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Research article

Impact of broiler litter and swine liquid manure on nutrient loss in runoff from three consecutive one acre-inch rainfall events

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ABSTRACT

Manure is an important source of plant nutrients and organic matter that can benefit soil health over time. However, indiscriminate use of manure can lead to environmental problems including eutrophication of water bodies caused by nutrient runoff during precipitation events. There is a need to understand the effect of manure source and application rate on nitrogen (N) and phosphorus (P) forms and their losses during runoff events. In this study, we assessed the impact of application rate of broiler litter (BL) and swine liquid manure (SLM) on runoff volume, soil, N, and P losses using a rainfall simulator and three consecutive 2.45 cm rainfall events. Surface Decatur silty clay loam (0–0.06 m) was collected and packed in trays (0.55 x 0.30 $\times$ 0.06 m^3). Manure was surface-applied to the soil at equivalent P rates ranging from 62 to 249 kg ha^{-1} for BL and 5–18 kg ha^{-1} for SLM, respectively. Rainfall events took place 7, 14, and 21 d after manure application. Results indicated that the runoff volume decreased at the highest manure application rate compared to the lowest manure application rate. The total suspended solids (TSS) loss was lower in control compared to BL and SLM treatments. The loss of nitrate-N (NO_3-N) dissolved reactive P (DRP) and dissolved organic P (DOP) in runoff water was maximum at the highest application rates for both the BL and SLM with respect to control. Mehlich 3 extractable P (M3P) and water soluble P (WSP) increased with increasing P application rates for both manure types in soils following post rainfall simulation study. An increase in M3P and WSP, along with a decrease in soil P storage capacity following post-rainfall simulation for higher P application rates, indicates caution should be taken for considering the manure application rate to prevent environmental nutrient loss during runoff events.

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1. Introduction

Manure application for agricultural production can be traced back to more than 6000 B.C [1]. Manure is considered a rich source of nutrients and organic matter, which may improve soil health and enhance soil productivity [2,3]. In the US, livestock such as cattle, swine, poultry, sheep, and horses produced manure, that contained approximately 6.44 M and 1.95 M tons of nitrogen (N) phosphorus (P), respectively in 2017 [4].

Manure application to soil can also pose a threat to water quality. The release of nutrients from land-applied manure depends on the forms of nutrients in manure [5], organic carbon content [6], moisture content [7], and manure age [8]. Research has demonstrated that the application of broiler litter (BL) and swine liquid manure (SLM) facilitated the loss of N and P from agricultural fields through runoff due to the presence of nutrients in soluble forms [9–12]. Hoover et al. [13] found that doubling the BL application rate significantly increased the nitrate-N (NO_3-N) concentration in tile drainage with the NO_3-N increasing from 16.2 mg L^{-1} to 25.6 mg L^{-1} for BL application at 168 kg N ha^{-1} and 336 kg N ha^{-1}, respectively. Increased ammonium-N (NH_4-N) and dissolved reactive phosphorus (DRP) loss in runoff was observed following swine manure application by Pote et al. [14]. For example, NH_4-N concentrations ranged from 12 mg L^{-1} to 23 mg L^{-1} with DRP values ranging from 9 mg L^{-1} to 16 mg L^{-1} for low (47.7 m^3 ha^{-1}) and high (95.4 m^3 ha^{-1}) application rates, respectively. Additionally, total phosphorus (TP) comprised more than 80 % of DRP in the runoff generated from manure-treated plots. The adverse impact of such losses of nutrients in runoff on surface water quality has been well-documented [15–17]. Likewise, the loss of sediment rich in nutrients due to erosion can pose a threat to water quality [18–21], contributing to siltation and eutrophication [22]. This may be further aggravated depending on agricultural management practices, particularly tillage [23–25].

Although manure application in the soil can potentially threaten water quality, the influence of manure application sources and their application rate on runoff volume, nutrient species in the runoff water, and their respective loss rates are poorly understood. A study by Sistani et al. [26] found that sediment losses were reduced with the application of BL at 22 kg P ha^{-1} in bermudagrass pastures, compared to a no-manure control. Jatana et al. [27] observed a decrease in soil loss with raw manure and separated liquids at different P application rates (25, 50, 75, and 100 kg P ha^{-1}) with respect to control. On the contrary, many authors have reported that manure application significantly increased runoff volume and sediment loss [28,29]. Given the potential risks associated with manure in agriculture, researchers have prescribed different land application rates for manure, depending on the soil and environmental conditions [12,30,31]. Such findings warrant further research to investigate the effect of animal manure application rates on runoff, sediment, and nutrient loss depending on soil management practices.

Conventional tillage (CT) has been reported to enhance soil erosion and runoff from agricultural fields [32–34], whereas some studies have reported that CT reduced soil erosion and runoff [35–37]. Usually, the impact of tillage conditions on runoff and soil loss is governed by the status of organic carbon and the associated physical properties of soil [38]. It is, therefore, imperative to mention that any soil amendment rich in organic carbon might affect runoff and soil loss depending on the tillage condition. Moreover, studies relating to the impact of manure application on runoff and soil loss under varying tillage conditions are limited [39–41]. We hypothesize that manure source, and their application rates will have differential effects on the runoff volume, soil, and nutrient losses (nitrate-nitrogen ammonium-nitrogen, dissolved reactive P, and dissolved organic P) in runoff under conventional tillage. In the context of the facts mentioned above, the present study evaluated the effect of SLM and BL application at different rates on runoff volume, soil, and nutrient loss in runoff under conventional tillage conditions.

2. Methodology

2.1. Soil and manure collection and characterization

Surface soil (0–0.06 m) was collected from a conventionally tilled field in North Alabama that is managed under a corn (*Zea mays* L.) – wheat (*Triticum aestivum* L.) – soybean (*Glycine max* L. Merr.) in rotation. The BL and SLM for this study were obtained from a poultry farm and swine farm in Alabama, respectively. The BL was a mixture of chicken feces and bedding material whereas SLM was collected from a non-agitated lagoon. Soil pH was determined using deionized water at a 1:1 (w/v) soil-to-water ratio. The pH of SLM was directly measured from a 25 ml uniformly mixed lagoon sample, whereas for BL, 1:2, v/v, was used [42]. Soil and manure total carbon (TC) and total nitrogen (TN) were analyzed by dry combustion [43] using a CHNS analyzer (Vario Max, Elementar, Germany). Manure total digestible P, K, Ca, Mg, and S were determined with USEPA Method 3050B using a microwave digester [44] followed by analyzing digest in inductively coupled plasma optical emission spectrometry (ICP OES; Spectro Ciros, Spectro Analytical Instruments Inc.). Water soluble P (WSP) was determined by extracting soil samples with deionized water at a 1:10 soil/water ratio. Total P in soil was analyzed using aqua regia with Na_2CO_3 fusion [45]. The WSP was analyzed using an autoanalyzer (FIAlab Instruments Inc., Seattle, WA) by the Murphy & Riley [46] procedure (USEPA, 1983, Method 365-1). Extractable soil P, K, Ca, Mg, Fe, and Al were determined using Mehlich-1 (0.0125 M H_2SO_4 + 0.05 M HCl) [47] and Mehlich 3 solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0.001 M EDTA) [48]. An additional soil subsample was submitted to the Analytical Lab and Maine Soil Testing Laboratory to conduct the Cornell Morgan test. Both soil test extractants (Melich 1 and 3) are commonly used in the Mid-Atlantic and southeastern states of the US. Mehlich 1 is a common soil test for Alabama soils whereas Morgan is used in New York and northeastern states. Soil NO_3-N and NH_4-N were extracted using 2M KCl (1:5 soil: solution) [49] and analyzed using the FIAlyzer-1000 flow injection analyzer (FIA Labs).

2.2. Rainfall simulation

Soil was air dried and mixed uniformly before packing into the trays. The soil was packed in trays (0.16 m^2) to mimic the bulk density (1.22 g cm^{-3}) of surface soil at the farm. Each tray received 10.2 kg of soil. According to Jatana et al. [27], soil pans were kept at a slope of 12.5 %, to facilitate the runoff. The BL and SLM were applied uniformly to the surface of the soil at four application rates (BL: 2.2, 4.5 6.7, and 8.9 Mg ha^{-1} and SLM: 47, 94, 140, and 187 kL ha^{-1}). The corresponding P application rates for BL were 62, 124, 186, and 249 kg ha^{-1}. In case of SLM, P application rates were 5, 9, 14, and 18 kg ha^{-1}. A control with no manure application was also included. Each treatment was replicated three times for a total of 30 trays. After broadcasting the manure, the trays were kept at room temperature (77 ± 2 °F) throughout the experiment inside the Auburn University facility.

Rainfall simulation studies were conducted using a portable 5-tray (0.55 x 0.30 × 0.06 m^3) rainfall simulator (Fig. S1 Conservation Demonstrations Inc., Salina, Kansas) described in NRCS (2020). The simulator consisted of a nozzle (orifice size 20 mm), a remote-controlled valve, pressure regulators, 3.8 L plastic bottles, and a connecting rod. A pressure of 0.2 bar was set for the nozzle operating on an oscillator motor to deliver a one-acre inch of rainfall to all the trays. The distance of the nozzle from the top of the trays was kept at 1.5 m so that each tray received one inch (0.0245 m) of rainfall. The nozzle distance to the tray also considered the rod's length and the frame's width so that the oscillating nozzle can equally overshoot the rain on both sides of the frame to initiate the runoff. Runoff was collected through a V-shaped gutter, which was inserted in the soil trays at the downslope of each tray to collect the runoff water. The V-shaped flume was accompanied by a transparent square-shaped canopy or plexiglass to exclude the direct input of rain into 3.8 L plastic runoff bottles. Before starting the simulation, the simulator was calibrated inside a closed room by running nine calibrations performed on empty soil pans. This procedure allowed for the determination of a target time of rainfall for each pan position. Time to receive one inch (2.45 cm) of rain for soil trays from the left to the right side of the simulator were 536, 548, 533, 624, and 649 s and each tray was covered with a transparent cover at the specified time for that particular soil tray.

For every rainfall simulation, soil trays were subjected to 2.45 cm of rainfall, and successive rainfall events were conducted 7, 14, and 21 days after manure application on the same soil trays. After every rainfall simulation, the trays were kept on the shelves indoors. The jars in front of the pans collected the runoff water, whereas the jars underneath the pans collected the infiltrate. The collected runoff was measured, shaken, subsampled to 0.5 L bottles, and stored at 4 °C until laboratory analysis. Runoff sub-samples were used to determine soil (sediment) loss and nutrient content. Infiltration was negligible in our study, hence no sample was collected for infiltration.

2.3. Runoff, soil, and nutrients

Total suspended solids (TSS) referred to hereafter as soil loss, was determined by filtering 70 ml runoff water through 1.6 μm pre-weighed filter paper and weighing again after drying at 105 °C in a forced-air drying oven for 60 min [50].

Nitrate-N and NH_4-N in water samples were determined by passing a subsample of runoff water through 0.45 μm filter paper and determined colorimetrically using a FIAlyzer-1000 flow injection analyzer (FIAlab Instruments Inc.). The total water-soluble inorganic N (TIN) load was calculated by multiplying concentration (NH_4^+ -N + NO_3^- -N) and total runoff volume.

Three species of P in runoff water were investigated in this study to understand the dominant P species transported with runoff water as a result of manure type and P application rate. These species were DRP, dissolved organic P (DOP), and total particulate P (TPP).

The DRP in runoff water samples was determined using Murphy and Riley procedure [46] by passing a subsample of runoff water through a 0.45 μm filter paper and determined colorimetrically using a FIAlyzer-1000 flow injection analyzer (FIAlab Instruments Inc.). A 5 ml aliquot of the filtered (0.45 μm filtered) and unfiltered runoff were digested with 5 ml nitric acid (1:1) at 60 °C for 30 min, followed by the addition of 3 ml of 30 % hydrogen peroxide. Digestion ended with a clear or pale supernatant color. This extract or supernatant was filtered through Whatman no. 42 filter paper, and extracted P was determined for TP and total dissolved P (TDP) using inductively coupled plasma optical emission spectrometry (ICP OES) [44].

2.4. Calculations

The 2.45 cm of rainfall is equivalent to 4198 ml amount of water for a 0.16 square meter soil pan. All five runoff bottles used are 3.8 L in capacity and marked with tape at a 3000 ml level. Following this, the rainfall simulator was run nine times using a stopwatch to record the time (minutes and seconds) required to fill each runoff bottle to the 3000 ml mark. Afterward, the following conversion was used to measure the time needed to generate 4198 ml rainfall for each tray: 4198 ml × (time measures to reach 3000 ml mark)/3000 ml.

Total particulate P (TPP) was calculated as the difference between TP and TDP, while DOP was estimated by subtracting DRP from TDP [51]. The runoff load for individual nutrients was determined by multiplying the runoff volume with the respective nutrient concentrations. Likewise, soil load was determined by multiplying soil concentration per ml with the runoff volume.

Soil phosphorus storage capacity (SPSC) was calculated using M3 extractant [52,53]. We calculated the SPSC for all P rates to understand the P release behavior of soil post-manure application. SPSC was calculated using:

$$SPSC_{M3}\ (\mathrm{mg\ kg^{-1}}) = PSR_{M3}\ \mathrm{Threshold} - \mathrm{Soil}\ PSR_{M3} \times (\mathrm{M3\text{-}Fe} + \mathrm{M3\text{-}Al}) \times 31 \qquad (1)$$

where, PSR in Eq. (1) is determined by using Eq. (2)

$$\text{Soil } PSR_{M3} = \text{Extractable-P}/[(\text{Extractable-Fe}) + (\text{Extractable-Al})] \quad (2)$$

PSR_{M3} Threshold is set to 0.1 for the southeastern United States [53], Soil PSR_{M3} is calculated using Mehlich3 extraction, M3-Fe is the Mehlich3 extractable Fe, M3-Al is the Mehlich3 extractable Al, and 31 is the conversion factor.

2.5. Statistical analysis

The experiment was set up in a randomized complete block design with three replications of five treatments of BL and SLM. The data were analyzed individually for each manure type using PROC GLIMMIX of SAS version 9.4 (SAS Institute, 2013). Replications (block) were considered random effects, whereas application rate, rainfall timing, and their interactions were considered fixed effects in the model. Treatment means were separated using Tukey-Kramer adjusted at 0.05 level of significance. Shapiro-Wilk test was used to check the normality assumption. When the residuals followed a Gaussian distribution, data were not transformed. Lognormal distribution was used when residuals were not normally distributed.

3. Results and discussion

3.1. Manure and soil characteristics

The soil had 0.1 % nitrogen and 1.1 % carbon (Table 1). The soil was Decatur silty clay loam (fine, kaolinitic, thermic Rhodic Paleudults), which is a dominant soil series in North Alabama [54]. The soil had 43 % sand, 45 % silt, and 13 % clay. The bulk density was 1.22 g cm^{-3}. Mehlich 1 (M1) soil test reported 23 mg kg^{-1} extractable P and 132 mg kg^{-1} extractable K. The corresponding Mehlich 3 (M3) extractable P and K values were 52 and 193 mg kg^{-1}, respectively. The Cornell Morgan test reported extractable P and K as 2 and 93 mg kg^{-1}, respectively. The soil pH was in acidic range whereas the pH of SLM and BL were 7.5 and 6.5, respectively (Table 2). Additionally, the BL (moisture content: 25 %) had a greater fertilizer grade (3-6-4) in contrast to SLM (0.03-0.02-0.05).

3.2. Runoff

The mean runoff volume obtained by taking average of runoff on individual rainfall events was lowest for control and greater for BL application treatments (Fig. 1A). The application of BL at 62, 124, 186, and 249 kg P ha^{-1} significantly increased the runoff volume by 55 %, 32 %, 31 %, and 27 %, respectively, compared to the control (0 kg P ha^{-1}). Further, BL application at P rates >124 kg P ha^{-1} significantly reduced runoff volume to that at the lowest rate (62 kg P ha^{-1}). Higher runoff volume from BL-amended soils compared to control might be due to the formation of a hydrophobic waxy layer at the soil surface, facilitating the runoff [55]. Generally, this layer is formed with the decomposition of organic matter which produces organic acids causing soil hydrophobicity. Sometimes the formation of hydrophobic compounds (necessary to initiate water repellency) might not be in equal proportion to the total organic carbon applied [56] and could lead to inconsistent water repellency. Even though hydrophobicity should increase with increasing BL application rates in this study, the raindrop (kinetic energy) and soil or litter interaction might have resulted in differences in runoff volume at varying BL application rates in our study.

In case of swine liquid manure (SLM) treatments, runoff volume from the lowest P (5 kg ha^{-1}) application rate (169×10^3 L ha^{-1}) differed significantly at ($P < 0.05$) from the highest P (18 kg ha^{-1}) application rate (125×10^3 L ha^{-1}) with no difference among all other SLM rates (Fig. 1B). The decrease in the runoff losses between the lowest and highest SLM application rates could be supported by the fact that organic matter from the manure can enhance the water retention and reduce runoff [9,12,57,58].

Irrespective of SLM and BL treatments, runoff losses were affected by the rainfall sequence (Fig. 1C and D). In case of BL, there was a significant increase in runoff at 14 days after application (DAP14) of BL and 21 days after application (DAP21) of BL compared to the 7 days after application (DAP7) of BL. As far as SLM is concerned, a significant difference in runoff volume was observed among the three rainfall events, accounting for the lowest (108×10^3 L ha^{-1}) and the highest (184×10^3 L ha^{-1}) runoff volumes on 1st and 3rd rainfall

Table 1
Chemical characterization of soil.

Soil properties	Units	Values		
Soil pH (1:1)		5.0		
Organic matter	%	2.7		
TC	%	1.1		
TN	%	0.1		
Total P	μg g^{-1} soil	400		
Extractable Nutrients		**Morgan**	**Mehlich-1**	**Mehlich-3**
Extractable P	μg g^{-1} soil	2.0	23	52
Extractable K	μg g^{-1} soil	93	132	193
Extractable Ca	μg g^{-1} soil	809	675	1063
Extractable Mg	μg g^{-1} soil	47	47	49
Extractable Al	μg g^{-1} soil	46	97	938
Extractable Fe	μg g^{-1} soil	1.0	3.0	92

Table 2
Chemical characterization of animal manure and their corresponding phosphorus application rate. Broiler litter (BL) and swine liquid manure (SLM) were applied on a fresh basis.

Parameters	BL (g kg^{-1})	SLM (g l^{-1})	BL Application rate (Mg ha^{-1})	Nutrients applied in BL (kg ha^{-1})	SLM Application rate (kL ha^{-1})	Nutrients applied in SLM (kg ha^{-1})
Total N	31	0.3	2.2	69	47	22
			4.5	139	94	45
			6.7	208	140	67
			8.9	278	187	90
Total P	27.7	0.2	2.2	62	47	5
			4.5	124	94	9
			6.7	186	140	14
			8.9	249	187	18
Total K	33.2	0.5	2.2	74	47	19
			4.5	149	94	37
			6.7	223	140	56
			8.9	298	187	75
Total Ca	37	0.1				
Total Mg	7	0.1				
Total S	2	<0.1				
pH	6.5	7.5				
Total C	410	12				
Moisture content (%)	25	99.8				

event, respectively. The limited soil depth (0.06 m) in pans could be a possible reason.

As the weekly rainfall events continued, soil in pans gradually became saturated, and consequently, raindrops could not move vertically downward in the tray of 0.06 m depth. Also, the increase in runoff volume in the subsequent rainfall events compared to the initial rainfall might be because of the increased splash erosion, which promoted surface sealing and reduced infiltration. Another factor influencing runoff volume was the higher antecedent moisture at 14 days after application of manure (BL and SLM) compared to the air-dried soil in the initial rainfall. However, the present study disagreed with the SLM and BL studies done by Edwards & Daniel [59] and Edwards et al. [60] respectively, on-field scales; they found no effect of the first rainfall event after 7 days over the runoff amount with the application rate of 220 kg N ha^{-1} (SLM) and 218 kg N ha^{-1} (BL), which means no sealing or organic matter effect was evident with application of BL and SLM.

3.3. Total suspended solids (soil loss)

We found a significant effect for BL application rate as well as rainfall events on soil loss (Table S1). The soil loss followed a similar trend as runoff volume. Additionally, soil loss did not show any trend with increasing P application rate but was significantly greater than the control (Fig. 2A). Higher soil loss in the BL treatments compared to the control can be attributed to the lightweight litter particles, which washed off with runoff water. This finding is in alignment with the findings of Kleinman & Sharpley [11] and Tabbara [61]. However, the findings of the present study contradicted a study carried out by Cui et al. [62] and Giddens & Barnett [63], where high litter application on fallow plots resulted in a decrease in soil loss compared to the no-litter fallow plot.

In case of SLM, application rate and rainfall events impacted soil loss and their interaction effect was not significant (P=0.83) (Table S1). The soil loss increased with increasing P application rate and then decreased at the highest P application rate (18 kg P ha^{-1}) (Fig. 2B). The soil loss was 665, 1457, 1644, 1597, and 872 kg ha^{-1} at SLM application of 0, 5, 9, 14 and 18 kg P ha^{-1}, respectively. A possible explanation for greater soil loss with increasing P application rate could be the surface sealing effect induced by liquid manure application [64]. However, at the highest P rate, surface stabilization due to organic matter accumulation (SML had 12 g/L total dissolved carbon) might have led to better infiltration and less runoff [61,65–67]. Gessel et al. [68] also found significantly lower soil loss with a SLM application rate twice the corn P requirement compared to lower application rates. However, Tabbara [61] observed no significant effect of manure and fertilizer application on the soil loss, but average losses from broadcasted manure were lower than the fertilizer broadcasted plot after 24 h of rainfall event.

For both manure types, soil loss during the first rainfall event was significantly lower than the second and third rainfall events (Fig. 2C and D). The water content of SLM caused the pre-wetting of soil [69] and enhanced the settling of readily transportable fine particles on the soil surface. This minimized erosion during the initial rainfall event. With regards to BL treatments, the dry soil readily absorbed the precipitation during 1st rainfall event and reduced the runoff volume. However, during the 2nd and 3rd rainfall event, soil pores were partially saturated with water from the 1st rain event. Additionally, the formation of the hydrophobic surface crust on topsoil (formed due to the wetting and drying cycle) impeded the raindrops from penetrating the soil surface, thereby increasing runoff [70,71] and soil loss from the surface layer with both BL and SLM application rates.

3.4. Nitrogen losses

Application rate and rainfall event impacted NH_4-N and NO_3-N losses (P < 0.05; Table S1) from both BL and SLM applications.

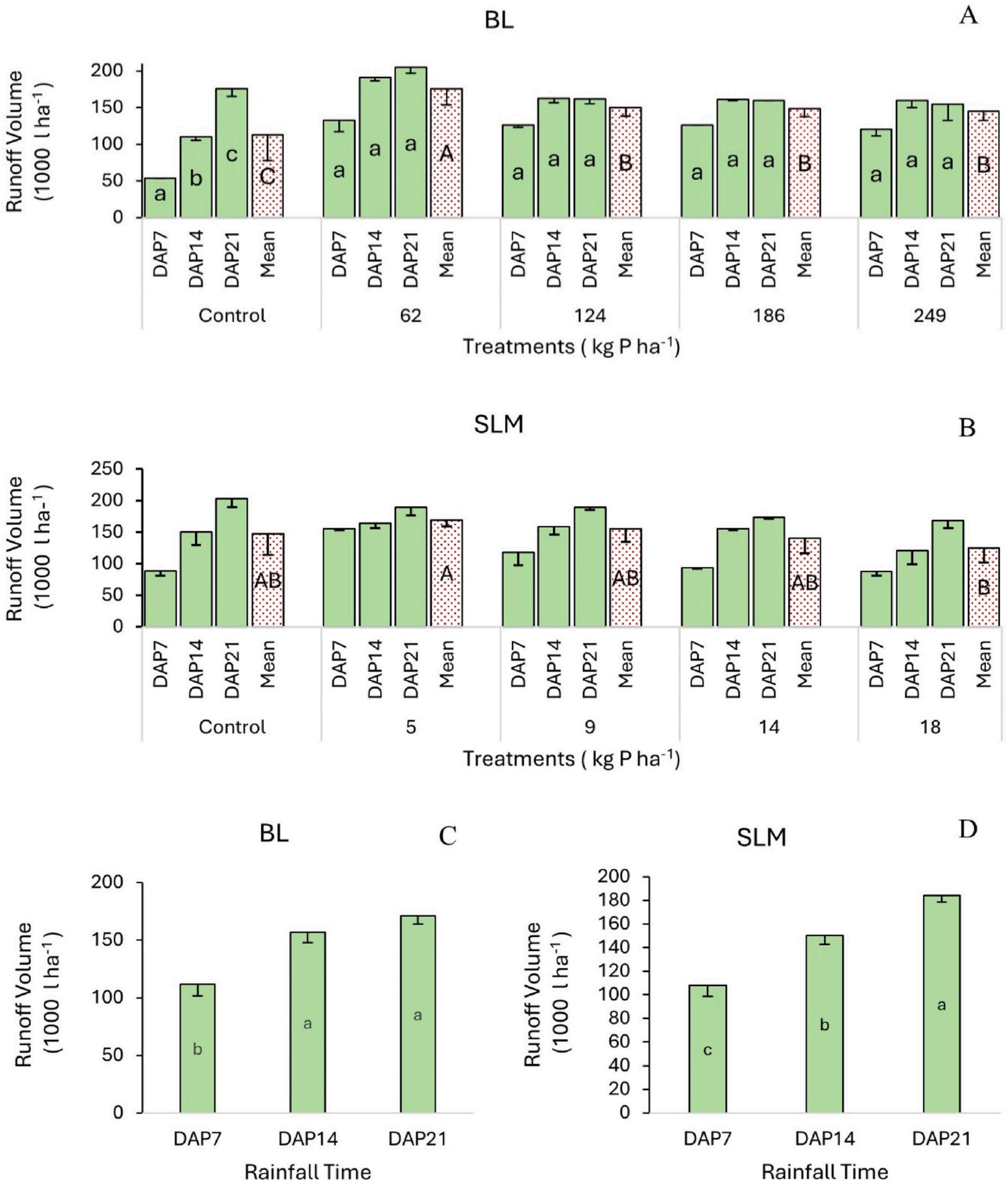

Fig. 1. Runoff volume at different application rates (A, B) and rainfall events (C, D) for broiler litter (BL) and swine liquid manure (SLM), respectively. DAP indicates days after application. Bars with small letters indicate a significant difference ($P < 0.05$) for interaction between rate x rainfall events (A). Bars with capital letters indicate a significant difference among P application rates in (A) and (B). Bars represented by different small letters indicate a significant difference ($P < 0.05$) for different rainfall events in (C) and (D). Error bars represent the standard error of the mean.

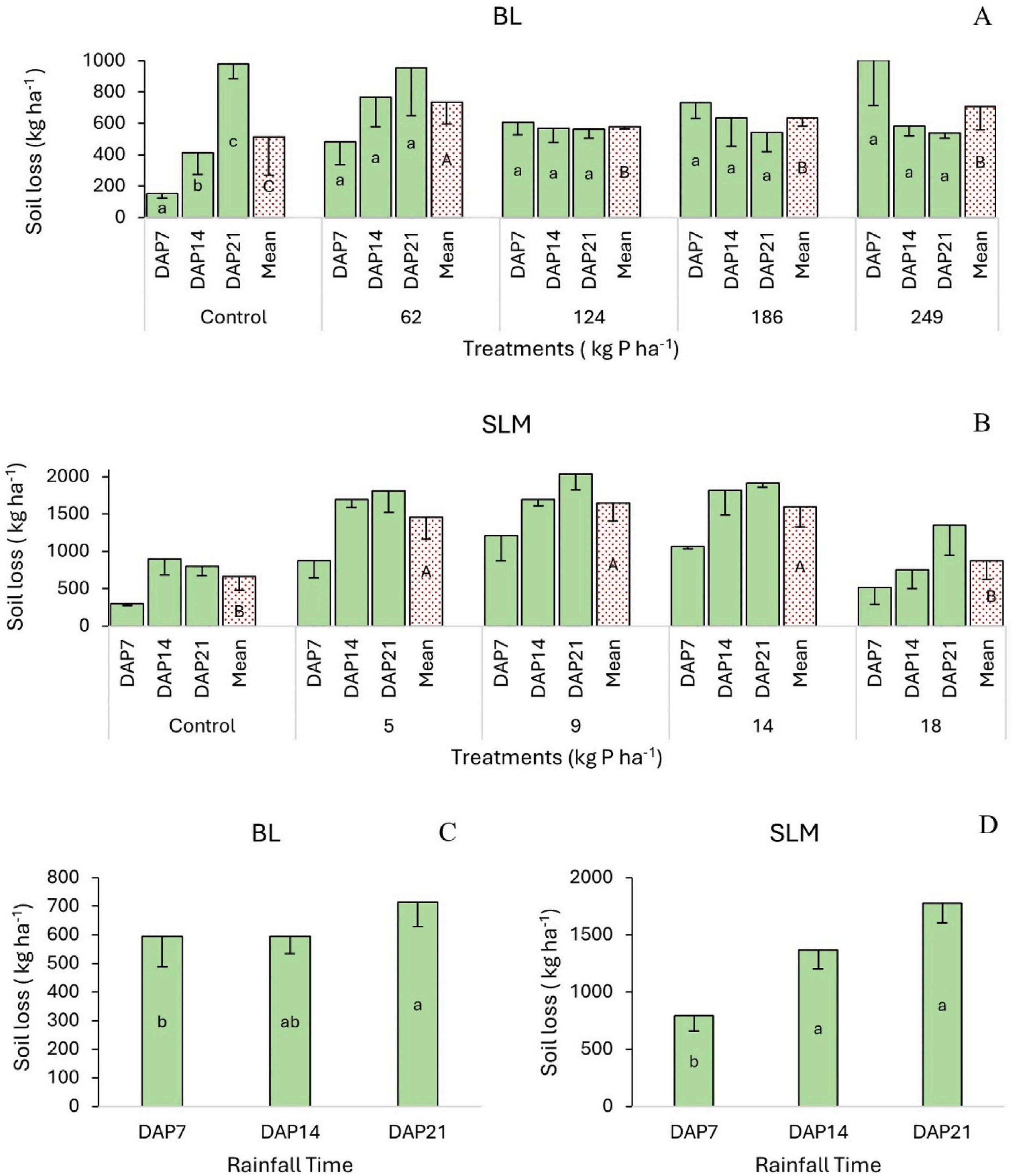

Fig. 2. Soil loss at different application rates (A, B) and rainfall events (C, D) for broiler litter (BL) and swine liquid manure (SLM), respectively. DAP indicates days after application. Bars with small letters indicate a significant difference ($P < 0.05$) for interaction between rate x rainfall events (A). Bars with capital letters indicate a significant difference among P application rates in (A) and (B). Bars represented by different small letters indicate significant a significant difference ($P < 0.05$) for different rainfall events in (C) and (D). Error bars represent standard error of the mean.

However, their interaction effect was also significant ($P < 0.05$). Although insignificant, increasing trends in NO_3-N load over time were observed in the control, suggesting soil organic N mineralization during the study. The NH_4-N and NO_3-N load in the runoff water was primarily driven by their concentration and less with runoff volume (Supplementary Fig. S2). On average, a higher BL-P

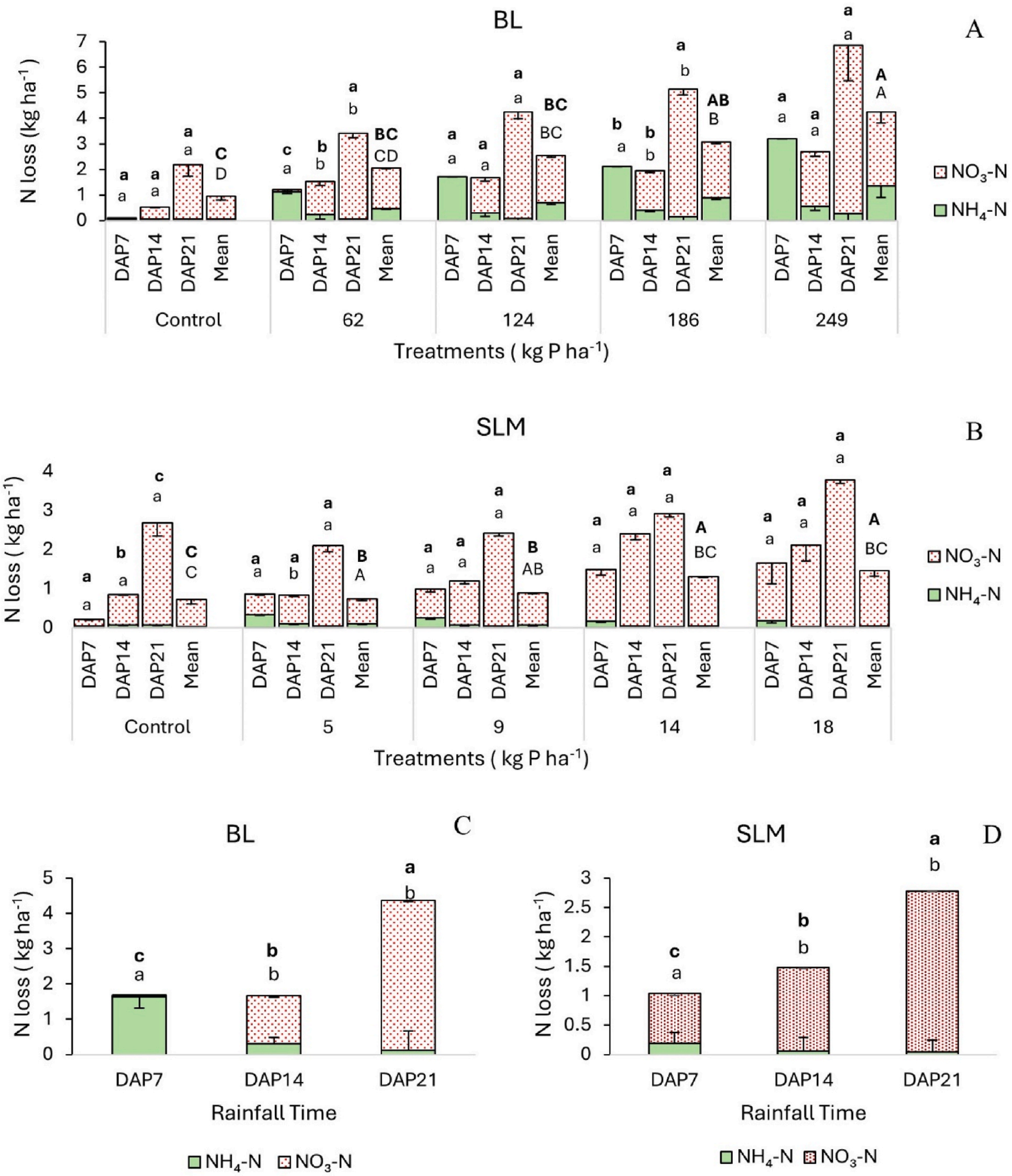

Fig. 3. Nitrogen losses at different application rates (A, B) and rainfall times (C, D) for broiler litter (BL) and swine liquid manure (SLM), respectively. DAP = Days after application. Bars with small letters indicate a significant difference ($P < 0.05$) in NH_4-N for interaction between rate x rainfall events in (A) and (B). Bars with capital letters indicate a significant difference in NH_4-N among P application rates in (A) and (B). Bars represented by different small letters indicate the statistical difference ($P < 0.05$) in NH_4-N for different rainfall events in (C) and (D). Bars with small (bold) letters indicate a significant difference ($P < 0.05$) in NO_3-N for interaction between rate x rainfall events in (A) and (B). Bars with capital (bold) letters indicate a significant difference among P application rates in (A) and (B). Bars with small (bold) letters indicate the statistical difference ($P < 0.05$) in NO_3-N for different rainfall events in (C) and (D).). Error bars represent standard error of the mean.

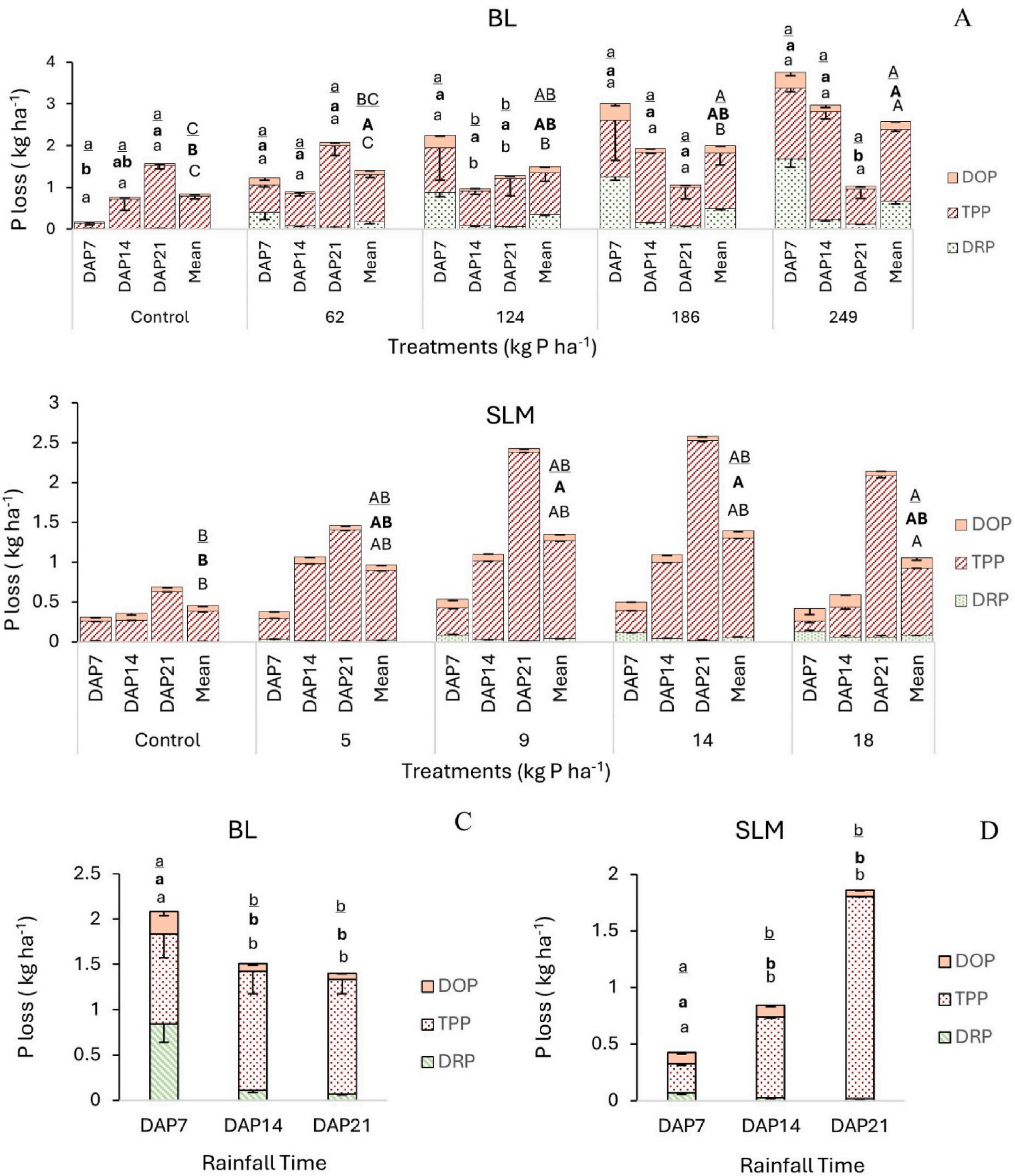

Fig. 4. Phosphorus losses at different application rates (A, B) and rainfall times (C, D) for broiler litter (BL) and swine liquid manure (SLM), respectively. DAP = Days after application. Bars with small and capital letters indicate a significant difference ($P < 0.05$) in dissolved reactive phosphorus (DRP) for interaction between rate x rainfall events and among means, respectively in (A) and (B). Bars with small letters indicate the significant difference ($P < 0.05$) in DRP for rainfall events in (C) and (D). Bars with small (bold) and capital letters (bold) indicate significant difference ($P < 0.05$) in total particulate phosphorus (TPP) for interaction between rate x rainfall events and among means, respectively in (A) and (B). Bars represented by different small letters (bold) indicate the statistical difference ($P < 0.05$) in TPP for rainfall events in (C) and (D). Bars with small (underlined) and capital letters (bold) indicate significant difference ($P < 0.05$) in dissolved organic phosphorus (DOP) in runoff for interaction between rate x rainfall events and among means, respectively in (A) and (B). Bars with small letters (bold) indicate the statistical difference ($P < 0.05$) in DOP in runoff for different rainfall events in (C) and (D). Error bars represent standard error of the mean.

application rate led to greater NH_4-N and NO_3-N losses (Fig. 3A). However, the proportion of NH_4-N to NO_3-N loss was low for both BL and SLM indicating the runoff was dominated by NO_3-N (Fig. 3A and B). The NO_3-N comprised 95 %, 77 %, 73 %, 71 %, and 60 % of total inorganic N from the BL applications at 62, 124, 186, and 249 kg P ha^{-1}, respectively. For BL, NH_4-N and NO_3-N losses increased

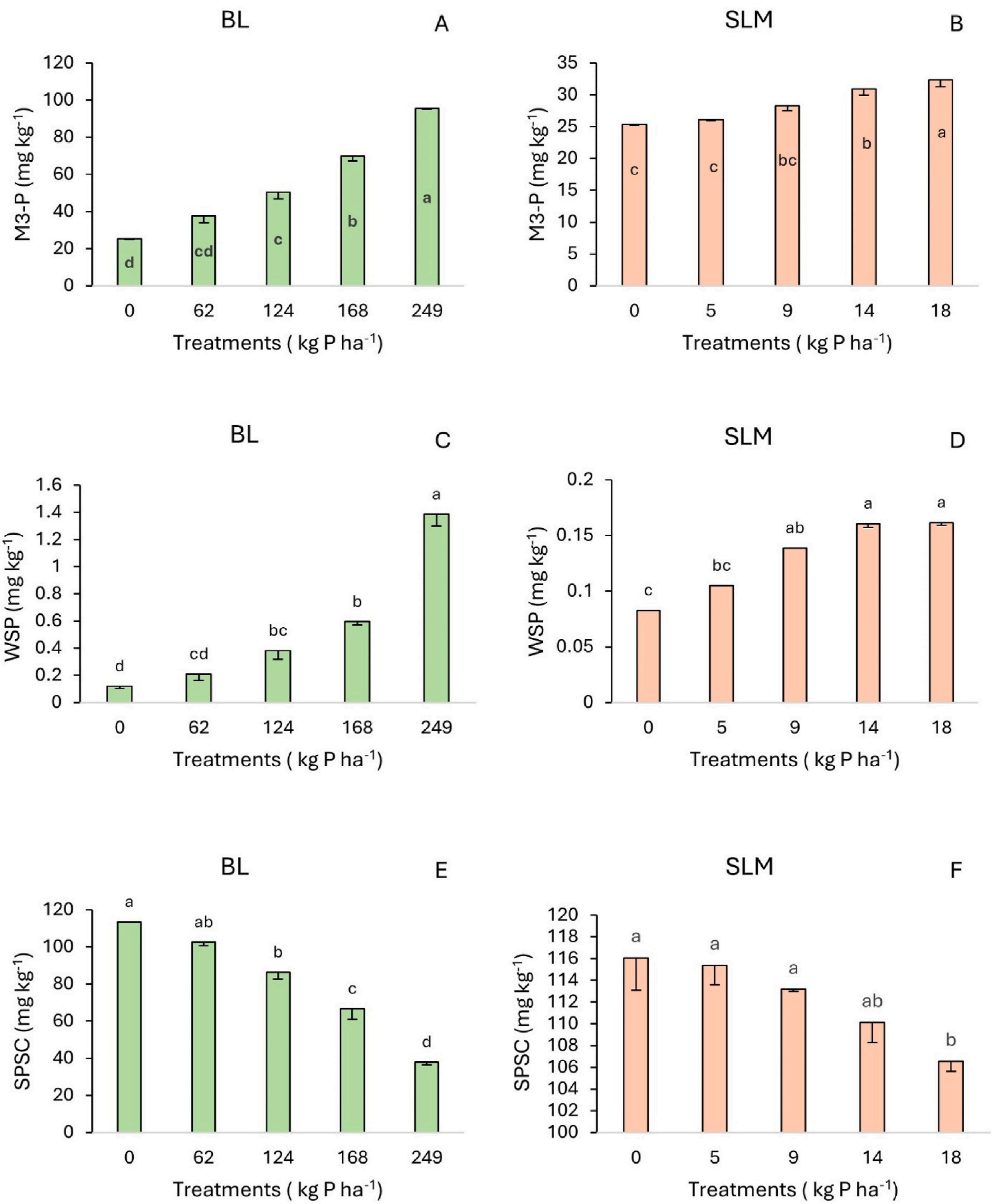

Fig. 5. Mehlich3-P (M3-P), Water soluble P (WSP), and soil phosphorus storage capacity (SPSC) from different application rates for PL; broiler litter (A, C, E) and swine liquid manure; SLM (B, D, F), respectively. Error bars represent standard error of the mean.

with a higher BL application rate. On the contrary, NH_4-N losses in runoff from SLM applications decreased with increased SLM-P application rates, which could be due to the continued ammonia (NH_3) volatilization from the SLM treated soil before the first rainfall event. This decrease with higher SLM application rates was associated with the increased soil water content which favored NH_3 volatilization by providing moist and warm conditions in soil [72]. Although this could be a possible explanation for less NH_4-N loss at higher SLM applications, no direct measurements were taken. However, a progressive increase in NO_3-N was observed with increasing SLM-P application rates. This again could be due to a greater manure P application leading to a significant N application.

The NH_4-N loss in 1st rainfall (DAP7) event was significantly higher than the other two rain events. With repeated rainfall events, NH_4-N losses decreased over time for both manure types (Fig. 3C and D) whereas NO_3-N losses increased. Greater NO_3-N losses in runoff water with subsequent rain events (2 and 3 times higher compared to the 1st rainfall event) can be attributed to nitrification-a process that is common in soil. These findings were consistent with previous studies, which also showed NO_3-N loss increased over time in runoff [59,73,74]. Sharpley [73] observed a similar increase in NO_3-N in the 10th rainfall event which occurred after seven days of BL application. However, NH_4-N concentration in the runoff water was equivalent to those from the control at the end of the experiment. Edwards & Daniel [59] found that NO_3-N loss in rainfall happening after 4 days of SLM application was less compared to the rainfall that occurred after 7 and 14 days of SLM application. Similarly, Smith et al. [74] observed that mean runoff NH_4-N concentrations were decreased temporally for both swine manure and BL. Among all the rainfall events, mean NO_3-N concentrations in runoff reached a peak in rainfall events occurring 8 days after fertilization.

3.5. *Phosphorus losses*

3.5.1. *Phosphorus species in runoff water*

Total particulate P (TPP) was the dominant P species followed by DRP and DOP in both BL and SLM (Fig. 4A and B). Phosphorus in runoff water can be present in both inorganic and organic forms and is bioavailable at different rates in different pools [75]. The DRP is readily bioavailable compared to other P species [76]. The concentration of TPP in runoff water (Supplementary Fig. S3) as well as its load did not increase with increasing P application rate but were significantly greater than control for both BL and SLM. Alabama soils are highly weathered and susceptible to erosion. The addition of manure increased the TSS loss and was greater than control except for SLM at 18 kg P ha^{-1}. However, our results were not in agreement with Allen & Mallarino [9], Gilley & Risse [77], and J. K. Mitchell & R. W. Gunther [78]. Broiler litter application at 22 kg P ha^{-1} was effective in controlling the soil loss from bermudagrass pastures, and the highest losses were observed in control with no manure application [26]. In a swine manure study, Gessel et al. [68] reported that higher application rates (74 m^3 ha^{-1} yr^{-1}) resulted in less soil loss compared to lower application rates (18 and 37 m^3 ha^{-1} yr^{-1}) and control. A similar positive effect of SLM with application levels of 9.5 mm and 19 mm depth on total soil loss compared to control was observed by Gilley & Risse [77]. The SLM treatments had less soil loss than the control due to the high stability of the soil surface caused by SLM application. For both manure types, TPP loss on the 3rd rainfall event was greater than on the 1st rainfall event. (Fig. 4C and D). However, the increase was much higher in case of SLM.

The DRP and DOP losses increased with an increase in the P application rate for both BL and SLM (Fig. 4A and B). The DRP concentration and load in runoff water was highest on the 1st rain event and decreased significantly with 2nd and 3rd rain events for both BL and SLM treatments. This indicates the transformation of P from labile to stable P forms [52,79]. Edwards and Daniel [28] reported that the potential for P loss peaked immediately following P application and then declined over time as the applied P interacted with the soil and was converted from soluble to increasing non-soluble (recalcitrant) forms. Additionally previous studies have reported that BL has more than 50 % P in water soluble form, which is susceptible to loss risk during rainfall events [80].

3.5.2. *Phosphorus concentration post-rainfall simulation*

Soil M3-P and WSP concentrations increased with higher P application rate (Fig. 5A, B, 5C, and 5D) for both BL and SLM. A concomitant increase in M3-P concentration was observed with the increase in BL application rate; however such a trend was absent in case of SLM.

SLM and ranged between 1.5 and 4 times the M3-P concentration in control (0 P kg ha^{-1}). In SLM treatments, the slope of soil M3-P concentration was flat and ranged between 1 and 1.3 times greater than the control. We saw a similar trend in WSP. Soil WSP in BL treatments ranged between 1.7 and 11.5 folds compared to control, whereas in SLM the range was 1.3–2. This clearly indicated that greater P application from BL (0–249 kg P ha^{-1}) resulted in higher M3-P and WSP concentration as opposed to SLM (P application ranged between 0 and 18 kg P ha^{-1}). Smith et al. [74] reported that M3-P values in 0–2 cm soil depth from BL and SLM treatments were approximately 35 mg kg^{-1} and 12 mg kg^{-1} greater than the untreated soils post 1 day after fertilization. M3-P value increased to 107 mg kg^{-1} and 326 mg kg^{-1} in soil receiving BL at the rate of 2.2 Mg ha^{-1} yr^{-1} from the previous 5 and 10 years, respectively [81]. Broiler litter application at 200 kg total P ha^{-1} significantly increased WSP for the 0–5 cm soil depth [58]. It was 23 mg kg^{-1} and 16.2 mg kg^{-1} for BL-amended soils and untreated soils (control), respectively. Bousfield et al. [82] mentioned WSP increased by 149 % with swine manure application at 300 m^3 ha^{-1} yr^{-1} in the surface layer (0–10 cm) compared to the control treatment (WSP:4.58 mg kg^{-1}).

The SPSC values were positive for all P application rates irrespective of manure type (Fig. 5E and F). The SPSC provides an estimation of the remaining capacity of the soil before a condition of elevated P loss risk [83]. The magnitude of SPSC showed a decreasing trend with an increasing P application rate for both BL and SLM amended soils. However, the magnitude of SPSC declined more slowly for SLM than BL because of the differences in the P application rate. Nonetheless, the reduction in SPSC due to a greater P application rate of BL will eventually cause the soil to behave as a P source and could result in greater environmental P losses. Chakraborty et al. [84] have reported an increase in WSP (used as a surrogate for DRP) with increase in negative SPSC for Piedmont soil region of Alabama. Dari et al. [53] have also reported that P concentrations in runoff water are strongly correlated with SPSC and soils with negative SPSC values tend to release higher amounts of P in runoff water.

3.6. *Cumulative soil, TP, and TIN losses due to three-acre inch rain*

The cumulative soil loss over the three-rainfall event showed a linear trend with respect to the BL application rate (Fig. 6A). The cumulative soil loss for BL ranged from 0.9 Mg ha^{-1} for 0 P kg ha^{-1} to 2.12 Mg ha^{-1} for 249 P kg ha^{-1}. In case of SLM, the soil loss increased initially with increasing P application rate but then declined at a higher P application rate (Fig. 6B). A similar observation was reported by Gessel et al. [68] and Zanon et al. [17]. Gessel et al. [68] reported that soil loss in summer was less for SLM application at 56 kg P ha^{-1} yr^{-1} compared to the rate at 28 kg P ha^{-1} yr^{-1} and control. On the other hand, Zanon et al. [17] mentioned that surface application of liquid dairy manure (LDM) at the rate of 180 m^3 ha yr^{-1} significantly reduced the soil loss compared to other LDM application rates. Overall, the decrease in soil load at higher application rates occurred due to the increased organic matter facilitating the soil aggregation. The maximum soil loss observed in SLM was 4.9 Mg ha^{-1} for 9 kg P ha^{-1} application rate and the minimum was 1.99 Mg ha^{-1} for 0 P kg ha^{-1}. The soil loss was 2-fold greater for SLM application than BL even though the P application rate was greater for BL than SLM. The higher soil loss in SLM treatments can be attributed to the higher volume of water in SLM since it is a

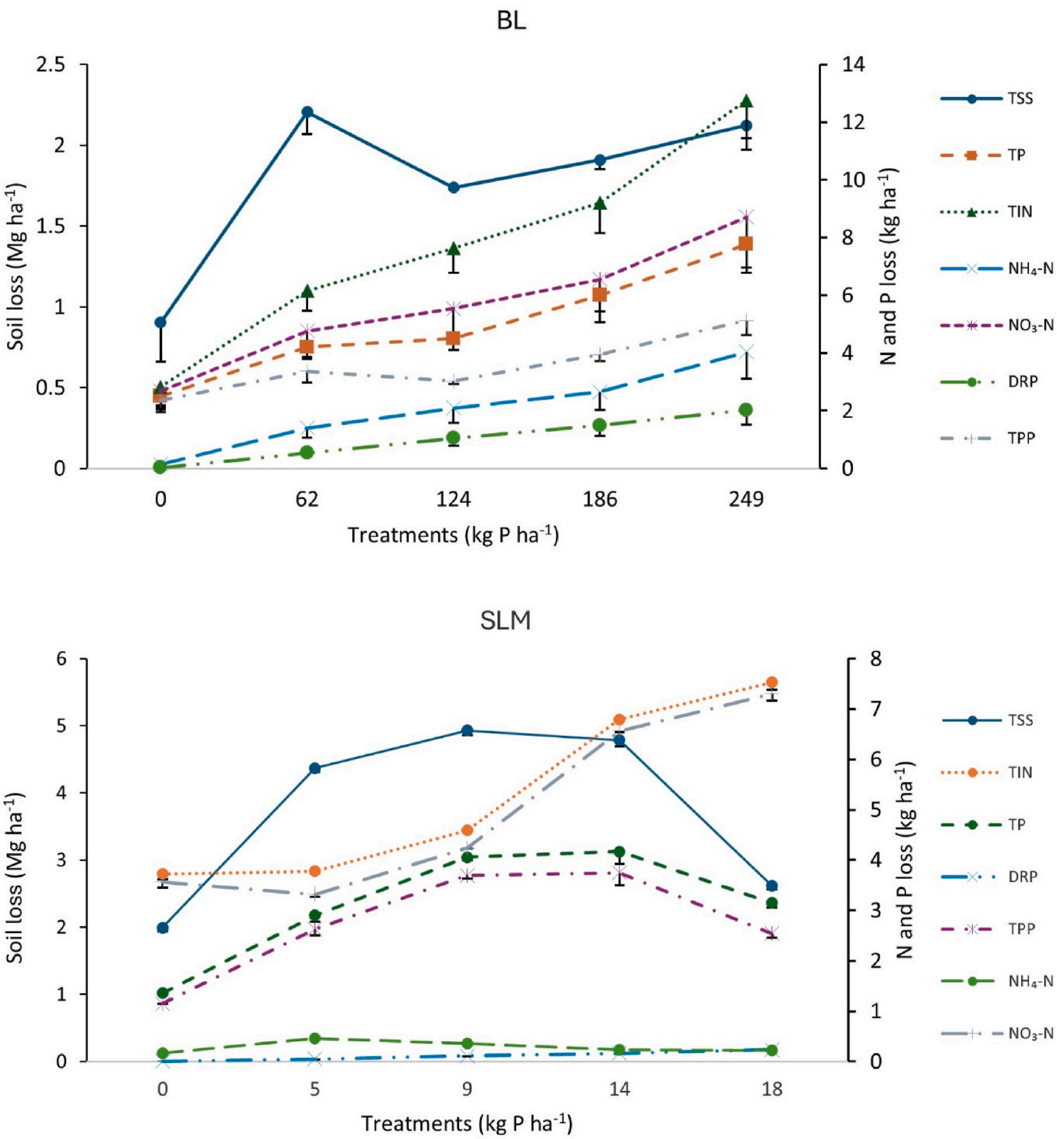

Fig. 6. TSS; soil loss, Cumulative losses (sum across three rainfall events) for soil loss, TP; total phosphorus, TIN; total inorganic nitrogen {sum of ammonical nitrogen (NH_4-N) and nitrate-N (NO_3-N)}, NH_4-N and NO_3-N, DRP; dissolved reactive phosphorus and TPP; total particulate phosphorus as influenced by different application rates of broiler litter (BL) and swine liquid manure (SLM) in (A) and (B), respectively. Error bars represent standard error of the mean.

liquid manure compared to BL which is a solid manure. Additionally, the fine particulate matter in SLM was greater than BL and contributed to greater soil loss with runoff water.

For BL, increasing the application rates increased the TP loss while no such trend was observed with SLM. The cumulative TP losses in BL ranged from 2.5 kg ha^{-1} in the 0 kg P ha^{-1} application rate to 7.7 kg ha^{-1} with the highest P application rate (249 kg P ha^{-1}). On the contrary, the cumulative TP losses in SLM were half of BL and ranged between 1.3 and 3.1 kg ha^{-1} for 0 and 18 kg P ha^{-1} application rate, respectively. Greater TP losses were observed in BL than in SLM because of higher P application with BL. Total cumulative inorganic N loss, which was a sum of NH_4-N and NO_3-N for three rain events, ranged between 6.1 kg ha^{-1} to 12.7 kg ha^{-1} for BL (for 62–249 kg P ha^{-1}) and 3.7 and 7.5 kg ha^{-1} for SLM (5–18 kg P ha^{-1}).

The cumulative DRP, TPP, NO_3-N, and NH_4-N losses for both manure types were calculated considering the sum of the cumulative loss of DRP, TPP, NO_3-N, and NH_4-N in runoff water over three rainfall events, respectively (Fig. 6A and B). Nitrate-N losses increased with increasing P application rate and amounted to 8.7 kg ha^{-1} and 7.3 kg ha^{-1} for the highest P application rates of BL and SLM, respectively. Total particulate P was the dominant P species in runoff water and amounted to a cumulative loss of 5.1 kg ha^{-1} for the highest rate of BL and 3.7 kg ha^{-1} for the 14 kg P ha^{-1} application rate of SLM. Cumulative DRP losses ranged between 0 and 2 kg ha^{-1} for BL and 0 and 0.2 kg ha^{-1} for SLM.

4. Summary and conclusion

Manure application can potentially contribute to nutrient loss during rainfall event due to its impact on runoff and soil loss. Results from the study indicated that maximum runoff volume and soil loss occurred with a BL application rate of 62 kg P ha^{-1}. However, the effect of SLM application on runoff volume was inconspicuous. The TSS loss, with respect to unamended control, increased due to SLM application up to 14 kg P ha^{-1}. The cumulative loss of soil increased with increasing rates of BL and decreased at the higher application rates for SLM. Further, N and P loss was maximum in case for BL application at 249 kg P ha^{-1}. Applying SLM at 18 kg P ha^{-1} resulted in a significantly increased NO_3-N, DRP, and DOP loss over the control. Further, increasing the application rates of BL increased the TP loss while no such trend was observed in case of SLM. The effects of successive rainfall events on runoff and soil loss were also evident in this study. As the number of rainfall events increased, runoff volume gradually increased for both BL and SLM-amended soil. Rainfall events also affected the loss of nutrient species from amended soils. With respect to 1st rainfall event, NO_3-N loss significantly increased, and NH_4-N loss significantly decreased during 3rd rainfall event. For the initial rainfall event, DRP and DOP loss from both the amended soils significantly decreased, while TPP loss increased significantly in the 3rd rainfall event.

We conclude that the application rates of BL and SLM should be decided in such a way that total nutrients or soil loss during runoff events does not surpass the state numeric permissible limits thereby reducing or preventing the environmental risk. Further studies are required to standardize the agronomic and environmental rates of manure application by taking into account the stability of soil to act as a sink or source of P, the economic consideration of manure application, and the inclusion of crop as a part of the system under varying rainfall conditions.

CRediT authorship contribution statement

Chhabi Raj: Writing – original draft, Formal analysis, Conceptualization. **Debolina Chakraborty:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Dexter B. Watts:** Writing – review & editing. **Tibor Horvath:** Writing – review & editing, Funding acquisition. **Quirine M. Ketterings:** Writing – review & editing. **David Blersch:** Writing – review & editing. **Abigail A. Tomasek:** Writing – review & editing. **Bernardo C. Cordoba:** Writing – review & editing, Software, Formal analysis. **Rishi Prasad:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Data and code availability

Date will be made available on request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e40062.

References

[1] A. I Bogaard, R. Fraser, T.H.E. Heaton, M. Wallace, P. Vaiglova, M. Charles, G. Jones, R.P. Evershed, A.K. Styring, N.H. Andersen, Crop manuring and intensive land management by Europe's first farmers, Proc. Natl. Acad. Sci. USA 110 (31) (2013) 12589–12594, https://doi.org/10.1073/pnas.1305918110.

[2] A.A. Ahmad, T.J.K. Radovich, H.V. Nguyen, J. Uyeda, A. Arakaki, J. Cadby, R. Paull, J. Sugano, G. Teves, Use of organic fertilizers to enhance soil fertility, plant growth, and yield in a tropical environment, Organic Fertilizers-from Basic Concepts to Applied Outcomes (2016) 85–108, https://doi.org/10.5772/62529.

[3] G.F. Antonious, Soil amendments for agricultural production, in: Organic Fertilizers: from Basic Concepts to Applied Outcomes, Intech, Rijeka, 2016, pp. 157–187, https://doi.org/10.5772/63047.

[4] US EPA, 2017 estimated animal agriculture nitrogen and phosphorus from manure, in: Office of Water, United States Environmental Protection Agency, 2017.

[5] A. Loss, R. Da, R. Couto, G. Brunetto, M. Da Veiga, M. Toselli, E. Baldi, Animal manure as fertilizer: changes in soil attributes, productivity and food composition, International Journal of Research-Granthaalayah 7 (9) (2019) 307, https://doi.org/10.5281/zenodo.3475563.

[6] K. Azim, B. Soudi, S. Boukhari, C. Perissol, S. Roussos, I. Thami Alami, Composting parameters and compost quality: a literature review, in: Organic Agriculture, vol. 8, Springer, Netherlands, 2018, pp. 141–158, https://doi.org/10.1007/s13165-017-0180-z. Issue 2.

[7] T. Luangwilai, H.S. Sidhu, M.I. Nelson, One-dimensional spatial model for self-heating in compost piles: investigating effects of moisture and air flow, Food Bioprod. Process. 108 (2018) 18–26, https://doi.org/10.1016/j.fbp.2017.12.001.

[8] Z. Ji, L. Zhang, Y. Liu, X. Li, Z. Li, Evaluation of composting parameters, technologies and maturity indexes for aerobic manure composting: a meta-analysis, Sci. Total Environ. 886 (2023) 163929, https://doi.org/10.1016/j.scitotenv.2023.163929.

[9] B.L. Allen, A.P. Mallarino, Effect of liquid swine manure rate, incorporation, and timing of rainfall on phosphorus loss with surface runoff, J. Environ. Qual. 37 (1) (2008) 125–137, https://doi.org/10.2134/jeq2007.0125.

[10] K.W. King, H.A. Torbert, Nitrate and ammonium losses from surface-applied organic and inorganic fertilizers, J. Agric. Sci. 145 (4) (2007) 385–393, https://doi.org/10.1017/S0021859607006946.

[11] P.J.A. Kleinman, A.N. Sharpley, Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events, J. Environ. Qual. 32 (3) (2003) 1072–1081, https://doi.org/10.2134/jeq2003.1072.

[12] D.B. Watts, T. Horvath, H. Allen Torbert, A.O. Adesemoye, Effects of selected manure sources on runoff, soil loss, and nutrient transport, Appl. Eng. Agric. 39 (6) (2023) 565–572, https://doi.org/10.13031/aea.15651.

[13] N.L. Hoover, J.Y. Law, L.A.M. Long, R.S. Kanwar, M.L. Soupir, Long-term impact of poultry manure on crop yield, soil and water quality, and crop revenue, J. Environ. Manag. 252 (2019) 109582, https://doi.org/10.1016/j.jenvman.2019.109582.

[14] D.H. Pote, B.A. Reed, T.C. Daniel, D.J. Nichols, P.A. Moore, D.R. Edwards, S. Formica, Water-quality effects of infiltration rate and manure application rate for, Soils Journal of Soil and Water Conservation 56 (1) (2001) 32–37.

[15] J. Fan, J. Xiao, D. Liu, G. Ye, J. Luo, D. Houlbrooke, S. Laurenson, J. Yan, L. Chen, J. Tian, W. Ding, Effect of application of dairy manure, effluent and inorganic fertilizer on nitrogen leaching in clayey fluvo-aquic soil: a lysimeter study, Sci. Total Environ. 592 (2017) 206–214, https://doi.org/10.1016/j.scitotenv.2017.03.060.

[16] B.K. Odhiambo, T. Coxon, H. Somers, Sediment and phosphorous fluxes analysis in Aquia Creek, a sub-watershed of the Chesapeake Bay basin, VA, USA, Water, Air, Soil Pollut. 229 (7) (2018) 1–15, https://doi.org/10.1007/s11270-018-3886-y.

[17] J.A. Zanon, N. Favaretto, G. Democh Goularte, J. Dieckow, G. Barth, Manure application at long-term in no-till: effects on runoff, sediment and nutrients losses in high rainfall events, Agric. Water Manag. 228 (2020), https://doi.org/10.1016/j.agwat.2019.105908.

[18] D.M. Endale, T.L. Potter, T.C. Strickland, D.D. Bosch, Sediment-bound total organic carbon and total organic nitrogen losses from conventional and strip tillage cropping systems, Soil Tillage Res. 171 (2017) 25–34, https://doi.org/10.1016/j.still.2017.04.004.

[19] A.C. Gellis, F.A. Fitzpatrick, J. Schubauer-Berigan, A manual to identify sources of fluvial sediment, USGS Rep. (2016) 30.

[20] G. Jiang, A. Lutgen, K. Mattern, N. Sienkiewicz, J. Kan, S. Inamdar, Streambank legacy sediment contributions to suspended sediment-bound nutrient yields from a mid-atlantic, Piedmont watershed, J. Am. Water Resour. Assoc. 56 (5) (2020) 820–841, https://doi.org/10.1111/1752-1688.12855.

[21] T.C. Strickland, T.L. Potter, C.C. Truman, D.H. Franklin, D.D. Bosch, G.L. Hawkins, Results of rainfall simulation to estimate sediment-bound carbon and nitrogen loss from an Atlantic Coastal Plain (USA) ultisol, Soil Tillage Res. 122 (2012) 12–21, https://doi.org/10.1016/j.still.2012.02.004.

[22] D.P. Cardoso, M.L.N. Silva, G. J. de Carvalho, D.A.F. De Freitas, J.C. Avanzi, Plantas de cobertura no controle das perdas de solo, água e nutrientes por erosão hídrica, Rev. Bras. Eng. Agrícola Ambient. 16 (2012) 632–638, https://doi.org/10.1590/S1415-43662012000600007.

[23] D. Elias, L. Wang, P.A. Jacinthe, A meta-analysis of pesticide loss in runoff under conventional tillage and no-till management, Environ. Monit. Assess. 190 (2018) 1–17, https://doi.org/10.1007/s10661-017-6441-1.

[24] A. Klik, J. Rosner, Long-term experience with conservation tillage practices in Austria: impacts on soil erosion processes, Soil Tillage Res. 203 (2020), https://doi.org/10.1016/j.still.2020.104669.

[25] A.R. Melland, D.L. Antille, Y.P. Dang, Effects of strategic tillage on short-term erosion, nutrient loss in runoff and greenhouse gas emissions, Soil Res. 55 (3) (2016) 201–214, https://doi.org/10.1071/SR16136.

[26] K.R. Sistani, G.E. Brink, J.L. Oldham, Managing broiler litter application rate and grazing to decrease watershed runoff losses, J. Environ. Qual. 37 (2) (2008) 718–724, https://doi.org/10.2134/jeq2007.0191.

[27] B.S. Jatana, R. Prasad, A. Tomasek, T. Horvath, Q.M. Ketterings, Impact of manure type and rate on soil loss and nutrient mobilization in runoff and infiltrate, Water Air Soil Pollut. 235 (6) (2024), https://doi.org/10.1007/s11270-024-07089-2.

[28] D.R. Edwards, T.C. Daniel, Abstractions and runoff from fescue plots receiving poultry litter and swine manure, Transactions of the ASAE 36 (2) (1993) 405–411, https://doi.org/10.13031/2013.28352.

[29] A. Mishra, B.L. Benham, S. Mostaghimi, Sediment and nutrient losses from field-scale cropland plots treated with animal manure and inorganic fertilizer, Water Air Soil Pollut. 175 (2006) 61–76, https://doi.org/10.1007/s11270-006-9111-4.

[30] A.O. Adekiya, O.I. Ogunboye, B.S. Ewulo, A. Olayanju, Effects of different rates of poultry manure and split applications of urea fertilizer on soil chemical properties, growth, and yield of maize, Sci. World J. (2020) 1–8, https://doi.org/10.1155/2020/4610515, 2020.

[31] R.D. Harmel, H.A. Torbert, B.E. Haggard, R. Haney, M. Dozier, Water quality impacts of converting to a poultry litter fertilization strategy, J. Environ. Qual. 33 (6) (2004) 2229–2242, https://doi.org/10.2134/jeq2004.2229.

[32] L. Carretta, P. Tarolli, A. Cardinali, P. Nasta, N. Romano, R. Masin, Evaluation of runoff and soil erosion under conventional tillage and no-till management: a case study in northeast Italy, Catena 197 (2021), https://doi.org/10.1016/j.catena.2020.104972.

[33] P.B. DeLaune, J.W. Sij, Impact of tillage on runoff in long term no-till wheat systems, Soil Tillage Res. 124 (2012) 32–35, https://doi.org/10.1016/j.still.2012.04.009.

[34] R.S. Kurothe, G. Kumar, R. Singh, H.B. Singh, S.P. Tiwari, A.K. Vishwakarma, D.R. Sena, V.C. Pande, Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India, Soil Tillage Res. 140 (2014) 126–134, https://doi.org/10.1016/j.still.2014.03.005.

[35] M. Busari, F. Salako, Effect of tillage and poultry manure application on soil infiltration rate and maize root growth in a sandy Alfisol, Agro-Science 11 (2) (2013) 24–31, https://doi.org/10.4314/as.v11i2.4.

[36] A.L. Cogle, K.P.C. Rao, D.F. Yule, G.D. Smith, P.J. George, S.T. Srinivasan, Jangawad & L, Soil management for Alfisols in the semiarid tropics: erosion, enrichment ratios and runoff, Soil Use Manag. 18 (2002) 10–17, https://doi.org/10.1079/SUM200194.

[37] C.S. Tan, C.F. Drury, W.D. Reynolds, J.D. Gaynor, T.Q. Zhang, H.Y. Ng, Effect of long-term conventional tillage and no-tillage systems on soil and water quality at the field scale, Water Sci. Technol. 46 (6–7) (2002) 183–190, https://doi.org/10.2166/wst.2002.0678.

[38] N. Mhazo, P. Chivenge, V. Chaplot, Tillage impact on soil erosion by water: discrepancies due to climate and soil characteristics, Agric. Ecosyst. Environ. 230 (2016) 231–241, https://doi.org/10.1016/j.agee.2016.04.033.

[39] M.J. Komiskey, T.D. Stuntebeck, D.R. Frame, F.W. Madison, Nutrients and sediment in frozen-ground runoff from no-till fields receiving liquid-dairy and solid-beef manures, J. Soil Water Conserv. 66 (5) (2011) 303–312, https://doi.org/10.2489/jswc.66.5.303.

[40] L.R. Prasad, A.M. Thompson, F.J. Arriaga, P.A. Vadas, Tillage and Manure Effects on Runoff Nitrogen and Phosphorus Losses from Frozen Soils, Wiley Online Library, 2022, https://doi.org/10.1002/jeq2.20396.

[41] M.N. Stock, F.J. Arriaga, P.A. Vadas, L.W. Good, M.D. Casler, K.G. Karthikeyan, Z. Zopp, Fall tillage reduced nutrient loads from liquid manure application during the freezing season, J. Environ. Qual. 48 (4) (2019) 889–898, https://doi.org/10.2134/jeq2018.11.0417.

[42] J. Peters, S. Combs, B. Hoskins, J. Jarman, J. Kovar, M. Watson, A. Wolf, N. Wolf, Recommended Methods of Manure Analysis, University of Wisconsin Cooperative Extension Publishing, Madison, WI, 2003.

[43] T. Provin, Total carbon and nitrogen and organic carbon via thermal combustion analyses, Soil Test Methods from the Southeastern United States (2014) 149–154.

[44] U. Environmental Protection Agency, Method 3050b Acid Digestion of Sediments, Sludges, and Soils 1.0 Scope and Application, 1996. Washington, DC, USA.

[45] A.R. Crosland, F.J. Zhao, S.P. McGrath, P.W. Lane, Comparison of aqua regia digestion with sodium carbonate fusion for the determination of total phosphorus in sous by inductively coupled plasma atomic emission spectroscopy (icp), Commun. Soil Sci. Plant Anal. 26 (9–10) (1995) 1357–1368, https://doi.org/10.1080/00103629509369377.

[46] J. Murphy, J.P. Riley, A modified single solution method for the determination of phosphate in natural waters, Anal. Chim. Acta 27 (1962) 31–36, https://doi.org/10.1016/S0003-2670(00)88444-5.

[47] A. Mehlich, Determination of P, Ca, Mg, K, Na. Na. And NH4, North Carolina Soil Test Division (Mimeo) 2 (1953) 23–89.

[48] A. Mehlich, Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant, Commun. Soil Sci. Plant Anal. 15 (12) (1984) 1409–1416.

[49] Nelson Keeney, Methods of soil analysis, Chemical and microbiological properties (1982) 1159, Part 2.

[50] U.S.E.P. Agency, Methods for chemical analysis of water and wastes–method 160.2, in: (gravimetric, Dried at 103–105° C), US Environmental Protection Agency, Washington, DC, 1983, pp. 59–61. EPA/600/4-79/020.

[51] G.S. Toor, S. Hunger, J.D. Peak, J.T. Sims, D.L. Sparks, Advances in the characterization of phosphorus in organic wastes: environmental and agronomic applications, Adv. Agron. 89 (2006) 1–72, https://doi.org/10.1016/S0065-2113(05)89001-7.

[52] D. Chakraborty, R. Prasad, A. Bhatta, H.A. Torbert, Understanding the environmental impact of phosphorus in acidic soils receiving repeated poultry litter applications, Sci. Total Environ. 779 (2021) 146267, https://doi.org/10.1016/j.scitotenv.2021.146267.

[53] B. Dari, V.D. Nair, A.N. Sharpley, P. Kleinman, D. Franklin, W.G. Harris, Consistency of the threshold phosphorus saturation ratio across a wide geographic range of acid soils, Agrosystems, Geosciences & Environment 1 (1) (2018) 1–8, https://doi.org/10.2134/age2018.08.0028.

[54] Soil Survey Staff, Soil survey staff, natural Resources conservation service, United States department of agriculture, Web Soil Survey (2022). Available online at: the following link: http://websoilsurvey.sc.egov.usda.gov/. (Accessed 5 June 2022).

[55] I.E. Olorunfemi, T.A. Ogunrinde, J.T. Fasinmirin, Soil hydrophobicity: an overview, Journal of Scientific Research and Reports 3 (8) (2014) 1003–1037.

[56] S.H. Doerr, R.A. Shakesby, Rpd Walsh, Soil water repellency: its causes, characteristics and hydro-geomorphological significance, Earth Sci. Rev. 51 (1–4) (2000) 33–65.

[57] B. Minasny, A.B. McBratney, Limited effect of organic matter on soil available water capacity, Eur. J. Soil Sci. 69 (1) (2018) 39–47, https://doi.org/10.1111/ejss.12475.

[58] M. Wiesmeier, M. Steffens, C.W. Mueller, A. Kölbl, A. Reszkowska, S. Peth, R. Horn, I. Kögel-Knabner, Aggregate stability and physical protection of soil organic carbon in semi-arid steppe soils, Eur. J. Soil Sci. 63 (1) (2012) 22–31, https://doi.org/10.1111/j.1365-2389.2011.01418.x.

[59] D.R. Edwards, T.C. Daniel, Drying interval effects on runoff from fescue plots receiving swine manure, Transactions of the ASAE 36 (6) (1993) 1673–1678, https://doi.org/10.13031/2013.28510.

[60] D.R. Edwards, T.C. Daniel, P.A. Moore, P.F. Vendrell, Drying interval effects on quality of runoff from fescue plots treated with poultry litter, Transactions of the ASAE 37 (3) (1994) 837–843, https://doi.org/10.13031/2013.28148.

[61] H. Tabbara, Phosphorus loss to runoff water twenty-four hours after application of liquid swine manure or fertilizer, J. Environ. Qual. 32 (3) (2003) 1044–1052, https://doi.org/10.2134/jeq2003.1044.

[62] H. Cui, Q. Liu, H. Zhang, Y. Zhang, W. Wei, W. Jiang, X. Xu, S. Liu, Long-term manure fertilization increases rill erosion resistance by improving soil aggregation and polyvalent cations, Catena 223 (2023), https://doi.org/10.1016/j.catena.2022.106909.

[63] J. Giddens, A.P. Barnett, Soil loss and microbiological quality of runoff from land treated with poultry litter, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America 9 (3) (1980) 518–520, https://doi.org/10.2134/jeq1980.00472425000900030038x.

[64] M.M. Maroneze, L.Q. Zepka, J.G. Vieira, M.I. Queiroz, E. Jacob-Lopes, A tecnologia de remoção de fósforo: Gerenciamento do elemento em resíduos industriais, Revista Ambiente e Agua 9 (2014) 445–458, https://doi.org/10.4136/ambi-agua.1403.

[65] R. Bhattacharyya, B.N. Ghosh, P. Dogra, P.K. Mishra, P. Santra, S. Kumar, M.A. Fullen, U.K. Mandal, K.S. Anil, M. Lalitha, D. Sarkar, D. Mukhopadhyay, K. Das, M. Pal, R. Yadav, V.P. Chaudhary, B. Parmar, Soil conservation issues in India, in: Sustainability (Switzerland), vol. 8, MDPI, 2016, https://doi.org/10.3390/su8060565. Issue 6.

[66] C. Dai, Y. Liu, T. Wang, Z. Li, Y. Zhou, Exploring optimal measures to reduce soil erosion and nutrient losses in southern China, Agric. Water Manag. 210 (2018) 41–48, https://doi.org/10.1016/j.agwat.2018.07.032.

[67] L. Gholami, S.H.R. Sadeghi, M. Homaee, Different effects of sheep manure conditioner on runoff and soil loss components in eroded soil, Catena 139 (2016) 99–104, https://doi.org/10.1016/j.catena.2015.12.011.

[68] P.D. Gessel, N.C. Hansen, J.F. Moncrief, M.A. Schmitt, Rate of fall-applied liquid swine manure: effects on runoff transport of sediment and phosphorus, J. Environ. Qual. 33 (5) (2004) 1839–1844, https://doi.org/10.2134/jeq2004.1839.

[69] I. Shainberg, D. Goldstein, G.J. Levy, Rill erosion dependence on soil water content, aging, and temperature, Soil Sci. Soc. Am. J. 60 (3) (1996) 916–922, https://doi.org/10.2136/sssaj1996.03615995006000030034x.

[70] C.K. Mutchler, C.E. Carter, Soil erodibility variation during the year, Transactions of the ASAE 26 (4) (1983) 1102–1104, https://doi.org/10.13031/2013.34084.

[71] E.E. Alberts, J.M. Laflen, R.G. Spomer, Between year variation in soil erodibility determined by rainfall simulation, Transactions of the ASAE 30 (4) (1987) 982–987, https://doi.org/10.13031/2013.30509.

[72] R.R. Sharpe, L.A. Harper, Ammonia and Nitrous Oxide Emissions from Sprinkler Irrigation Applications of Swine Effluent, Wiley Online Library, 1997.

[73] A.N. Sharpley, Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America 26 (4) (1997) 1127–1132, https://doi.org/10.2134/jeq1997.00472425002600040026x.

[74] D.R. Smith, P.R. Owens, A.B. Leytem, E.A. Warnemuende, Nutrient losses from manure and fertilizer applications as impacted by time to first runoff event, Environmental Pollution 147 (1) (2007) 131–137, https://doi.org/10.1016/j.envpol.2006.08.021.

[75] D. Chakraborty, R. Prasad, Phosphorus basics: phosphorus species disruptive to freshwater systems, Alabama Coop. Ext. Syst. (2024). https://www.aces.edu/blog/topics/crop-production/phosphorus-basics-phosphorus-species-disruptive-to-freshwater-systems.

[76] K.C. Ruttenberg, The global phosphorus cycle, Treatise on Geochemistry 8 (2003) 682.

[77] J.E. Gilley, L.M. Risse, Runoff and soil loss as affected by the application of manure, Transactions of the ASAE 43 (6) (2000) 1583–1588.

[78] J.K. Mitchell, R.W. Gunther, The effects of manure applications on runoff, erosion and nitrate losses, Transactions of the ASAE 19 (6) (1976) 1104–1106, https://doi.org/10.13031/2013.36185.

[79] J.W. White, F.J. Coale, J.T. Sims, A.L. Shober, Phosphorus runoff from waste water treatment biosolids and poultry litter applied to agricultural soils, J. Environ. Qual. 39 (1) (2010) 314–323, https://doi.org/10.2134/jeq2009.0106.

[80] Z. Dou, J.D. Toth, D.T. Galligan, C.F. Ramberg Jr, J.D. Ferguson, Laboratory procedures for characterizing manure phosphorus, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America 29 (2) (2000) 508–514, https://doi.org/10.2134/jeq2000.00472425002900020019x.

[81] Z. He, C.W. Honeycutt, I.A. Tazisong, Z.N. Senwo, D. Zhang, Nitrogen and phosphorus accumulation in pasture soil from repeated poultry litter application, Commun. Soil Sci. Plant Anal. 40 (1–6) (2009) 587–598, https://doi.org/10.1080/00103620902861971.

[82] S.W. Bousfield, N. Favaretto, A.C.V. Motta, G. Barth, L.S. Celante, V.F. Cherobim, Environmental soil phosphorus threshold under no-tillage and swine manure application, Braz. Arch. Biol. Technol. 63 (2020) e20190536, https://doi.org/10.1590/1678-4324-solo-2020190536.
[83] D. Chakraborty, V.D. Nair, M. Chrysostome, W.G. Harris, Soil phosphorus storage capacity in manure-impacted Alaquods: implications for water table management, Agric. Ecosyst. Environ. 142 (3–4) (2011) 167–175, https://doi.org/10.1016/j.agee.2011.04.019.
[84] D. Chakraborty, R. Prasad, A. Bhatta, H.A. Torbert, Understanding the environmental impact of phosphorus in acidic soils receiving repeated poultry litter applications, Sci. Total Environ. 779 (2021) 146267.