef	4.04gh	4.69fg	

† EC values determined 2 wk after incubation.

‡ Means within column and across rows followed by the same letter are not significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

concentration of Al plus Fe in the DWTR compared with the IRR, which is high in only Fe (Table 1).

**Soils Treated with Drinking Water Treatment Residue and Iron-Rich Residue**

Matapeake soil pH progressively increased with increased application rates of both IRR and DWTR; however, significant reductions in pH were noted at Week 7 compared with Weeks 2 and 4 (Table 5). The reductions in pH over time may have been related to microbial activity in the soil, which released  $\text{H}^+$  as organic matter was metabolized. In all cases, the DWTR treatment increased the soil pH above that of the IRR-treated soils.

The EC values of Matapeake soil were unchanged with the DWTR treatments but were significantly increased with increased application rates of IRR (Table 5). This increase may be due to the higher chloride content in IRR compared with DWTR (Table 1). It is important to note that the resulting EC values for the 50  $\text{g kg}^{-1}$  rate for the IRR were three times higher than the DWTR material in Matapeake soil after 2 wk of incubation.

Significant reductions in water-soluble P concentration in the Matapeake soil were observed with increased application rates of both residue materials (Table 5). Likewise, there were small reductions in water-soluble P in the nontreated control soil over the 7-wk incubation period. Drinking water treatment residue was more effective in reducing water-soluble P concentrations at the 10 and 25  $\text{g kg}^{-1}$  application rates compared with IRR. However, the differences in reductions between

the two residues were smaller at the 50  $\text{g kg}^{-1}$  application rate for the three dates (Table 6).

The BK-1 P in the Matapeake soil was progressively reduced with increased application rates of both residues (Table 5); however, the results for both the control soil and the treated soils exhibited variation in BK-1 P values from Weeks 2 to 7. The reason for the overall lower BK-1 P values at Week 4 are uncertain. In general, IRR appeared much less effective in lowering BK-1 P than DWTR at all application rates. For example, at 7 wk, there were 36 and 83% reductions in BK-1 P at the 50  $\text{g kg}^{-1}$  application rate for IRR and DWTR, respectively (Table 6).

**Table 4. Percent reduction in water-soluble P and Bray and Kurtz no. 1-extractable P in poultry litter amended with drinking water treatment residue (DWTR) and iron-rich residue (IRR).**

Residues	Rates	Incubation time		
		Week 2	Week 4	Week 7
	$\text{g kg}^{-1}$	Reduction in water-soluble P, %		
DWTR	25	26	25	48
	50	59	63	72
	100	58	87	88
IRR	25	13	14	39
	50	24	10	41
	100	43	42	62
		Reduction in Bray and Kurtz no. 1-extractable P, %		
DWTR	25	24	34	38
	50	51	60	60
	100	81	84	82
IRR	25	3	20	19
	50	13	24	22
	100	30	45	44

**Table 5. Matapeake soil pH, electrical conductivity (EC), water-soluble P, and Bray and Kurtz no. 1–extractable P at 2, 4, and 7 wk after incubation with drinking water treatment residue (DWTR) and iron-rich residue (IRR).**

Residue	Application rate	Incubation time			Electrical conductivity
		Week 2	Week 4	Week 7	
	$\text{g kg}^{-1}$	pH			$\text{mS cm}^{-1}\ddagger$
Control	0	5.2lm‡	5.2lm	5.1n	3.49d
DWTR	10	5.6i	5.7h	5.2l	3.45d
	25	5.9e	6.1d	5.7hi	3.41d
	50	6.3b	6.4a	6.1d	3.39d
IRR	10	5.5k	5.6j	5.2m	4.76c
	25	5.8f	5.8f	5.3l	6.47b
	50	6.1c	6.1c	5.8f	9.34a
		Water-soluble P, $\text{mg kg}^{-1}$			
Control	0	29.34a	23.33b	23.25c	
DWTR	10	15.40d	4.84h	3.17i	
	25	7.25f	2.28ij	1.67jk	
	50	5.04gh	1.14jk	0.86k	
IRR	10	27.44b	13.00e	12.34e	
	25	12.32e	6.20fg	7.24f	
	50	4.75h	2.17ijk	3.21i	
		Bray and Kurtz no. 1–extractable P, $\text{g kg}^{-1}$			
Control	0	1.33a	1.15b	1.35a	
DWTR	10	0.96d	0.78f	0.99dc	
	25	0.64g	0.52h	0.62g	
	50	0.24i	0.21i	0.23i	
IRR	10	1.21b	1.04c	1.20b	
	25	1.04c	0.87e	1.05c	
	50	0.87e	0.74f	0.86c	

† EC values determined 2 wk after incubation.

‡ Means within column and across rows followed by the same letter are not significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

As was reported for the Matapeake soil in Table 5, there were declines in pH in the control treatment for Woodstown soil from 6.0 to 5.3 over the 7-wk incubation period (Table 7). With respect to the DWTR- and IRR-treated soils, pH values were significantly increased with increased residue application rates for the two materials. For example, compared with the control, pH increased from 6.0 to 6.7 and from 6.0 to 6.7 for the 50  $\text{g kg}^{-1}$  rate of DWTR and IRR, respectively, at 2 wk of incubation. Overall, pH values progressively declined from Weeks 4 to 7. As previously stated, the reductions in pH over time were probably related to microbial activity in the litter-amended soils, because the reductions were also observed in the control treatments. As was reported for

the Matapeake soil (Table 5), EC values showed no significant change upon the addition of DWTR at 2 wk of incubation, but EC increased with increasing rates of IRR addition (Table 7). The resulting EC values for the 50  $\text{g kg}^{-1}$  rate for the IRR material were about five times the values noted for the DWTR material.

The effects of the two residue materials on water-soluble P in the Woodstown soil are summarized in Table 7. There were rapid declines in water-soluble P concentrations within 2 wk following application with resultant P concentrations below 6.3  $\text{mg kg}^{-1}$  for the 25 and 50  $\text{g kg}^{-1}$  rates for both materials. Water-soluble P results for the DWTR were statistically similar for the 25 and 50  $\text{g kg}^{-1}$  rate for Weeks 4 to 7 (Table 7). The

**Table 6. Percent reduction in water-soluble P and Bray and Kurtz no. 1–extractable P in three soils amended with drinking water treatment residue (DWTR) and iron-rich residue (IRR).**

Residue	Application rate	Weeks								
		Matapeake			Woodstown			Evesboro		
	$\text{g kg}^{-1}$	2	4	7	2	4	7	2	4	7
		Reduction in water-soluble P, %								
DWT	10	48	79	86	72	85	93	69	82	85
	25	75	90	93	86	99	98	88	97	96
	50	83	95	96	90	99	99	91	98	99
IRR	10	6	44	47	67	62	56	60	65	45
	25	58	73	69	85	87	79	86	91	88
	50	84	91	86	96	98	94	98	99	97
		Reduction in Bray and Kurtz no. 1–extractable P, %								
DWT	10	28	32	27	31	20	21	35	18	25
	25	52	55	54	64	55	52	65	54	54
	50	82	82	76	82	89	89	91	89	87
IRR	10	9	9	11	11	19	5	10	4	8
	25	22	24	22	15	16	11	29	18	22
	50	35	36	36	50	46	38	44	34	38

**Table 7. Woodstown soil pH, electrical conductivity (EC), water-soluble P, and Bray and Kurtz no. 1-extractable P at 2, 4, and 7 wk after incubation with drinking water treatment residue (DWTR) and iron-rich residue (IRR).**

Residue	Application rate	Incubation time			Electrical conductivity
		Week 2	Week 4	Week 7	
	$\text{g kg}^{-1}$	pH			$\text{mS cm}^{-1}\dagger$
Control	0	6.0e‡	5.6fg	5.3k	0.87d
DWTR	10	6.4c	5.4h	5.1i	0.82d
	25	6.5b	5.7f	5.6f	0.91d
	50	6.7a	6.2d	6.1e	0.92d
IRR	10	6.2d	6.0e	4.7j	1.71c
	25	6.5bc	6.5bc	5.5gh	2.78b
	50	6.7a	6.7a	6.5bc	4.51a
		Water-soluble P, $\text{mg kg}^{-1}$			
Control	0	42.57a	37.64b	45.44a	
DWTR	10	11.69de	5.58g	3.02ghij	
	25	5.87fg	0.55j	0.74ij	
	50	4.40ghi	0.37j	0.50j	
IRR	10	13.91d	14.39d	20.10c	
	25	6.29fg	4.77gh	9.57ef	
	50	1.80hij	0.93ij	2.63ghij	
		Bray and Kurtz no. 1-extractable P, $\text{g kg}^{-1}$			
Control	0	1.04ab	1.08a	1.12a	
DWTR	10	0.71e	0.86d	0.89cd	
	25	0.37h	0.49g	0.50g	
	50	0.19i	0.12i	0.12i	
IRR	10	0.93bcd	0.88d	1.06a	
	25	0.88d	0.91cd	1.00abc	
	50	0.52g	0.58fg	0.69ef	

† EC values determined 2 wk after incubation.

‡ Means within column and across rows followed by the same letter are not significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

IRR treatments were much less effective in lowering soluble P concentration in the Woodstown soil compared with the DWTR material with only the 50  $\text{g kg}^{-1}$  rates being comparable in effectiveness.

The Woodstown soil BK-1 P results were similar to

those seen for the Matapeake soil and confirm the superior P immobilizing ability of DWTR compared with IRR. The BK-1 P results for the 10 and 25  $\text{g kg}^{-1}$  rates for the IRR-treated soil were similar to the nontreated control after 7 wk of incubation. The higher BK-1 P

**Table 8. Evesboro soil pH, electrical conductivity (EC), water-soluble P, and Bray and Kurtz no. 1-extractable P at 2, 4, and 7 wk after incubation with drinking water treatment residue (DWTR) and iron-rich residue (IRR).**

Residue	Application rates	Incubation time			Electrical conductivity
		Week 2	Week 4	Week 7	
	$\text{g kg}^{-1}$	pH			$\text{mS cm}^{-1}\dagger$
Control	0	5.8m‡	5.5n	5.2p	0.73d
DWTR	10	6.2h	5.9k	5.8m	0.69d
	25	6.4e	6.3f	6.1i	0.71d
	50	6.6a	6.5b	6.3ef	0.69d
IRR	10	6.0j	5.9k	5.3o	1.37c
	25	6.2g	6.3f	6.0j	2.64b
	50	6.4d	6.5c	6.3f	4.28a
		Water-soluble P, $\text{mg kg}^{-1}$			
Control	0	59.69a	58.02a	58.81a	
DWTR	10	18.38d	10.44e	8.96ef	
	25	7.46efgh	1.77j	2.17ij	
	50	5.31gh	0.75j	0.79j	
IRR	10	23.65c	20.26d	31.18b	
	25	8.19efg	5.11hi	7.34fgh	
	50	1.20j	0.71j	1.88j	
		Bray and Kurtz no. 1-extractable P, $\text{g kg}^{-1}$			
Control	0	1.08a	0.95c	1.02ba	
DWTR	10	0.70e	0.78d	0.77de	
	25	0.38h	0.44gh	0.47g	
	50	0.10i	0.10i	0.13i	
IRR	10	0.97bc	0.91c	0.94c	
	25	0.77de	0.79d	0.80d	
	50	0.60f	0.63f	0.63f	

† EC values determined 2 wk after incubation.

‡ Means within column and across rows followed by the same letter are not significantly different ( $p < 0.05$ ) using Duncan's multiple range test.

values observed after 7 wk of incubation for the IRR-treated soil may relate to the mineralization of organic P (Table 7). With the exception of the 50 g kg<sup>-1</sup> rate of both residues, the pH values for the treated soil were ≤5.6 for the 10 and 25 g kg<sup>-1</sup> rates after 7 wk of incubation. Increases in water-soluble P and BK-1 P at 7 wk may have been due to hydrolysis of organic phosphates for the 10 and 25 g kg<sup>-1</sup> treatments, since the pH values were below the optimum range (4.7–7.1) for P absorption reported by Hsu (1976). At all application rates, the percent reduction in BK-1 P was larger for the DWTR treatment than for IRR. For example, BK-1 P levels for the DWTR-treated soil were 89% reduced at the 50 g kg<sup>-1</sup> rate after 7 wk compared with 38% for IRR (Table 6).

In general, pH, EC, water-soluble P, and BK-1 P responses for the Evesboro soil following amendments and incubation with the DWTR and IRR materials were comparable with the Woodstown soil (Tables 6–8).

### SUMMARY AND CONCLUSIONS

The results from the incubation studies with poultry litter and long-term litter-amended soils collected from the production areas on the eastern shore of Maryland confirm the promise of using relatively inexpensive industrial and municipal by-product materials containing Fe and Al to reduce both water-soluble P and BK-1 P concentrations in poultry litter prior to application to soil or when mixed with high-P soils from litter disposal practices. Increased rates of application of DWTR and IRR increased the litter pH and reduced the water-soluble P and BK-1 P of litter. The general ranking for the residues in terms of their ability to decrease extractable P levels in poultry litter was DWTR > IRR.

Water-soluble P and BK-1 P of the soils were likewise reduced with increased application rates of both residue materials. Water-soluble P levels were typically below 10 mg kg<sup>-1</sup> for all three soils after 2 wk of incubation with both residues at the 25 g kg<sup>-1</sup> application rate. The BK-1 P levels were progressively lowered with increased rates of application for the two residues with DWTR appearing more effective in immobilizing water-soluble P and BK-1 P in litter and BK-1 P in soils than IRR. The greater reduction in BK-1 P and water-soluble P with the use of DWTR compared with IRR may have resulted from the higher concentrations of Al in the DWTR.

The three soils used in this laboratory incubation study involving DWTR and IRR materials were collected from poultry farms on the eastern shore of Maryland where field trials to immobilize soil P were being planned. The results found in this laboratory study suggest that at the lower rates of application (i.e., 10 g kg<sup>-1</sup>), IRR would probably not be as effective in lowering water-soluble P and BK-1 P levels as DWTR. Also, the higher increases in soil EC that resulted from the amendment with IRR may present problems with early seedling establishment until the salts are leached from the root zone. Followup studies to assess the effects of DWTR- and IRR-treated soils on plant growth prior to actual field application appear warranted. The in-

creased soil pH that resulted from application of both residues at the 25 and 50 g kg<sup>-1</sup> rates did not exceed the range (6.0 ± 0.5) recommended for corn and soybean production in Maryland; therefore, the rise in pH should not present a problem in future field application of these residues to immobilize P in high-P soils.

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