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Nutrient Removal Structures Using Locally-Sourced Iron and Aluminum By-Products Reduce Nutrient Runoff from Broiler Production Facilities

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Abstract

A common issue with filters designed to remove nutrients from runoff is their reduced effectiveness in high-flow conditions. To overcome this challenge, it was determined that nutrient removal from broiler-house fan dust could be more effective if nutrient removal was conducted at the nutrient source. The objective of this study was to evaluate the effectiveness of containment trays (CTs) holding locally sourced by-products installed adjacent to broiler house fans at the University of Arkansas Savoy broiler production facility to capture nutrients released from dust during rainfall over four years (2013 to 2017). By-products used were locally sourced, iron-based red mud (RM) generated during the manufacture of steel belts for tires and alum-based drinking water treatment residual (WTR), where both materials have large phosphorus (P) sorption capacities. Four-year mean annual concentrations of dissolved P of through-flow from RM CTs were consistently below 0.7 $mg \cdot L^{-1}$ and below 1.6 $mg \cdot L^{-1}$ for WTR CT through-flow. This equated to an average 11- and 4-fold decrease for RM and WTR, relative to concentrations in runoff from same-sized plots adjacent to sidewall fans, demonstrating their potential to trap P at the source and decrease P runoff to nearby flowing waters. While there was no significant decline in RM or WTR effectiveness over the four-year study, further work needs to be conducted to determine the lifespan of CTs. Use of RM and WTR in CTs at poultry broiler production facilities, along with their subsequent land application, has the potential to reduce the amount of by-product materials that are currently landfilled.

Keywords

Nitrogen Runoff, Phosphorus Runoff, Poultry Production, Red Mud, Water Quality, Water Quality, Water Treatment Residual

1. Introduction

Accelerated cultural eutrophication continues to be a concern in the U.S. and globally [1], with agricultural production systems identified as a major contributor, for example in the Chesapeake Bay Watershed [2] [3], Mississippi River Basin [4], Florida's inland and coastal waters [5], Lake Erie Basin [6] [7] [8] and China [9]. Concerns have centered on regions with spatially concentrated livestock systems, where nutrients, particularly P, in manure produced exceed local crop requirements, leading to an increased risk of P runoff [10]. For broiler production systems, additional concerns were focused on nutrient runoff from dust deposit adjacent to broiler house ventilation fans [11] [12].

Accentuating the potential loss of nutrients is the fact that the water solubility of dust P was, on average, three times greater than that in the litter [11]. Strategies to reduce nutrient runoff now target nutrient sources, rather than treating receiving waters, to most effectively decrease impairment [13] [14] [15]. Thus, removing nutrients from runoff water prior to water leaving the production area is the most cost-effective, on-farm conservation practice (CP).

To be consistently effective, P-removal systems must able to treat and transmit large volumes of runoff. As runoff volumes from land around broiler production houses can easily overload available systems, P-removal systems would not be consistently effective. In addition, installation and maintenance of P-removal systems are expensive and labor intensive, making P-removal systems unrealistic as a permanent, on-farm solution. Removing P at the source avoids the issue of hydraulic overload, because it would no longer be necessary to treat large volumes of runoff.

Herron *et al.* [16] [17] reported RM and WTR could sorb 25 and 10 $g{\cdot}P{\cdot}kg^{-1}$ of by-product, respectively, with hydraulic conductivities of 8.0 and 15.4 $cm{\cdot}cm^{-1}$, prior to being used to sorb P from broiler-house ventilation dust. Further research by Herron *et al.* [17] [18] determined an optimal thickness of 8 cm for the RM and WTR by-products to retain P and at the same time allow infiltration of water for efficient P removal (96% to 99% of added P by WTR and RM, respectively).

To be most cost-effective, P retention media need to be locally sourced, readily available, and inexpensive. Industrial by-products with large P-retention capacities that are currently being landfilled are ideal candidates if the by-products do not contain hazardous materials. Two such byproducts are alum-based WTRs, generated where alum is used to flocculate suspended solids from municipal water supplies, and any of a group of by-products variously referred to as red muds or iron filter cakes, which consist primarily of iron oxides and oxyhydroxides. The effectiveness of a CT is not only a function of the design and placement, but is also a function of the capacity of the retention media to capture and retain the target nutrients [19] [20].

This paper describes a four-year study to test the hypothesis that CTs filled with P-sorbing materials and recessed into the ground adjacent to broiler house fan outlets, could sequester P from dust and decrease P runoff potential. Dust from broiler houses settles on top of the P-sorbing materials. During a rainfall event, rainfall first encounters the dust and leaches nutrients into the underlying P-sorbing materials where they are sequestered. In the research described in this paper, the bottom of CTs was enclosed by plastic so that through-flow could be collected and analyzed. If effective, on-farm CTs would not have enclosed bases, allowing through-flow to drain into underlying soil.

2. Material and Methods

2.1. Containment Tray Design

Containment trays were constructed of polyvinyl chloride (PVC) side boards (1.9-cm thick and 22.9-cm wide) and vinyl-coated wire mesh bottoms. The CTs were then installed adjacent to four sidewall ventilation fans at the University of Arkansas Savoy broiler production facility in northwest Arkansas in April 2013. Containment trays were sized to capture the majority of dust particles where they were deposited and were 1.2-m wide by 1.8-m long (**Figure 1(a)**). Landscape

Figure 1. Containment tray structure (a), design (b), and installation (c) at Savoy Broiler Production Facility.

fabric lined the bottom and inner sides of the CT to retain the by-product and trapped dust. Soil below and along the sides of the CTs was lined with 6-mm PVC sheeting to capture leachate for analyses (**Figure 1(b)**). Mesh covering the CTs helped retain dust exhausted from the ventilation fans (**Figure 1(c)**).

Installed trays were recessed into the ground level, so rainfall would percolate through the dust and by-product evenly (**Figure 1(c)**). A 2.5-cm interior diameter PVC pipe was installed at one corner to allow access for a pump tube to collect the leachate, which was accomplished using a long, flexible tube connected to a peristaltic pump. Duplicate CTs were filled with RM or WTR, leaving 5 cm of the tray exposed to eliminate runoff or run on of water. Thus, CTs adjacent to fans 1 and 3 were filled with RM and those adjacent to fans 2 and 4 filled with WTR [16].

Natural rain falling on the CTs leached the dust through the by-product, trapping particulate matter and sorbing P. A 10.2-cm free air space below the by-product allowed capture of the leachate, which was pumped out after each rainfall event and analyzed for P and nitrogen (N) (**Figure 2**). For broader use of the CTs, leachate would be allowed to infiltrate into the underlying soil. Annual rainfall at the study site was 117, 91, 137, and 91 cm in 2013, 2014, 2015, and 2016, respectively, with a 30-year average of 116 cm (from U.S. Climate Data at https://www.usclimatedata.com/climate/fayetteville/arkansas/united-states/usar0189).

2.2. Containment Tray Leachate Collection and Analyses

Following storm events that generated runoff, leachate was pumped from the cavity beneath the CTs. Leachate was subsampled and 1 L was retained from each tray for analysis. Leachate was filtered through a 0.45-µm membrane filter

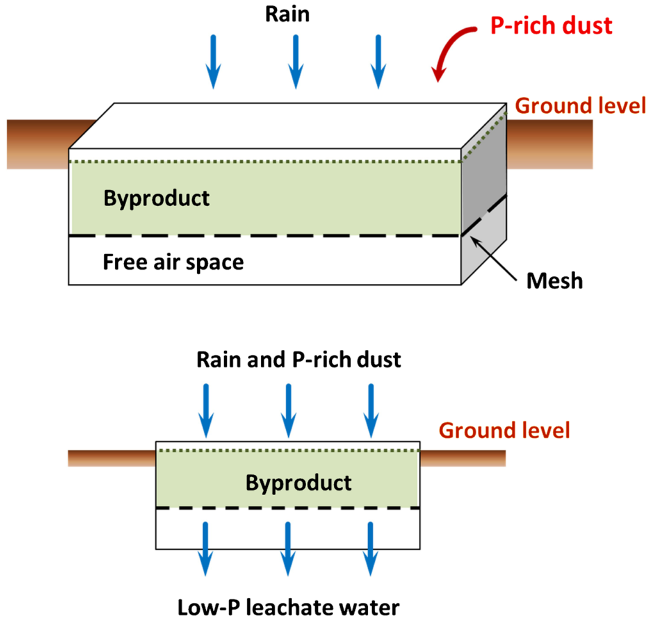

Figure 2. Schematic of containment tray design.

immediately after collection and stored at 4˚C until analyzed for dissolved P (DP) by the colorimetric molybdenum-blue method of Murphy and Riley [21]. Nitrate-N (NO_3-N) and ammonium-N (NH_4-N) were analyzed colorimetrically by flow-injection analysis (Lachat Instruments QuickChem 8500, Loveland, CO). One hundred twenty-five milliliters were acidified with 12 drops of concentrated sulfuric acid for sample preservation, and analyzed for TP and TN using persulfate/autoclave digestion [22]. Total P 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 gravimetrically analyzed for total solids after oven drying at 105˚C for 12 hours.

2.3. Statistical Analyses

Statistical differences among mean concentrations of DP, TP, NH_4-N, NO_3-N, and TN of CT through-flow were determined by t-tests as a function of RM and WTR by-products and as a function of year for each CT using JMP Version 14.1 [23]. All relationships are reported as statistically significant at the $p < 0.05$ level.

3. Results and Discussion

3.1. Nutrients in Containment Tray Through-Flow

The concentration of DP measured in each through-flow event from the CTs is depicted in **Figure 3** for RM CT1 and WRT CT2. The DP concentration of through-flow from the CTs decreased with consecutive rainfall events; however, with an extended dry period between rainfalls (*i.e.*, > four weeks), DP concentration increased due to a buildup of sidewall fan dust on the CTs. Similar trends were observed from RM CT3 and WTR CT4 and for TP, NO_3-N, NH_4-N, and TN concentrations (data not shown).

The concentration of P in CT through-flow was consistently less for RM than WTR ($p < 0.05$; **Table 1**). For instance, mean annual DP concentration of through-flow for RM CTs was consistently below 0.7 mg·L^{-1}, and varied little ($p > 0.05$) among years and between duplicate trays (**Table 1**). For WTR, through-flow DP concentrations were below 1.6 mg·L^{-1}.

There was no difference in mean annual P and N concentrations, except for TN in the RM CT, of through-flow for RM or WTR CTs among study years ($p < 0.05$; **Table 1**). This was the case even though through-flow volume varied from year to year, indicating a consistency in performance of the by-products to remove P irrespective of through-flow volume. Through-flow volume varied as a function of rainfall, with annual rainfalls of 117, 91, 137, and 91 cm in 2013, 2014, 2015, and 2016, respectively.

While there was no difference ($p > 0.05$) in through-flow P concentration of WTR CTs, mean annual concentration of DP in 2016 was greater than that in 2013 (**Table 1**). This indicates that the retention capacity of WTR may have been starting to decrease.

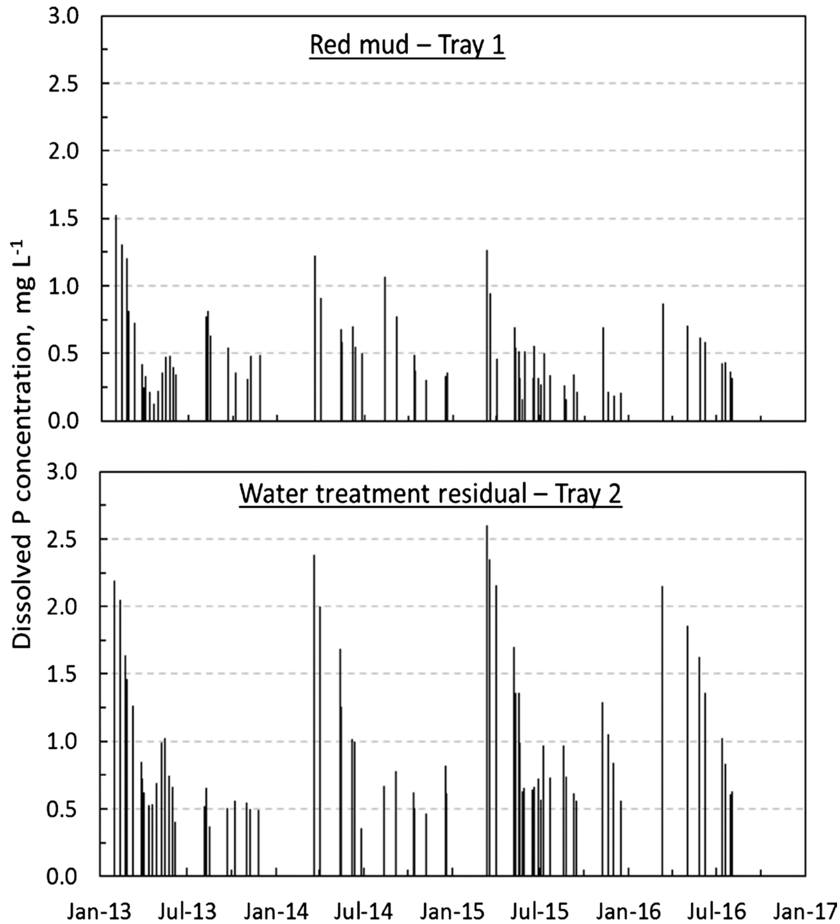

Figure 3. Dissolved P concentration in through-flow events from red mud (Tray 1) and waters treatment residual (Tray 2) containment trays, adjacent to sidewall fans 1 and 2 for 2013 to 2016 study period.

Averaged across the four years of study (2013 to 2017), through-flow P and N concentrations were similar for duplicate RM and WTR CTs (**Table 1**). However, the four-year average concentrations of DP, TP, NO_3-N, and NH_4-N, and TN were significantly lower in through-flow from RM than WTR CTs ($p < 0.05$; **Table 1**).

3.2. Efficacy of Nutrient Removal by Containment Trays

The concentrations of P and N released from poultry house dust were estimated as the mean concentration of P and N in runoff induced from simulated rainfall plots adjacent to the four sidewall fans of the poultry houses on the Savoy Farm, as reported in Herron *et al.* [16]. Mean concentrations of DP, TP, NO_3-N, NH_4-N, and TN of runoff from sidewall plots adjacent to sidewall fans were 5.5, 8.7, 21.2, 25.2, and 51.8 mg·L^{-1}, respectively.

Assuming these runoff concentrations approximate the potential concentrations of P and N released to CTs from house dust during rainfall, both RM and WTR appreciably decreased DP and TP concentrations (**Figure 4**). For DP, this amounted to an average 11- and 4-fold decrease and a 13- and 5-fold TP decrease for RM and WTR, respectively. For N, RM and WTR CTs decreased the concentration of NO_3-N, NH_4-N, and TN in through-flow compared with approximated concentrations leached from house dust to a smaller extent than for P (Figure 5).

Table 1. Through-flow volumes and mean annual concentrations of P and N in red mud and water treatment residual containment trays and four-year study average.

Year	No. flow events	Through-flow L	Dissolved P	Total P	Nitrate-N	Ammonium-N	Total N
			mg·L^{-1}				
			Red mud –Tray 1				
2013	24	2,41	0.565a†	0.735a	23.54a	7.03a	35.26a
2014	14	2338	0.630a	0.747a	24.01a	1.27a	29.21ab
2015	24	3565	0.435a	0.534a	16.03b	3.01a	24.11b
2016	8	961	0.537a	0.688a	14.97b	5.23a	25.17ab
			Red mud –Tray 3				
2013	24	2347	0.586a	0.727a	16.06a	5.07a	26.70a
2014	14	1595	0.506a	0.738a	25.35a	1.03a	29.33a
2015	24	3624	0.403a	0.534a	14.25a	7.20a	26.11a
2016	8	941	0.468a	0.561a	13.13a	7.50a	22.16a
			Water treatment residual –Tray 2				
2013	24	2346	0.852a	1.001a	49.00a	34.66a	87.25a
2014	14	1773	1.010a	1.368a	51.46a	33.40a	96.32a
2015	24	4275	1.052a	1.230a	43.72a	15.00a	65.35a
2016	8	921	1.259a	1.398a	38.32a	35.59a	88.98a
			Water treatment residual –Tray 4				
2013	24	2601	0.820a	0.987a	44.87a	39.60a	91.13a
2014	14	2119	1.012a	1.190a	71.47a	17.59b	98.44a
2015	24	4127	1.137a	1.300a	54.06a	33.99a	95.94a
2016	8	1120	1.506a	1.634a	49.05a	40.66a	104.86a
			Four-year total through-flow and average concentration ‡				
Red mud tray 1		9605a	0.530b	0.663b	20.08c	4.30b	29.07c
Red mud tray 3		8506a	0.494b	0.644b	16.96c	5.27b	26.51c
Water trt. tray 2		9315a	0.998a	1.198a	46.46b	27.77a	81.75b
Water trt. tray 4		9937a	1.046a	1.209a	53.82a	33.40a	95.81a

†Concentration means followed by the same letter are not significantly different at a $p < 0.05$ level. Through-flow of total volume of water captured in containment tray each year. ‡Through-flow volume and average concentration for each treatment followed by the same letter are not significantly different at a $p < 0.05$ level.

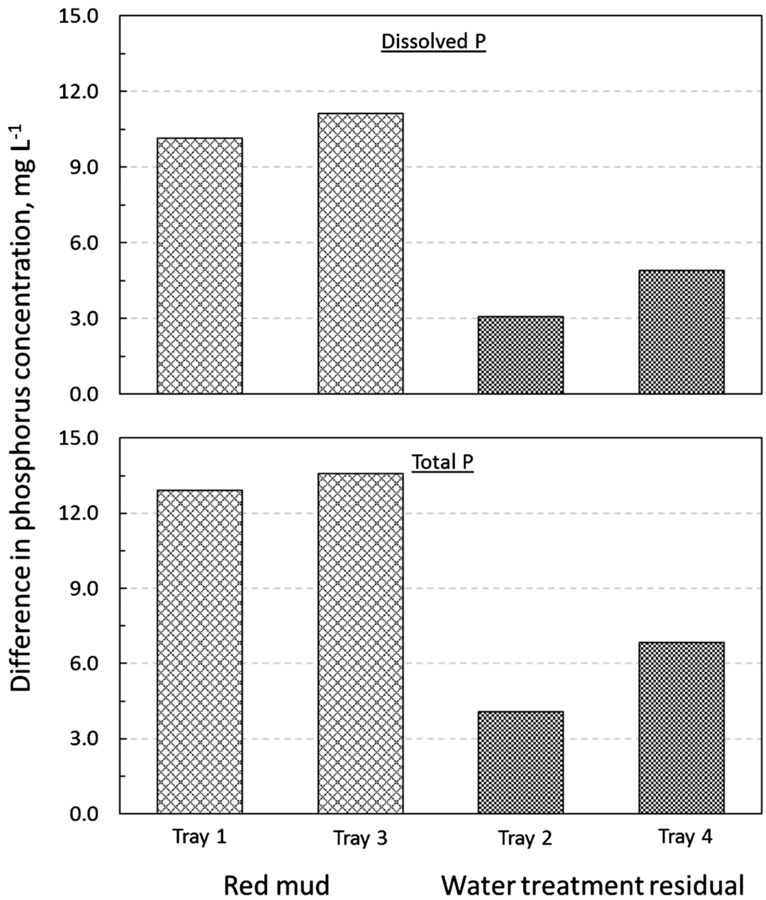

Figure 4. Difference between the 4-year mean concentrations of dissolved and total P in red mud and water-treatment residual containment trays and fan runoff induced by simulated rainfall. Simulated rainfall concentrations from Herron *et al.* [16].

4. Conclusions

Designed with PVC and vinyl-coated mesh, the CTs were resistant to environmental degradation from ultraviolet light, bacteria, and mold. The CTs also retained their structural integrity, despite being exposed to heavy rainfall (maximum of 9.3 cm in 24 h) and outdoor temperatures exceeding 38˚C and as low as −12˚C during the four-year study (2013 to 2017).

The trays functioned properly to trap broiler house dust and percolate rain and runoff water. Visual observations of the system during and directly following a rainfall event showed that dust accumulates on the surface and reduces infiltration of rainwater through the by-product, but does not pond and overtop the tray. The slowed infiltration rate increased contact time between through-flow and by-product in the CTs, which enhanced the effectiveness of P removal.

Once saturated with P or clogged, the by-product would be removed from the CT and land applied with broiler litter from house clean out, as evaluated and reported by Brennan *et al.* [24]. Evaluation of the lifespan of the 8-cm thickness of the by-products in CTs still needs to be conducted. However, this research demonstrated the potential of RM and WTR by-products placed in CTs to

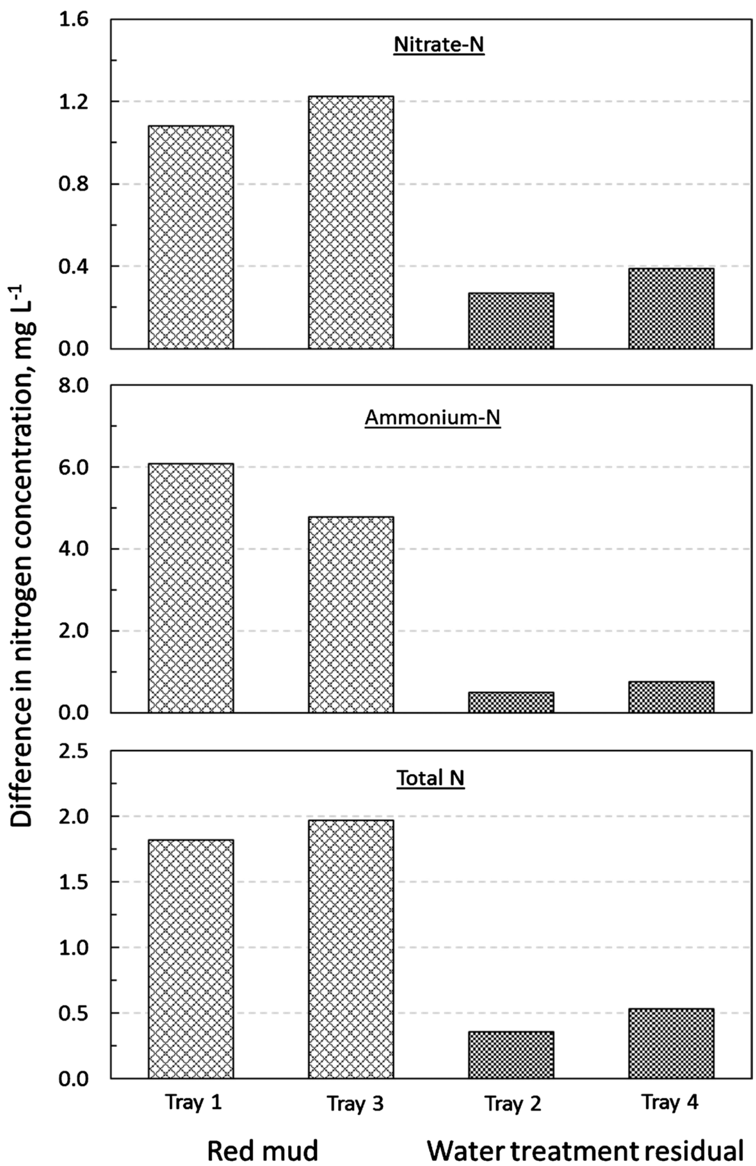

Figure 5. Difference between the 4-year mean concentration of nitrate-N, ammonium-N, and total N in red mud and water-treatment residual containment trays and fan runoff induced by simulated rainfall. Simulated rainfall concentrations from Herron *et al.* [16].

sequester P in house dust; thereby decreasing the quantity of P that could runoff and be transported to nearby flowing waters. In addition, use of RM and WTR in CTs at poultry-broiler production facilities has the potential to reduce the amount of the by-products that are currently landfilled.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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