Journal of Environmental Management 328 (2023) 117005

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Evaluation of phosphorus runoff from sandy soils under conservation tillage with surface broadcasted recovered phosphates

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ARTICLE INFO

Keywords:
Phosphorus runoff
Rainfall simulation
Manure nutrients recycling
Turkey litter ash
Sandy soils
Environment

ABSTRACT

Potential new sources of phosphorus (P) fertilizer are the recovered P from livestock wastewater through chemical precipitation and the ash from combusting animal manures. Although most of the research on P losses from conservation tillage include high water-soluble P compounds from commercial fertilizer sources, information on the use of non-conventional, low water-soluble, recycled P sources is scarce. Particularly for sandy soils of the United States (US) Southeastern Coastal Plain region, research driven information on P loss into the environment is needed to determine recommendations for a direct use of new recycled P sources as crop P fertilizers. The objective of this study is to investigate the potential P runoff from sandy soils under conservation tillage, fertilized with recovered P from liquid swine manure and turkey litter ash in comparison with commercial P fertilizer triple superphosphate (TSP). The field study included two typical sandy soils of the US Southeastern Coastal Plain region, the Noboco and Norfolk. Simulated rain corresponding to the annual 30-min rainfall in the study site (Florence County, South Carolina) was applied to plots treated with recovered P from liquid swine manure, turkey litter ash, and TSP, including a control with no P added. The runoff was monitored and sampled every 5 min during the test and composite soil samples were collected from the top (0–15 cm) and subsurface (15–30 cm) soil layers in each plot. Laboratory analyses were conducted to quantify both total P (TP) and soluble reactive P (SRP) in runoff samples, and the soil test P in the soil layers. Two-way analyses of variances show significant treatment effects on both TP and SRP runoff. The quantities of SRP runoff from plots treated with the recovered P from swine manure and turkey litter ash represent respectively 1% and 7–8% of SRP runoff from plots treated with TSP. Hence, the use of the recovered P materials as crop P fertilizers through surface broadcast application present less environmental risks compared to commercial TSP.

1. Introduction

Application of phosphorus (P) fertilizers is essential to sustain high crop productivity and meet the increasing global food demand (Mogollón et al., 2018). The origin of most P fertilizers used in crop production is from phosphate rock mines located in a handful of countries across the globe. In the United States (US), the existing P mining resources are limited and expected to deplete in the coming decades (Kunhikrishnan et al., 2022; Cordell et al., 2009). In contrast, livestock production in the US generates a large amount of manure with nutrient contents equaling approximately 4 million metric tons P per year (IPNI, 2012; USDA, 2020). Hence, recycling P from non-mining sources such as animal manure, offers a viable alternative for mitigating the depleting P mining reserves in the US. Unfortunately, P recycling through crop production accounts for only 40% of the P contained in manures. The rest of manure P concentrates in the soils of high livestock production areas, and the excess soil P eventually washes-off into local stream networks (Spiegal et al., 2020). Several studies have pinpointed the manure management practices and the physical distance separating livestock production areas from P deficient fields as causes of the poor manure nutrient recycling (Spiegal et al., 2020; Kast et al., 2019; Sharara et al., 2017). In this context, byproducts from advanced manure treatment systems and bioenergy production can increase manure P recycling in US agriculture. Some of such byproducts are recovered P from liquid swine manure through chemical precipitation processes (Vanotti et al., 2009; Vanotti and Szogi, 2009) and ashes from the

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https://doi.org/10.1016/j.jenvman.2022.117005
Received 22 September 2022; Received in revised form 28 November 2022; Accepted 7 December 2022
Available online 9 December 2022
0301-4797/Published by Elsevier Ltd.

Table 1
Description of the soil properties at the experimental site.

Soil series	Granulometry			Soil Texture	pH	Element content		Cation exchange capacity (CEC)
	Sand	Silt	Clay			Phosphorus (P)	Potassium (K)	
Noboco	79%	18%	3%	Loamy Sand	6.2	47 kg/ha	57 kg/ha	3.2 meq/100 g
Norfolk	81%	18%	1%	Loamy Sand	6.8	40 kg/ha	66 kg/ha	3.3 meq/100 g

combustion of poultry litter in bioenergy power plants (Bauer et al., 2019; Lynch et al., 2013; Crozier et al., 2009). These P-rich materials are convenient for transport and direct application on P deficient croplands often located far from intensive livestock production sites. Indeed, the amount of bioavailable P is in a relatively high concentration in some of these materials suggesting their direct use as P fertilizers. For instance, the potential to use the recovered P from swine manure and turkey litter ash in crop production is evident in the Southeastern Coastal Plain US given the livestock (i.e., swine and turkey) production capacity and the favorable policies on manure nutrient recycling and bioenergy production in the region. However, soils in the Southeastern Coastal Plain are predominantly sandy with poor organic matter contents and low water-nutrient retention capacities (Sohoulande et al., 2020). To preserve soil health and properties, conservation tillage is recommended on these sandy soils (Farmaha et al., 2022; Naderman et al., 2004). Wang et al. (2022) evaluated the combined effect of tillage with broadcast manure application on P losses and highlighted the role of conservation tillage to balance P loss reduction. Likewise, Sharpley and al. (2004) highlighted conservation tillage as a best management practice to reduce P runoff from croplands. Although these studies sustain the benefit of conservation tillage, the broadcast applications of P materials still exposes croplands to a risk of P losses into the environment via surface runoff (Wang et al., 2022; Church et al., 2021; Vadas et al., 2008; Novak and Watts, 2004). Indeed, phosphorus losses from croplands have a double disadvantage. On one hand, P wash-off decreases P availability for plants development and could thereby affect crop yields (Withers et al., 2019). On the other hand, P wash-off from cropland often ends up in local streams where it could trigger algal blooms and subsequent water eutrophication (Barcellos et al., 2019). Indeed, the role of P runoff on surface water body eutrophication is well established such that strategies aiming to control water eutrophication generally focus on mitigating P release into the environment (Yin et al., 2020; Chen et al., 2018; Wang et al., 2017). Hence, a thorough understanding of environment risks is needed to determine recommendations for a direct use of the recovered P from swine manure and turkey litter ash as P fertilizers on sandy soils under conservation tillage.

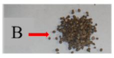
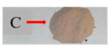
Most of the research on P losses from conservation tillage fields is with fertilizer sources with high water-soluble P compounds. Chien et al. (2011) reviewed the literature on the agronomic and environmental aspects of P fertilizers with different water-solubilities and concluded that there is insufficient information on the use of non-conventional, low water-soluble, P sources. A few investigations (Shigaki et al., 2007; Shigaki et al., 2006; Hart et al., 2004) provided evidence that these low water-soluble P sources can reduce P in runoff from pastures and conservation tillage fields. For instance, Shigaki et al. (2006) found both soluble reactive P (SRP) and total P (TP) in runoff increased linearly with water-solubility of four fertilizer P sources including North Carolina rock P, swine manure, low-grade single superphosphate, and triple superphosphate broadcasted on a loamy soil. In the Southeastern Coastal Plain, a few studies (Szogi et al., 2012; Crozier et al., 2009) have reported no differences in crop yields while comparing soil fertilized with animal manure ash enhanced with phosphoric acid or recovered calcium phosphate from liquid swine manure and soil fertilized with commercial triple superphosphate (TSP). However, research findings on P losses from croplands into the environment cannot be systematically generalized to new P sources because these materials have different forms and variable water-solubility (Chien et al., 2011). As a result, research driven information to support recommendations for a direct use of new non-conventional, low water-soluble, recycled P sources are still scarce. In the particular case of the recovered P from swine manure and turkey litter ash, less is known on the potential P runoff and the environmental risks of a direct field application of these new P materials in comparison with conventional TSP. The objective of this research is to evaluate the potential P runoff losses from plots receiving applications of recovered P materials compared with commercial TSP on sandy soils typical of the Southeastern Coastal Plain under conservation tillage, using a rainfall simulation. This paper reports the research findings and outlined insightful information on the environmental benefits of the new recovered P materials relative to commercial TSP under the context of the Southeastern Coastal Plain region.

2. Materials and Methods

2.1. Site and soil characteristics

The study site is at the Clemson University PeeDee Research and Education Center in Florence County, South Carolina (latitude 34.30° N, longitude 79.74° W). The site is located in the Southern Coastal Plain's land resource area (LRA) which encompasses highly weathered soil series with sandy textures and low organic matter contents (USDA-NRCS, 2006). The field experiment was conducted separately on the Noboco loamy sand and Norfolk loamy sand soil series under conservation tillage. These two sandy soils are common in the Southern Coastal Plain's LRA, but they differ in terms of landscape position, slope, layer thickness, and the presence and depth of a clay layer in their profile (Karlen et al., 1990). Compared to Norfolk soils, Noboco soils have a relatively thick surface, a shallow water table, and the presence of a clay layer in its profile (Sohoulande et al., 2020; Karlen et al., 1990). The selected soil sites have a history of soybean, corn, and cotton crop rotations under conservation tillage. Conservation tillage consisted of deep tilling once a year to a depth of 40 cm using a six-shanked para-till before soybean, corn, or cotton planting to break the hardpan. The para-till has shanks spaced 66 cm apart followed by a roller mounted on the back of the unit to compress and even the soil surface traversed across the field with minimal incorporation of surface residue. After fall harvesting, crop residues remained in the field and both fields were left fallow until planting the following year. The runoff tests on the Noboco soil were conducted during spring 2019, and the same tests were repeated on the Norfolk soil during spring 2020 before planting. According to the USDA Natural Resource Conservation Service (https://soilseries.sc.egov.usda.gov), the Noboco (fine-loamy, siliceous, sub-active, thermic Oxyaquic Paleudult) soils are characterized by a thick surface, a relatively shallow water table, an average carbon (C) content of 5.39 ± 0.60 g/kg, and an average nitrogen (N) content of 0.39 ± 0.06 g/kg. The Norfolk (fine-loamy, kaolinitic, thermic Typic Kandiudults) soils are characterized by a moderately thick surface, a deep-water table, an average C content of 3.92 ± 1.29 g/kg, and an average N content of 0.34 ± 0.14 g/kg. Site-specific measurements of soil characteristic properties such as the granulometry, pH, P content, potassium content, and cation exchange capacity are reported in Table 1. The values in Table 1 show that these two soils are relatively similar, but they differ slightly in their landscape position. Indeed, the Noboco soils are moderately well drained and in lower landscape positions compared to the Norfolk soils which are well drained and in higher landscape positions.

Table 2
Treatments and characterization of the phosphorus fertilizer materials tested.

Treatments		Citrate-soluble P (%)[a]
A	Control	0
	Triple super phosphate (TSP)	21.17[b]
	Recovered P from swine manure	6.75
	Turkey litter ash	4.11

[a] Citrate-soluble P are determined by AOAC Method 960.02 (AOAC International, 2000).
[b] P content in commercial TSP is reported according to Lambers and Barrow (2020).

2.2. *Experimental approach*

A field experiment was conducted to evaluate P runoff from control plots and plots treated with three different P fertilizer sources (Table 2). The commercial TSP had a granule size in the range of 2.0–4.0 mm, the recovered P from swine manure was calcium phosphate with a granule size in the range of 0.5–1.0 mm (Bauer et al., 2012), and the recovered P from turkey litter ash (obtained from a power plant in North Carolina) with granule sizes distributed as 28% < 0.5 mm, 79% between 0.5 and 12.5 mm, and 3% > 12.5 mm (Bauer et al., 2019). Hence, the fertilizer treatments included (i) a control with no P added, (ii) a commercial TSP fertilizer containing 21.2% of citrate-soluble P, (iii) a recovered P from swine manure containing 6.8% of citrate-soluble P, and (iv) a turkey litter ash containing 4.1% of citrate-soluble P. Based on their P concentration values (Table 2), an equivalent of 14.9 g of P in these materials were surface broadcasted on 3 m^2 (i.e., 49 kg P/ha based on soil test recommended P) plots of sandy soil under conservation tillage. The experimental design (Fig. 1) was a Latin square design with 4 replicates (Box, 1980).

A rainfall simulator (Fig. 2a) with a single square full cone nozzle (FullJet ½ HH-W50SQ) was built and calibrated to simulate a 56 mm/h rain which corresponds to an annual storm rate within the study region (NOAA Atlas 14). The plot size (i.e., 1.5 m × 2 m) and the rainfall simulator were designed in accordance with previous plot-scale runoff studies (Sharpley and Kleinman, 2003; Humphry et al., 2002; Miller, 1987; Meyer and Harmon, 1979). The pressure-intensity curve of the FullJet nozzle (Fig. 2b) and a rainfall intensity distribution test (Fig. 2c) were considered for calibrating the rainfall simulator. The calibration result is presented in Fig. 2d, which is a heatmap showing a relatively homogenous rainfall intensity distribution over a runoff plot area. A 30-min rain was simulated on each individual plot, and the surface run-off was collected for consecutive 5-min periods (i.e., 0–5, 5–10, 10–15, 20, 25, 30, and 35 min after the rain started). For each 5-min

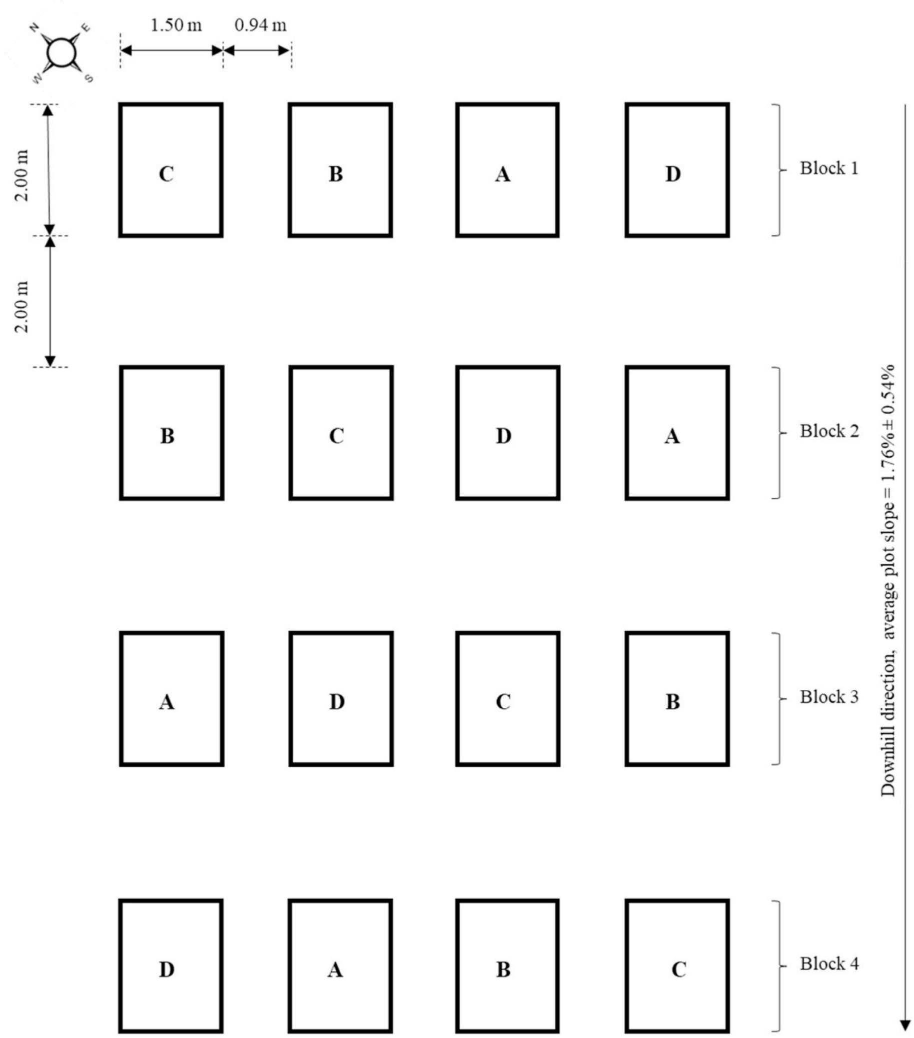


Fig. 1. Experimental design used for the P runoff test on sandy soils under conservation tillage. Treatments include (A) control, (B) triple super phosphate, (C) recovered P from swine manure, and (D) turkey litter ash.

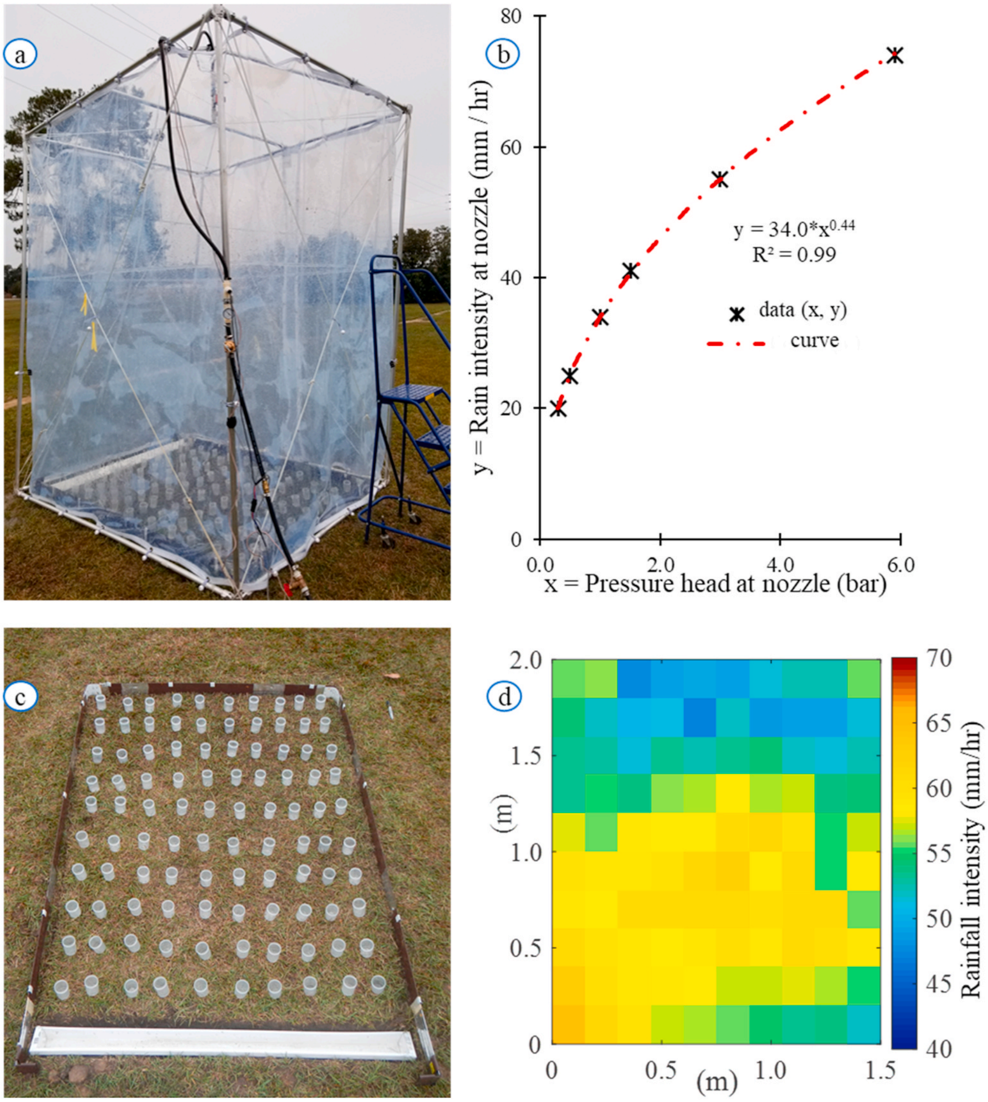


Fig. 2. Rainfall simulator and setting for the rainfall uniformity test (a) designed rainfall simulator (b) pressure versus intensity curve for the FullJet nozzle ½ HH-W50SQ (c) setting of 100 containers for rainfall uniformity test (d) heatmap showing the simulated rainfall intensity distribution over an experimental plot area.

period the surface runoff was captured in a buried gutter and pumped into a container for volumetric measurement, and sub-sampling for laboratory analyses of TP and SRP concentrations. However, the unpumped sediments in the gutter were added to the last runoff sample (i.e., 35 min sample). At the end of the runoff test, composite soil samples were also collected for the top (0–15 cm) and the subsurface (15–30 cm) soil layers of each plot. The soil samples were analyzed to determine soil test P in the soil based on Mehlich 1 extracts using ICP-OES (Kovar and Pierzynski, 2009). These measurements are later used to evaluate the potential effect of the treatments and the soils type on P movement through the soil layers.

2.3. Chemical analyses

Runoff samples were analyzed for TP and SRP content. For TP measurement, the runoff samples were first digested using nitric acid with peroxide (Method 3050 B; EPA, 1996) adapted to a block digester (Peters, 2003). The TP in the digests was later quantified by inductively coupled plasma (ICP-OES) (Standard Method 3125; APHA, 1998). For the SRP measurement, a sub-sample of the runoff was filtered through a 0.45 μm pvdf filter and subsequently analyzed for SRP by the malachite green method (D'Angelo et al., 2001). Particulate P is considered the difference between TP and SRP. Soil test P in the soil was measured in Mehlich 1 extracts using ICP-OES (Kovar and Pierzynski, 2009). Citrate-soluble P in the fertilizer sources (i.e., TSP, recovered P from swine manure, turkey litter ash) were quantified based on the Association of Official Agricultural Chemists (AOAC) method 960.02 (AOAC International, 2000).

2.4. Statistical analyses

The study used two-way analysis of variances (ANOVA) to evaluate the effect of soil, treatment, and their interaction on runoff of TP and SRP. Likewise, this analytical procedure was applied separately to measurements of soil test P in the top (0–15 cm) and subsurface (15–30 cm) soil layers to examine the potential effect of soil and treatments on P movement in the two soil layers. The two-way ANOVA was also applied to evaluate the effect of treatment, time, and their interaction on TP and SRP concentration in the runoff. Nine null hypotheses were tested including (i) H_a: there is no effect of soil on soil test P in top/subsurface soil layers, (ii) H_b: there is no effect of treatment on soil test P in top/subsurface soil layers, (iii) H_c: there is no interaction between soil and treatment for soil test P in top/subsurface soil layers, (iv) H_d: there is no effect of soil on TP/SRP runoff, (v) H_e: there is no effect of treatment on

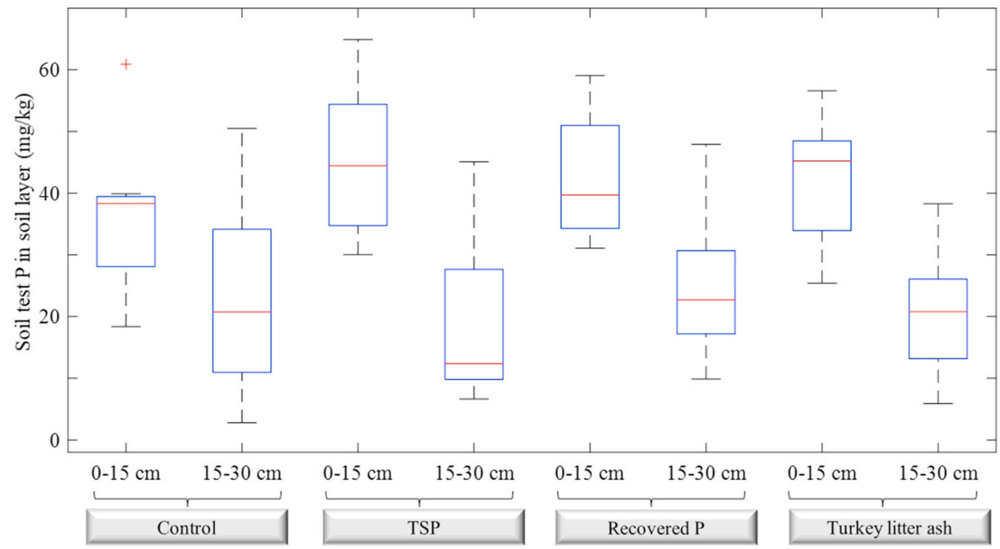


Fig. 3. Boxplots of soil test P in the top and subsurface soil layers following 30 min of rainfall simulation. The top (0–15 cm) and subsurface (15–30 cm) soil layers were separately sampled for each individual plot.

Table 3
Two-way ANOVA showing the effect of soil, treatment, and the interaction soil x treatment on soil test P in the top and subsurface soil layers after the rainfall simulation.

Soil layer	Source of variation	Sum of squares	df	Mean square	F	R	RMSE
Topsoil layer (0–15 cm)	Model	2484.65	7	354.95	1.33ns	0.27	16.33
	Soil	873.62	1	873.62	3.27ns		
	Treatment	656.59	3	218.86	0.82ns		
	Soil x Treatment	954.44	3	318.14	1.19ns		
	Residual	6403.93	24	266.83			
	Total	8888.58	31	286.72			
Subsurface soil layer (15–30 cm)	Model	1402.53	7	200.36	1.36ns	0.28	12.14
	Soil	1149.47	1	1149.47	7.8*		
	Treatment	157.03	3	52.34	0.35ns		
	Soil x Treatment	96.02	3	32.01	0.22ns		
	Residual	3538.88	24	147.45			
	Total	4941.41	31	159.40			

Following ANOVA, ** and * indicate hypotheses of no effect (H_a, H_b, H_c) are rejected at p-value = 0.01 and 0.05 respectively implying a significant effect; ns indicates the hypotheses cannot be rejected at p-value = 0.05.

TP/SRP runoff, (vi) H_f: there is no interaction between soil and treatment for TP/SRP runoff, (vii) H_g: there is no effect of treatment on TP/SRP concentrations in runoff from Noboco and Norfolk soils, (viii) H_h: there is no effect of time on TP/SRP concentrations in runoff from Noboco and Norfolk soils, (iv) H_i: there is no interaction between treatment and time for TP/SRP concentrations in runoff from Noboco and Norfolk soils. These hypotheses were tested at p-value = 0.05 and the outcomes are reported in the results section.

3. Results

3.1. Soil and phosphorus runoff

Fig. 3 presents the boxplots of soil test P measurements in the top (0–15 cm) and subsurface (15–30 cm) soil layers following the rainfall simulation. For the three fertilizer treatments, soil test P concentrations in the topsoil layers are all above the concentration of the subsurface soil layer. However, the disparity between top and subsurface soil layers do not seem specific to the P fertilizer sources given that the control also shows a similar pattern, and both soils were under conservation tillage management. Yet, soil test P in topsoil layers of plots with P fertilizer treatments are above soil test P in the topsoil layers of the control plots (Fig. 3). This suggests the 30 min rain did not cause a substantial movement of P from the topsoil toward the subsurface soil layer. To further evaluate this pattern and elucidate the potential weight of soil types, two-way ANOVA was separately applied to soil test P measurements in the top and subsurface soil layers. Results presented in Table 3, show no effect of soil and treatment in the topsoil layers, but the soil effect was statistically significant in the subsurface soil layer. The two-way ANOVA was also carried out to evaluate the effect of soil, treatment, and their interaction on cumulative TP and SRP runoff. The results presented in Table 3, confirm non-significant soil effects, but a significant treatment effect for both cumulative TP and SRP runoff. On one hand, the results in Tables 2 and 3 sustain that the P fates on soil surface and in the topsoil layers, are similar for both Noboco and Norfolk soils. On the other hand, the results indicate a soil effect on P content in the subsurface soil layer. Additional analyses of the treatments' effect on P wash-off from the soil surface are reported in the next sub-section.

3.2. Treatments and phosphorus runoff

Runoff volumes and TP/SRP concentrations are used to calculate the cumulative TP/SRP washed-off from the plots during the runoff tests. Fig. 4 presents the average values observed at different times during the runoff test. The plotted values include the TP/SRP concentrations in the runoff and the cumulative TP/SRP wash-off from the plots. The graphs

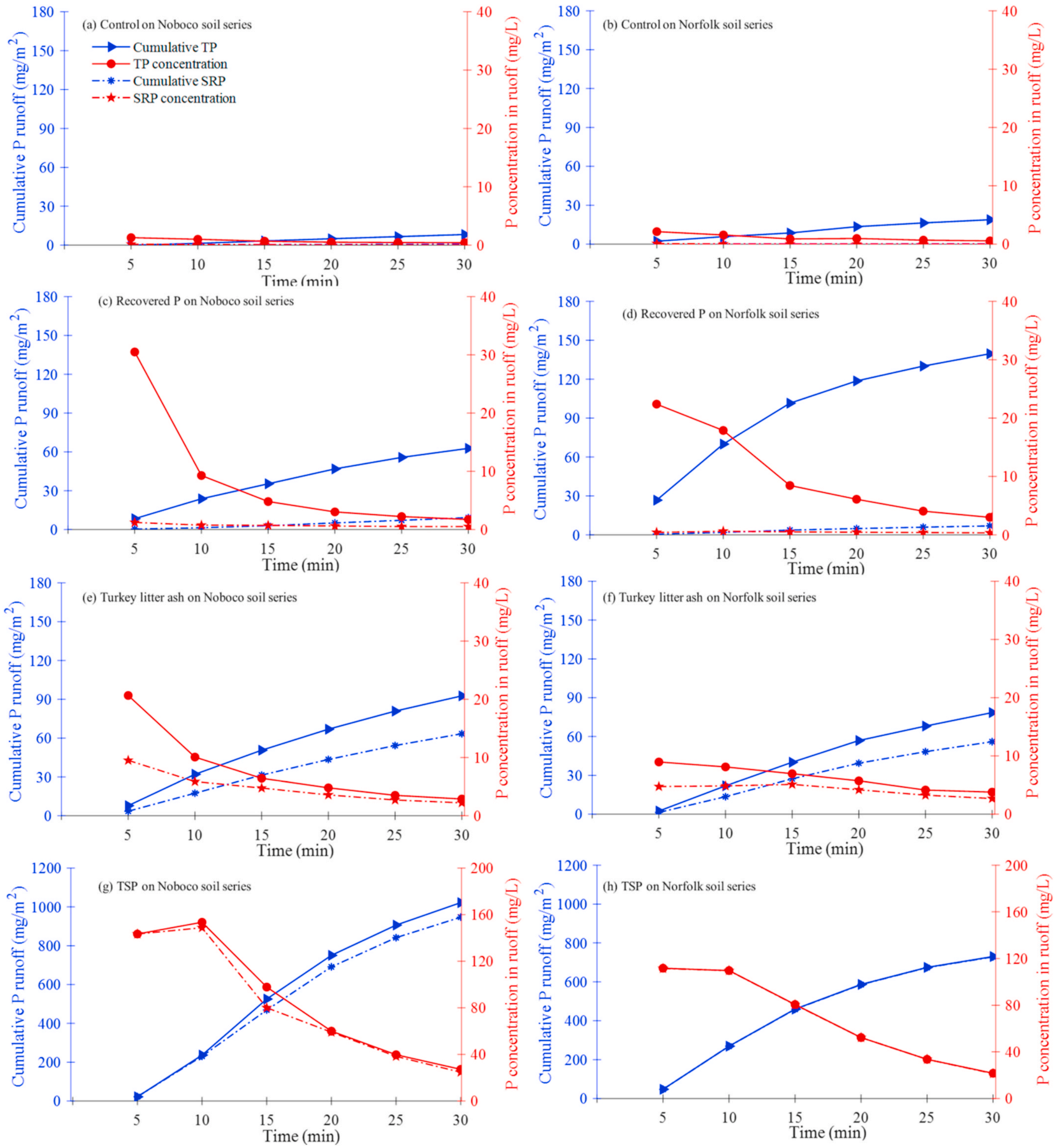


Fig. 4. Cumulative total phosphorus (TP) and soluble reactive phosphorus (SRP) runoff and the related concentrations in runoff water.

reporting separately Noboco and Norfolk soils (Fig. 4), show apparent disparities between treatments. Specifically, for the low water-soluble recycled P sources (i.e., recovered P from swine manure, and turkey litter ash), the amount of TP/SRP wash-off is relatively low compared to the TSP. With all three fertilizer sources, P concentration is high at the beginning of the runoff then it gradually decreases over the time. However, an increase of TP concentration is noted at 35 min because the rain simulation stopped at 30 min, unpumped sediments in the gutter were added to the last runoff sample collected from 30 to 35 min. This last sample (30–35 min runoff) has a higher particulate P (i.e., non-water-soluble P material) and thereby high TP concentration at the end of the runoff test. To further understand the patterns shown in Fig. 4, two-way ANOVA was conducted to evaluate the effect of treatment, time, and their interaction on TP/SRP concentration in the runoff. Results reported in Table 5 show significant effects of treatment, time, and their interaction on TP/SRP concentration in runoff from the Noboco soil. In the case of the Norfolk soil, only the treatment effect was found statistically significant. This contrast between the Noboco and the

Table 4
Two-way ANOVA showing the effect of soil, treatment, and the interaction soil x treatment on cumulative total (TP) and soluble reactive phosphorus (SRP) runoff per square meter.

Variable	Source of variation	Sum of squared	df	Mean Square	F	R^2	RMSE
TP	Model	4364830.9	7	623547.27	11.94*	0.77	228.48
	Soil	19480.42	1	19480.42	0.37 ns		
	Treatment	4151388.3	3	1383796.1	26.51**		
	Soil x Treatment	193962.2	3	64654.07	1.24 ns		
	Residual	1252878.8	24	52203.28			
	Total	5617709.7	31	181216.44			
SRP	Model	4328615.9	7	618373.7	12.25*	0.78	224.66
	Soil	30519.32	1	30519.32	0.60 ns		
	Treatment	4215433.2	3	1405144.4	27.84**		
	Soil x Treatment	82663.45	3	27554.48	0.55 ns		
	Residual	1211352.3	24	50473.01			
	Total	5539968.2	31	178708.65			

Following ANOVA, ** and * indicate hypotheses of no effect (H_d, H_e, H_f) are rejected at p-value = 0.01 and 0.05 respectively implying a significant effect; ns indicates the hypotheses cannot be rejected at p-value = 0.05.

Table 5
Two-way ANOVA showing the effect of treatment, time, and the interaction treatment x time on total phosphorus (TP) and soluble reactive phosphorus (SRP) concentration in the runoff water during the rainfall simulation on Noboco and Norfolk soils.

Soil series	Variable	Source of variation	Sum of squared	df	Mean Square	F	R^2	RMSE
Noboco	TP	Model	136805.29	27	5066.86	6.23**	0.67	28.51
		Treatment	86403.49	3	28801.16	35.44**		
		Time	15156.62	6	2526.10	3.11**		
		Treatment x Time	35245.18	18	1958.07	2.41**		
		Residual	68264.37	84	812.67			
		Total	205069.66	111	1847.47			
	SRP	Model	127248.26	27	4712.90	5.56**	0.64	29.12
		Treatment	81659.64	3	27219.88	32.11**		
		Time	12115.78	6	2019.30	2.38*		
		Treatment x Time	33472.84	18	1859.60	2.19**		
		Residual	71216.74	84	847.82			
		Total	198465.00	111	1787.97			
Norfolk	TP	Model	102857.86	27	3809.55	3.51**	0.53	32.96
		Treatment	64118.76	3	21372.92	19.67**		
		Time	11963.56	6	1993.93	1.83ns		
		Treatment x Time	26775.54	18	1487.53	1.37ns		
		Residual	91277.47	84	1086.64			
		Total	194135.32	111	1748.97			
	SRP	Model	112619.02	27	4171.07	4.02**	0.56	32.21
		Treatment	74000.44	3	24666.81	23.77**		
		Time	10037.75	6	1672.96	1.61ns		
		Treatment x Time	28580.83	18	1587.82	1.53ns		
		Residual	87163.22	84	1037.66			
		Total	199782.24	111	1799.84			

Following ANOVA, ** and * indicate hypotheses of no effect (H_g, H_h, H_i) are rejected at p-value = 0.01 and 0.05 respectively implying a significant effect; ns indicates the hypotheses cannot be rejected at p-value = 0.05.

Norfolk complements the results presented earlier in Table 3 which shows a significant soil effect on soil test P in the subsurface soil layer. However, the significant treatment effect on TP and SRP concentration in runoff from both Noboco and Norfolk soils, aligns with the results in Table 4 which sustains a significant treatment effect regardless of the soil type.

4. Synthesis and discussion

Field experiments quantified and compared the P runoff potential of three P fertilizer sources including recovered P from liquid swine manure, turkey litter ash, and commencial TSP. Based on their citrate-soluble P contents, the three fertilizer sources were equally applied at a rate of 49 kg P ha^{-1} (soil test recommended P) on two different sandy soils under conservation tillage. However, the runoff tests show significant discrepancies in terms of TP and SRP runoff losses. For instance, two-way ANOVA tests show significant treatment effects for the cumulative TP and SRP runoff per m^2. Likewise, the analyses show a significant treatment effect on TP and SRP concentrations in surface runoff. Fig. 5 and Table 6 summarize the average amounts of TP and SRP runoff per unit plot area. The barplot in Fig. 5 clearly highlights the difference between TSP and the recovered P sources. Hence, the quantities of SRP runoff from plots treated with the recovered P from swine manure and turkey litter ash represent respectively 1% and 7–8% of SRP runoff from TSP treated plots (Table 6). While these percentages of SRP in the runoff are very similar for both the Noboco and Norfolk soils, the actual amounts of SRP are relatively higher in the runoff for the Noboco soil.

Although the two sandy soils in this study have the same texture (i.e., loamy sand), an explanation for the soil effect on soil test P concentration in the subsurface layer could be related to slight differences in landscape position, slope, thickness of surface layers, and the presence and depth of a clay layer in the profile (Karlen et al., 1990). However, the fields used in this study have a history of reduced-till management. Therefore, the stratification of soil P is expected to have higher concentrations on the topsoil because of the conservation tillage management. With conventional tillage the broadcast P would be incorporated in the subsurface soil layer (Ye et al., 2020; Cade-Menun et al., 2015; Garcia et al., 2007). Yet, the analyses sustained the 30 min rain did not

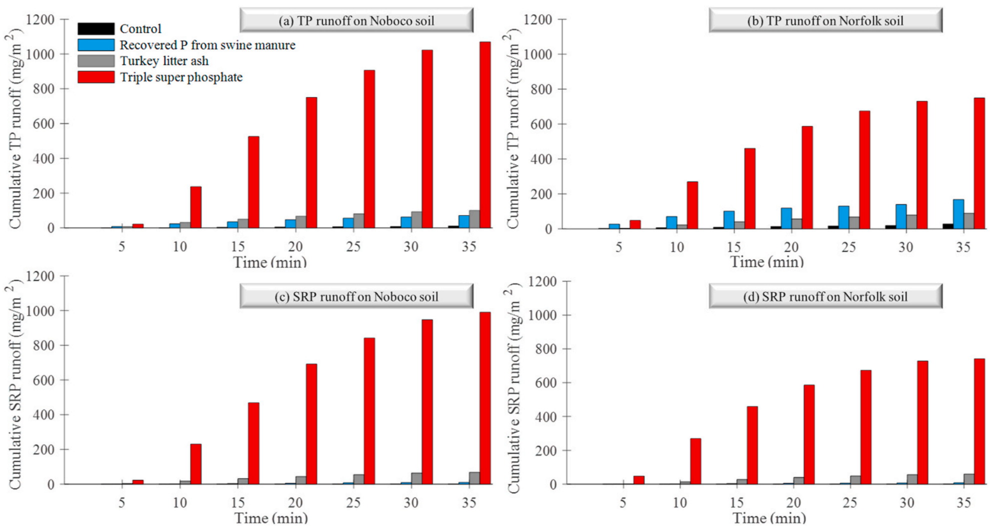


Fig. 5. Cumulative total phosphorus (TP) and soluble reactive phosphorus (SRP) wash-off at different time steps of the runoff test on Noboco and Norfolk soils.

Table 6
Summary of the average P wash-off from the experimental plots following the 30 min artificial rain. Percentages of total phosphorus (TP) and soluble reactive phosphorus (SRP) in columns 5 and 6 are calculated relative to the TSP values.

Soil	Treatments	TP (mg/m^2)	SRP (mg/m^2)	%TP relative to TSP	%SRP relative to TSP
Noboco	Control	10.8	1.1	1%	0.1%
	Recovered P from swine manure	71.5	10.0	7%	1%
	Turkey litter ash	100.2	67.8	9%	7%
	TSP	1069.5	990.5	100%	100%
Norfolk	Control	27.61	0.46	4%	0.1%
	Recovered P from swine manure	168.01	7.47	22%	1%
	Turkey litter ash	88.81	59.66	12%	8%
	TSP	749.01	741.55	100%	100%

cause substantial movement of P from top to subsurface soil layer. This corroborates with the poor P sorption capacity known for southeastern Coastal Plain soils (Novak and Watts, 2004) and their low organic matter contents (USDA-NRCS, 2006). Indeed, studies have shown that soil organic matter contents play a role on P translocation through soil columns (Julich et al., 2022; Kang et al., 2011). In the case of this experiment, the fractions of the P materials remaining on the field after the runoff are essentially concentrated in the topsoil as shown by the soil test P plots in Fig. 3.

From an environmental perspective, the results show that amounts of P translocated through the soil profiles following the broadcast application of the P sources, are negligible compared to the quantity of P washed-off from cropland into the environment via surface runoff. However, the low SRP runoff observed from plots treated with the recovered P from swine manure and turkey litter ash, shows that these two materials would present less environmental risk when used as P fertilizers on sandy soils under conservation tillage. The disparity of SRP runoff among the P sources is likely driven by their water-solubility as Shigaki et al. (2006) reported that P runoff increases linearly with the water-solubility of the P materials. In the present case, the recovered P from swine manure and turkey litter ash are both low water-soluble P sources compared to the commercial TSP (Bauer et al., 2019; Vanotti et al., 2009; Vanotti and Szogi, 2009). Aligning with previous studies which substantiated the inclusion of recycled P materials in P management practices (Kumaragamage and Akinremi, 2018; Sharpley et al., 2004), the use of the recovered P from swine manure and turkey litter ash as P fertilizer on sandy soils under conservation tillage, could become profitable as it reduces P losses from cropland and subsequent risks of water eutrophication (Yin et al., 2020; Barcellos et al., 2019). In addition, these recycled P materials remain a stable plant nutrient source and they can be an alternative to commercial TSP in a circular economy with the potential to enhance soil nutrient management by recycling P from livestock wastes. Despite the Southern Coastal Plain's LRA encompasses a diversity of sandy soil series, these soils have similar textures, poor organic matter contents, and low water-nutrient retention capacity. Thus, the runoff potentials described with Noboco and Norfolk soils will more likely be close to most of these sandy soils of the Southern Coastal Plain's LRA. However, a generalization of the outcomes is limited given that the study did not address interactive effects of continuous applications of non-conventional P materials, P buildup in soil, tillage, and crops on P losses. Yet, further research on these interactive effects is needed for a holistic understanding of the short and long-term environmental benefits of these new non conventional recycled P materials as well as the mechanisms controlling their movement above and through the soil profile.

5. Conclusions

The study shows the P runoff potentials of recovered P from swine manure and turkey litter ash are far below the P runoff potential of TSP. The results indicate the two recovered P-rich materials present less risks of being transported from croplands into the stream network compared to commercial TSP. In particular, the amount of SRP wash-off from plots treated with recovered P from swine manure and turkey litter ash represent small fractions of SRP runoff from plots treated with commercial TSP. The findings of this study are highly relevant for the management of sandy soils of the Southeastern Coastal Plain region known for their poor nutrient holding capacity (Sohoulande et al., 2019, 2020). Indeed, using turkey litter ash or recovered P from swine manure as P fertilizer could be an alternative to enhance soil nutrient management under conservation tillage in the region and substantially increase livestock nutrient recycling at the regional scale. Future research will further investigate the mechanism controlling water-nutrient dynamic in the soil profile as well as the P runoff losses of the recovered P sources.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Disclaimer and acknowledgement

This research was part of USDA-ARS National Programs 211 Water Availability and Watershed Management, Project 6082-13000-010-00D; and 212 Soil and Air ARS Project 6082-12630-001-00D. The authors are grateful to Mr. Tillman Myers, Mr. Don Watts, and Mr. Ohene Okuoko for their assistance with samples collection. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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