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Locally Sourced Iron and Aluminum Byproducts Decrease Phosphorus Leached from Broiler House Dust Deposited near Ventilation Fans

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Abstract

Freshwater impairment by eutrophication, as a result of excessive phosphorus (P) inputs from runoff in particular, remains a ubiquitous environmental concern. A common issue with systems designed to remove P and nitrogen (N) from runoff is their reduced effectiveness under high-flow conditions. To overcome this, P removal from broiler-house fan dust would be more effective if removal occurred at the nutrient source, where the water volume is limited to direct rainfall. The P removal efficiencies of different thicknesses of locally sourced, iron-rich red mud (RM) generated during the manufacture of steel belts for tires and alum-based drinking water treatment residual (WT) byproducts were investigated. Byproduct thicknesses of 4, 8, and 12 cm were tested using 57-L leaching columns. The columns were filled with the specified byproduct thickness and a 3-mm thickness of poultry house dust was surface applied prior to receiving six, 30-min simulated rainfalls (at 7 $cm \cdot hr^{-1}$) at 1-day intervals. The 8-cm thickness of both RM and WT outperformed the other thicknesses in terms of sorbing P released from the added broiler house dust, removing 99 and 96% of the added P, respectively, over the six simulated rainfall events. The 12-cm thickness of both RM and WT showed no additional benefit for P removal over the 8-cm thickness. As the 4-cm-thick WT treatment was less effective (89% of added P removed), the 8-cm thickness was the optimal thickness for field testing. Locally sourced materials with large P-sorbing capacities can offer a convenient, relatively inexpensive alternative for P removal from areas around poultry houses impacted by P-containing, exhausted broiler house dust.

Keywords

Phosphorus Runoff, Poultry Production, Red Muds, Water Quality, Water Treatment Residual

1. Introduction

Freshwater-use impairment by accelerated eutrophication from increased nutrient inputs, particularly phosphorus (P), remains despite widespread conservation efforts [1] [2] [3]. For instance, harmful algal blooms have been linked to excess P in western Lake Erie [4] [5] and Florida [6] [7], as well as to hypoxia in the Northern Gulf of Mexico [8] [9] [10].

The potential for P and nitrogen (N) runoff from land around poultry production facilities has been noted with two major sources being dust exhausted from the production houses by fans [11] and poultry litter material tracked from houses during bird removal and clean-out [7]. While dust and broiler litter have similar total P concentrations, the impact of P release from ventilation fan dust is exacerbated due to the water solubility of dust P being, on average, three times greater than that in the litter [12]. Removing nutrients from runoff water prior to water leaving the poultry production area is likely the most cost-effective on-farm mitigation practice. Similarly, in an effort to most cost-effectively decrease impairment, strategies to reduce nutrient runoff at a watershed scale are more successful when targeting nutrient sources rather than treating receiving waters [13] [14] [15].

Substantial research has been conducted evaluating material that can sorb large amounts of P and structures to contain such materials [16] [17]. To be cost-effective, the P-retention material needs to be locally sourced, readily available, and inexpensive. Two such byproduct materials are a group referred to as red muds (RM) or iron filter cakes, which consist primarily of iron oxides and oxyhydroxides, and an alum-based water treatment (WT) residual.

The byproducts used in this study were an iron filter cake RM from a company in northwest Arkansas, generated during the manufacture of steel belts for tires, and an alum-based WT generated by the Beaver Water District in northwest Arkansas during flocculation of suspended solids from raw municipal water supplies. Currently, a major portion of these materials is land filled. The P-sorption characteristics and hydraulic properties of these materials have been shown to provide potential as on-site sinks for P [11]. For instance, Herron *et al.* [11] reported RM and WT could sorb 25 and 10 g P kg^{-1} of byproduct, respectively, with hydraulic conductivities of 8.0 and 15.4 $cm \cdot min^{-1}$ [18], prior to being used to sorb P from broiler house ventilation dust. However, the capacity of these materials to sorb and retain P released from ventilation fan dust must be assessed under conditions approximating those encountered in the field under environmental exposure.

The objective of this study was to evaluate the capacity of different thicknesses (*i.e.*, 4, 8, and 12 cm) of RM and WT byproducts to sorb and retain P and N released from broiler house fan dust as a result of sequential simulated rainfall events (7 cm·hr^{-1}) applied to leachate columns. It was anticipated that the two byproducts would behave similarly, but that an optimum byproduct thickness would be identified.

2. Materials and Methods

2.1. Experimental Design

It was specifically hypothesized that an on-farm nutrient removal system could be designed to reduce nutrients in stormwater runoff to within acceptable limits by trapping the nutrients at the source. To test this hypothesis, a rainfall simulation and a small-scale containment structure were used to test various byproduct thicknesses for nutrient removal from broiler house dust (BHD). The containment structure (*i.e.*, leachate column) was designed by adapting 56.8-L buckets to contain the RM and WT byproducts. Dust was applied to the surface of the byproducts in each leachate column followed by simulated rainfall application. The leachate produced was then collected for chemical analysis.

2.2. Column Configuration

Prior testing of the RM and WT byproducts [11] showed the hydraulic conductivity of 6-mm-diameter particles of RM was 123 cm 30 min^{-1}, while that of the 6-mm-diameter particles of WT was 138 cm 30 min^{-1}. These hydraulic conductivities were determined to be more than adequate to transmit the calculated volume of rainfall that would fall to the ground adjacent to broiler house fan outlets during a 25-yr, 30 min storm event (*i.e.*, 33 cm per 30 min).

Three byproduct thicknesses (*i.e.*, 4, 8, and 12 cm) were tested using the 56.8-L leachate columns. The columns were constructed by removing the bottoms of 27, 56.8-L buckets, leaving the remainder of the bucket for the specified byproduct thickness plus 7.6 cm of open space at the top. Welded wire mesh, with 1.27 cm openings, was attached to the bottom of the buckets and landscape fabric was placed on top of the wire mesh. The byproduct was placed on the landscape fabric. The cut buckets were placed inside uncut 56.8-L buckets, perforated on the sides to allow airflow, to capture leachate during the experiment (**Figure 1**). Leaching experiments were conducted in triplicate for each byproduct-thickness treatment combination, including controls for each byproduct that received no dust and dust only treatments (*i.e.*, no byproduct).

Dust collected off fan shutters from four broiler facilities in northwest Arkansas was combined and mixed thoroughly as described by Herron *et al.* [12]. The dust application rate for the experiment was calculated based on direct measurements of dust thicknesses that had settled on the ground adjacent to fan outlets during one grow-out cycle (flock) of birds (approximately 6 weeks), which averaged 3.2 mm per flock. Based on the surface area of the leachate

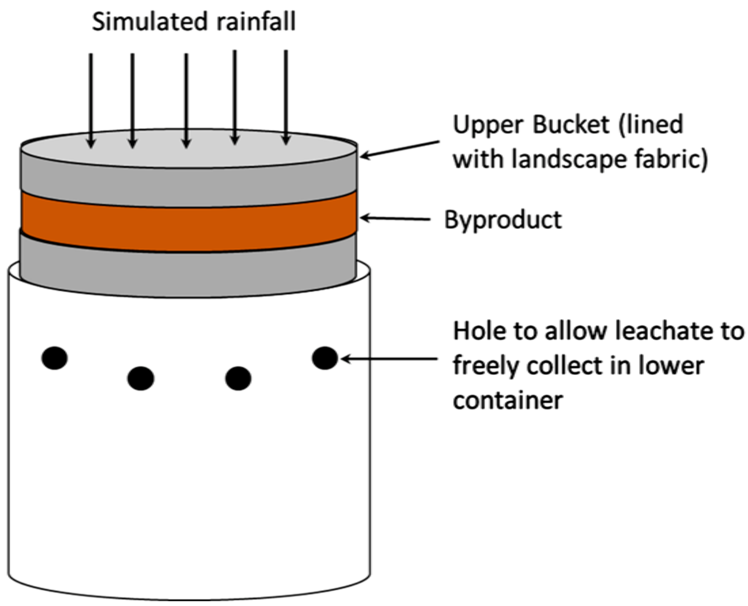

Figure 1. Schematic of stacked columns used in rainfall simulation experiment.

column (638 cm^2) and the estimated bulk density of the dust (0.23 $g \cdot cm^{-3}$), 45.43 g of dust were used for each byproduct-thickness treatment combination. The dust was analyzed by the University of Arkansas Agricultural Diagnostic Laboratory and contained 4312 mg water extractable P kg^{-1}, 10,400 mg total P kg^{-1}, 3,785 mg NH_4-N kg^{-1}, 277 mg NO_3-N kg^{-1}, and 97,600 mg total N kg^{-1}. The dust was applied by hand uniformly to the surface of byproduct in each column. For the no-byproduct treatment, dust was applied by hand uniformly directly to the landscape fabric.

2.3. Rainfall Simulation

The rainfall simulator used for this experiment was based on the design of Miller (1987). The dimensions for the area under the simulator were 2.0 meters wide by 1.5 meters long. The frame was built of hollow metal tubing, on which a 25-mm-diameter, polyvinyl chloride (PVC), water-supply pipe was mounted. Polyvinyl chloride windscreens were attached to four sides to limit wind effects on rainfall distribution. A water hose supplying water from the city water supply was attached to the water-supply pipe. A single, fixed nozzle (TeeJet™ 1/2HH-SS-5OWSQ, TeeJet, Glendale Heights, IL), designed for a flow rate of 210 $mL \cdot sec^{-1}$, was installed on the water-supply pipe and centered at the top of the frame, 3 m above the surface of the leachate columns [19]. A low-pressure regulator and an oil-filled pressure gauge were used to maintain the water pressure at 37.9 kPa (5.5 PSI). An in-line filter was placed in the supply pipe to prevent particles clogging the line and nozzle during water delivery.

Leachate columns were randomly placed under the rainfall simulator in three zones, one zone for each replicate set of treatment combinations (Figure 2, Figure 3). Rainfall intensity was verified and distribution uniformity was determined by

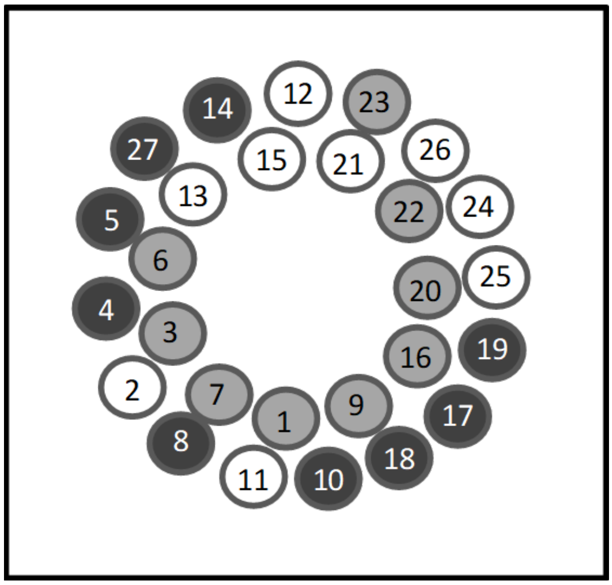

Figure 2. Assignment of columns into three groups (white, gray, and black) based on randomization plan.

Figure 3. Actual layout of columns under rainfall simulator based on rainfall uniformity test.

simulating rainfall three times onto the area where the leachate columns were to be placed and measuring the resulting rainfall volume. The exact locations of the three zones were then selected based on the results of the rainfall uniformity tests. The coefficient of uniformity was determined using the method described by Christiansen [20], which expresses uniformity as a percentage according to the formula coefficient of uniformity = 100 * (1.0 − Σd/m * n), where d is the standard deviation of individual observations from the mean value m, and n is the number of observations [21].

Rainfall simulations were conducted at an intensity of 7 cm·hr^{-1} based on a 2-year, 24-hour storm rate and leachate was collected for a total of 30 minutes according to the National Phosphorus Research Project [19]. Leachate columns received 30 minutes of simulated rainfall prior to the first treatment with dust to equalize their water contents. After the first rainfall simulation, dust was surface applied to the byproducts in each column, which then received simulated rainfall. Six consecutive dust applications were followed by 30 minutes of simulated rainfall at a rate of 7 cm·hr^{-1}, the combination of which occurred at one-day intervals. Dust applications approximated the amount of dust deposited on the soil outside a broiler house fan during one year of typical operation (*i.e.*, the production of six flocks of birds; [12]).

2.4. Chemical Analyses

Following each rainfall simulation, leachate was collected from the bottom of the columns. Leachate volume was measured and a 1-L sub-sample was stored at 4˚C and analyzed within 24 hours of collection. A sample of source water used for the simulated rainfall was collected and similarly retained for analysis. Forty milliliters of leachate were filtered (0.45-μm membrane) immediately after collection and stored at 4˚C until analyzed for dissolved-reactive P (DRP) by the colorimetric molybdenum-blue method [22]. Ammonium-N (NH_4-N) and nitrate-N (NO_3-N) were analyzed colorimetrically by flow-injection analyses (Lachat Instruments QuikChem 8500, Loveland, CO). One hundred twenty-five milliliters of leachate were acidified to a pH ≤ 2 with 12 drops of concentrated sulfuric acid for sample preservation and analyzed for total P and N following persulfate-autoclave digestion [23]. Total P (TP) was determined by spectrophotometry (Beckman Coulter, Pasadena, CA) and total N (TN) was determined by flow-injection analysis (Lachat Instruments QuickChem 8500, Loveland, CO). One hundred twenty-five milliliters were analyzed gravimetrically for total solids after oven drying at 105˚C for 12 h.

2.5. Statistical Analyses

The TP results were tested for and had homogeneous variances. Therefore, a two-factor analysis of variance (ANOVA) was conducted on the concentrations of TP to evaluate the effects of byproduct, byproduct thickness, and their interaction. Due to non-homogeneous variances, separate one-factor ANOVAs were conducted on the leachate concentrations of DRP, NH4-N, NO3-N, and TN to separately evaluate the effect of byproduct for each thickness and thickness for each byproduct. All relationships were reported as statistically significant at the $p < 0.05$ level unless noted otherwise. Wolfram Mathematica (online beta version 2014, Wolfram, Champaign, IL) was used to conduct all statistical analyses.

3. Results and Discussion

3.1. Simulated Rainfall Distribution

The average rainfall uniformity was 95%, 94%, and 87% for zones 1, 2, and 3, respectively, as determined by the coefficient of uniformity (**Table 1**). Additionally, the coefficient of uniformity among the three consecutive 30 min, 7 cm·hr^{-1}

Table 1. Coefficient of uniformity of rainfall on the columns for three rainfall events.

Byproduct material/ Size fractions	≤2 mm		≤6 mm		≤12.5 mm	
	cm^3	% of total	cm^3	% of total	cm^3	% of total
Red mud iron filter cake						
8 - 12.5 mm	0.0	0	0.0	0	1592.0	32
6 - 8 mm	0.0	0	0.0	0	1530.5	31
4 - 6 mm	0.0	0	902.1	30	563.0	11
2 - 4 mm	0.0	0	831.4	27	563.0	11
<2 mm	1202.9	100	1291.3	43	688.2	14
Total	1202.9	100	3024.8	100	4936.8	100
Water treatment residual						
8 - 12.5 mm	0.0	0	0.0	0	1592.0	31
6 - 8 mm	0.0	0	0.0	0	1611.7	31
4 - 6 mm	0.0	0	1132.1	31	638.4	12
2 - 4 mm	0.0	0	902.1	25	572.3	11
<2 mm	2211.1	100	1645.1	45	715.4	14
Total	2211.1	100	3679.3	100	5129.8	100

rainfalls was 93%. Thus, the configuration of leachate columns in the rainfall simulator produced uniform and repeatable rainfall both within the simulator footprint and among individual simulated rainfall events. For instance, coefficients of uniformity of 90% to 93% were considered excellent by Humphry *et al.* [21] and Miller [24], and the National Phosphorus Research Project protocol [19] recommends a coefficient of uniformity of 85% or greater for standardized rainfall simulations using the same rainfall simulation equipment as used in this study.

3.2. Rainfall Simulation on Byproducts Treated with Broiler House Dust

Leachate concentrations for all thicknesses of RM ranged from 0.001 to 1.8 mg DRP L^{-1}, 0.28 to 16.7 mg TP L^{-1}, 0.6 to 442.5 mg NH_4-N L^{-1}, 0.0 to 4.8 mg NO_3-N L^{-1}, and 5.5 to 450.2 mg TN L^{-1} (Table 2). Leachate concentrations for all thicknesses of WT ranged from 0.03 to 9.8 mg DRP L^{-1}, 0.43 to 23.3 mg TP L^{-1}, 51.4 to 307.3 mg NH_4-N L^{-1}, 0 to 114.0 mg NO_3-N L^{-1}, and 0.4 to 346.6 mg TN L^{-1} (Table 2). Neither thickness, byproduct type, nor their interaction affected ($p > 0.05$) the concentrations of DRP, TP, NH_4-N, NO_3-N, or TN (Table 2), when the thicknesses and byproducts were compared together. However, when the thicknesses and type of byproduct were compared separately, the DRP concentration was lower ($p < 0.05$) for RM than for WT for the 4- and 12-cm byproduct thicknesses (Table 2). Similarly, the NH_4-N concentration was also lower ($p = 0.02$) for RM than for WT for the 8-cm byproduct thickness (Table 2). In addition, the NO_3-N concentration was lower ($p < 0.002$) for RM than for

Table 2. Byproduct column study—average dissolved P, total P, ammonium-N (NH_4-N), nitrate-N (NO_3-N), and total N concentrations in leachate..

Product/Statistic	Thickness	DRP#	TP	NH_4-N	NO_3-N	TN
	cm		----------------	mg·L^{-1}	----------------	
Dust	n/a	31.70	55.62	156.16	2.00	233.67
RM (control)	12	0.08	0.39	4.39	0.25	10.71
RM	4	0.32	4.94	81.74	1.93	133.45
RM	8	0.20	3.52	38.47	1.67	89.48
RM	12	0.48	5.10	87.80	1.59	130.95
WT (control)	12	0.02	0.22	39.82	8.05	55.11
WT	4	3.42	8.46	96.93	10.89	161.63
WT	8	1.21	7.16	136.04	42.54	211.34
WT	12	1.70	7.72	152.53	22.26	198.70
Two-Way Analysis of Variances P-value*						
Byproduct			0.14			
Thickness			0.89			
Interaction			0.95			
One-Way Analysis of Variance P-value†						
RM	4, 8, 12	0.25		0.61	0.90	0.81
WT	4, 8, 12	0.22		0.42	0.35	0.63
RM/WT	4	0.047		0.71	0.14	0.60
RM/WT	8	0.07		0.02	0.001	0.06
RM/WT	12	0.04		0.26	0.002	0.29

#Dissolved reactive phosphorus (DRP), total phosphorus (TP), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and total nitrogen (TN). *Two-way ANOVA conducted on data with homogeneous variances. †One-way ANOVA conducted on data without homogeneous variances.

WT for the 8- and 12-cm byproduct thicknesses. Comparing the leachate analyses of dust without byproduct to the dust with byproduct treatments, the 8-cm-thick treatments of both byproducts were effective at reducing leachate TP, with RM sorbing up to 94% and WT up to 87% of P leached from dust (Table 3). In the case of N, the RM was more effective than WT in reducing leachate NH_4-N concentrations. The 8 cm-depth treatment of RM reduced leachate NH_4-N concentrations by 75%.

4. Summary and Conclusions

Based on the observations of the physical characteristics of the byproducts and the average leachate concentrations for DRP and TP, the 8-cm thickness appears to be the desired thickness for subsequent field-testing. Additionally, the intent of this project was to design a cost-effective treatment system. While there was no cost to obtain the byproducts, there was significant cost to pretreat byproducts,

Table 3. Mean dissolved P concentrations of column leachate and P removal by byproducts treated with broiler house dust and subject to six simulated rainfalls.

Byproduct depth	Dissolved P	P Removal
cm	mg·L^{-1}	%
	Dust Only	
4	30.35	--
	Iron Filter Cake (RM)	
4	0.32	98.9
8	0.30	99.0
12	0.48	98.4
	Alum Sludge (WT)	
4	3.34	89.0
8	1.21	96.0
12	1.44	95.3

in terms of drying and creating an appropriate particle-size range. Therefore, it was determined that using a thinner layer (*i.e.*, 8- rather than 12-cm thickness) of byproduct in containment structures would require less byproduct and result in beneficial cost savings to the end user, especially as little difference in P removal was observed between the 8- and 12-cm thicknesses.

Field-testing of RM and WT byproducts for their effectiveness in sorbing nutrients from broiler house dust is needed for future design criteria for on-farm P reduction practices. Preliminary findings from the analyses of the leachate from rainfall simulations indicate both RM and WT byproducts are effective at removing P from broiler house dust prior to the P entering stormwater runoff. Additional opportunities for use of these byproducts in agricultural applications, such as containment in ponds, containment to intercept runoff in drainage swales, and land application at nutrient sources should be explored.

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