

Runoff Water Quality Assessment from Furrow-Irrigated Rice Treated with Poultry Litter

Diego Della Lunga^{*✉}, Eric Simon, Mike Daniels, Kris Brye, Lee Riley, James Burke, Jace Clark

Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA

Email: *ddellalu@uark.edu

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Abstract

Poultry litter (PL) has been suggested as a soil amendment to enhance soil fertility and general soil health in intensively cultivated agroecosystems. However, continuous annual land application of PL can lead to excess nutrients that may run off and contaminate local water bodies. The impact of PL on nutrient runoff in furrow-irrigated rice (*Oryza sativa*) systems in Arkansas is currently understudied. The objectives of this study were i) to assess trends and magnitude of nutrient concentrations and loads [*i.e.*, nitrate (NO_3^-) and nitrite (NO_2^-), total nitrogen (TN), total phosphorus (TP), soluble-reactive phosphorus (SRP), potassium (K), total suspended solids (TSS), and sulfate (SO_4^{2-})] in runoff water, ii) to determine the relationship between nutrient runoff and rainfall events, and iii) to evaluate nutrient budgets (*i.e.*, P and K) for a previously land-leveled, furrow-irrigated rice system in northeast Arkansas between 2022 and 2024. The numeric peak $\text{NO}_3^- + \text{NO}_2^-$ ($6.9 \text{ mg}\cdot\text{L}^{-1}$) and TN ($22.9 \text{ mg}\cdot\text{L}^{-1}$) runoff concentrations occurred on 13 June 2022; the numeric peak SO_4^{2-} ($39 \text{ mg}\cdot\text{L}^{-1}$) runoff concentration occurred on 12 June 2023; and the numeric peak SRP ($3.5 \text{ mg}\cdot\text{L}^{-1}$), TP ($4.3 \text{ mg}\cdot\text{L}^{-1}$), and K ($36 \text{ mg}\cdot\text{L}^{-1}$) runoff concentrations occurred right after rice harvest on 31 October 2022. Regression models describing the relationship between runoff concentration and total rainfall between sampling dates were significant ($P < 0.05$) for all the response variables (*i.e.*, $\text{NO}_3^- + \text{NO}_2^-$, TN, TP, SRP, K, SO_4^{2-} , and TSS). Phosphorus and K budgets were associated with nutrient accumulation in the topsoil, although large variability occurred between years. The organic matter accumulation over time from PL additions can represent an effective management benefit to enhance soil health. Future studies should assess PL application rates and application timing to enhance crop productivity while limiting environmental risks.

Keywords

Land Leveling, Soil Erosion, Nutrient Budgets

1. Introduction

The increasing worldwide demand for egg and meat products has contributed to the rise of the poultry sector among agro-based industries [1]. In the poultry production process, a waste product (*i.e.*, litter) is generated in large quantities [1]. Poultry litter (PL) is composed of a mix of bedding material, feathers, feces, split feed, and water [2]. More than 14 million metric tons (MMT) of PL are generated annually in the United States (US) [3]. Although a waste product, PL is regarded as a valuable organic amendment for land application due to its relatively large nutrient concentrations, especially of nitrogen (N) and phosphorus (P), and its large protein and amino acid concentrations [3]. Additionally, PL can increase extractable zinc (Zn) in soils [4] and correct Zn deficiency commonly observed in many rice-producing soils in Arkansas [5]. However, PL's nutrient composition is highly variable and related to factors such as the size of the poultry house, the number of flocks grown, diet and feed ratios, litter storage procedures, and handling conditions [6].

Poultry litter contains both organic and inorganic forms of N, giving PL the ability to provide N in short- and long-term spans [3]. When land-applied, ammonium (NH_4^+) and nitrate (NO_3^-) present in the PL are immediately available for plant uptake or microbial processes, while more complex forms of N contained in the PL take longer to degrade and mineralize into available inorganic forms [7]. Between 90% and 100% of the P and potassium (K) present in PL are considered plant available after mineralization, while only 25% of the initial N is considered readily available, conferring PL characteristics similar to common inorganic fertilizers [7].

The poultry industry in Arkansas produces 1.3 MMT of PL every year, ranking second in the US for PL production [8]. On average, PL generated in Arkansas contains 3% N, 1.2% P, and 2.2% K, although nutrient values are strictly related to the moisture content of the organic material, which, on average, is around 23% [9]. The organic matter contained in PL can also improve crop production, thus enhancing soil water-holding capacity, nutrient retention, and soil protection from wind and water erosion, and stabilizing soil pH and microbial community biomass [10]. Therefore, PL application to agricultural fields can counteract soil organic matter (SOM) degradation and the subsequent loss of soil productivity commonly reported in intensively cultivated agricultural production systems [11]. Poultry litter increased soil carbon (C) in the topsoil of agricultural fields on silt loam soils in North Alabama when used as an N- or P-source compared to common inorganic fertilizers [12]. An increase in soil C by 33% over five years was reported in cropping systems on sandy loam soils in Alabama when PL was used

as a P source in soybean (*Glycine max*) fields and as an N source in corn (*Zea mays*) fields [11]. Soil C sequestration in both PL-treated soybean and corn topsoil was also greater under no-tillage (NT) than under conventional tillage, while the NT effect on soil C accumulation was reported at depths greater than 5 cm regardless of the nutrient source used [11].

Poultry litter application in crop production systems allows recycling of a waste product generated by the poultry industry, while positively affecting soil physical and chemical properties to benefit crop production [13]. Due to the physical and economic difficulties of transporting PL long distances, agronomic recommendations for the application of organic amendments have often been associated with crop production systems relatively close to the production site of the waste product [13]. Only during the last decade have new poultry integrators been established near crop-production areas in Arkansas. Due to the large rice (*Oryza sativa*)-producing area in Arkansas, which represents almost 45% of the total US planted-rice area, PL has often been considered a viable and now economically feasible alternative fertilizer-nutrient source and soil amendment for rice cultivation [9].

University of Arkansas Division of Agriculture recommendations for P management in crop production systems suggest applying organic amendments at a rate that corresponds to the plant-P need and the current soil-test P (STP) concentration (STP, 25 ppm) [9]. In the delayed-flooded management scheme, where rice fields are flooded at the 4- to 5-leaf stage (*i.e.*, 30 to 40 days after planting), the NO_3^- and soluble-reactive P (SRP) concentrations in the PL can be subjected to losses, such as leaching and runoff, reducing the amount of N and P available for plant uptake and potentially resulting in local water-quality issues that can lead to eutrophication [7] [9] [14].

Several environmental concerns have been associated with the large PL application rates in crop production systems worldwide [13]. Since the N:P ratio of PL (*i.e.*, 1:1) is lower than the ratio removed from the soil through rice-plant uptake (*i.e.*, 6:1), continuous annual PL application can result in soil nutrient buildup [14]. In soils that are characterized by low nutrient-holding capacity, PL application can substantially contribute to the loss of important elements necessary for optimal crop production and to the contamination of surface and groundwater [14] [15]. In addition, PL can contain trace metals, such as arsenic (As), copper (Cu), cadmium (Cd), and selenium (Se), along with pathogens, commonly *Acetivobacillus* and *Salmonella*, that can contribute to the contamination risks associated with frequent PL application [13].

Laboratory and plot-scale studies showed that increasing PL application rates are directly linked to P loss from runoff events, although the relationship is also affected by PL application timing, management strategies, and rainfall frequency and magnitude [16]. In Arkansas, studies on runoff processes related to PL application have been limited and focused mainly on pasturelands and in the karst regions of northwest Arkansas [16] [17]. In comparison, less information is availa-

ble on nutrient losses from cropland in relation to continuous PL applications [18]. Among agricultural practices that can have a substantial impact on PL-derived, runoff-P losses, irrigation water management represents one of the main drivers [19].

In the last decade, the delayed-flood rice production system in Arkansas has been slowly replaced by the increasingly popular furrow-irrigated (FIR) water regime, where previous studies indicated a 46% increase in water-use efficiency and a 48% reduction in water usage under FIR compared to flooded conditions [20]. The frequent irrigation applications during a rice growing season can substantially impact the movement of nutrients and sediment along the predominant slope of a FI-managed field [21]. The dynamic environmental conditions of a FI-managed field compared to a flooded system create a completely different set of environmental and soil characteristics, where many factors can impact nutrient loss via runoff [19]. Furrow length, residence time of water in the furrow, stream velocity, and water infiltration rate are understudied parameters that, in FI-managed fields, can impact runoff processes during the growing season [22]. Under flooded conditions, the entire soil surface interacts with the layer of water, while in a FI-managed field, a dual process takes place where water flow from irrigation interacts with only the soil surface in the furrow, whereas rainfall events will impact the entire field equally [23] [24].

Management practices can also impact the mobility of nutrients from commercial, inorganic fertilizers or organic amendment additions [25]. When nutrient inputs are incorporated into the soil, existing soil physical and chemical processes will impact nutrient release and potential losses through runoff differently compared to conditions when inputs are surface applied [25]. A study conducted in Idaho on silt-loam soils reported that runoff dissolved organic carbon (DOC) and NO_3^- - and NH_4^+ -N concentrations differed significantly between rototilled furrow-irrigated fields, fields treated with moldboard, and fields irrigated with a buried or on-surface polypipe [19].

Due to the limited data on nutrient runoff from furrow-irrigated rice fields in Arkansas, efforts have concentrated on assessing the magnitudes and temporal trends of nutrient losses from various agronomic practices currently in use. Subsequent steps should aim to further develop and/or refine best nutrient management practices to reduce overall nutrient losses from runoff. The overall objective of this study was to evaluate runoff nutrient losses, including NO_3^- , total nitrogen (TN), SRP, total P (TP), K, sulfate (SO_4^{2-}), and total suspended solids (TSS) from a furrow-irrigated rice field in northeast Arkansas amended with a single, yearly PL rate ($4.9 \text{ Mg}\cdot\text{ha}^{-1}$) over the course of three growing seasons (*i.e.*, 2022 through 2024). Specific sub-objectives were to: i) assess the temporal runoff trends for individual nutrients, ii) assess the temporal relationship between nutrient runoff and rainfall, iii) estimate and evaluate the annual P and K budgets, and iv) compare the directly measured change in near-surface soil properties over time to similar estimations from the P and K budgets. It was hypothesized that all measured

runoff properties were temporally related to rainfall, with an annual association stronger at the beginning of the year and weaker toward the end of the year. It was hypothesized that there would be a linear relationship between runoff nutrient concentrations and rainfall. It was also hypothesized that, using the elemental budget approach, approximately 20% of total outputs would be represented by runoff, as previously reported in irrigated crop systems [26] [27]. Furthermore, it was hypothesized that continuous PL applications would increase SOM and soil nutrients (*i.e.*, P, K, Ca, Mg, Fe, Mn, Na, S, and Zn), highlighting the role of PL as a practice to enhance soil fertility and soil health in agricultural settings.

This field study is novel in providing multi-year assessments of nutrient runoff at the field scale where annual management practices were identically maintained.

2. Materials and Methods

2.1. Site Description

This study was conducted between February 2022 and August 2024 in a 14-ha, furrow-irrigated field near Newport in Jackson County, northeast Arkansas. The study region is in Major Land Resource Area (MLRA) 131A, which is the Southern Mississippi River Alluvium [28]. The specific study area was mapped with a combination of Amagon silt loam (fine-silty, mixed, active, thermic Typic Endoaqualfs), Forestdale silt loam (fine, smectitic, thermic Typic Endoaqualfs), and Egam silty clay loam (fine, mixed, active, thermic Cumulic Hapludolls) [29]. The Amagon and Forestdale series are very deep, poorly drained, slowly permeable soils, commonly formed in alluvium on low terraces in the Lower Mississippi River Valley, while the Egam series is very deep and well drained, commonly formed in clayey alluvium on flood plains. The Amagon and Forestdale series represented ~25% of the furrow-irrigated field, while the remaining 75% was mapped as Egam [29]. The field was approximately 400 m long and 360 m wide. The 30-year (*i.e.*, 1990-2020) average monthly air temperature in the study area ranges between 3°C in January and 27°C in July, with a 30-year average annual cumulative precipitation of 130 cm [30].

2.2. Field Management

The field has been under agricultural production since 1954, mainly managed as dryland with soybean being the main crop until 2020. After the 2020 growing season, the field was precision land-leveled (NRCS Conservation Practice 464: Irrigation Land Leveling) [31] to create a uniform slope of ~0.1% with a west-east orientation. Since 2021, the entire field has been managed as an NT, furrow-irrigated rice production system. After land leveling, a fall application of 4.9 Mg·ha⁻¹ of locally sourced PL has been surface-broadcast each year. The entire study area was seeded between April and May each year with the hybrid cultivar FPDG263 (Dyna-Gro, McCrory, AR) at a rate of 23.5 kg·seed·ha⁻¹ to a depth of 1.6 cm according to University of Arkansas recommendations for furrow-irrigated rice [32]. Seeding was conducted with a row spacing of 15 cm and an intra-seed spac-

ing of 9 cm.

Each year, the field was broadcast with 336 kg·N·ha⁻¹ as urea (fertilizer grade: 46-0-0) and 93 kg·K·ha⁻¹ as muriate of potash (fertilizer grade: 0-0-60). Nitrogen and K fertilization occurred at the beginning of May for the current study (*i.e.*, 2022, 2023, and 2024). Herbicide and pesticide applications were made according to the University of Arkansas recommendations [33]. Irrigation was applied as groundwater with a polyvinyl chloride (PVC) polypipe installed on the upper corner of the field on the western edge. Irrigation was applied roughly once a week uniformly throughout the entire field. Individual irrigation applications were ~1 ha·cm of water each. The field was combine-harvested in September each year.

2.3. Soil Sampling and Analysis

Soil samples were collected manually with a 2-cm-diameter push probe for soil physical and chemical analyses on 27 October 2021, 13 April 2023, 16 April 2024, and 17 October 2024. Soil samples collected in 2021 represented the soil properties at the beginning of the study after land leveling and prior to any PL application. Soil samples collected in April 2023 and April 2024 were considered representative of the soil properties at the end of the 2022 and 2023 growing seasons, respectively, and were used to represent soil properties at the beginning of the 2023 and 2024 growing seasons, respectively. It was assumed the soil properties measured in April 2023 and 2024, ~6 months after PL application, could be used as mid-points between the end of the past growing season and the beginning of the subsequent growing season to represent an estimation of both timeframes. While a more intense and timely planned soil sampling regime could provide more accurate data, the same soil processes were assumed to operate each year at a similar rate, conferring to the soil samples collected in April characteristics that can be considered transitory from the end of a growing season to the beginning of the next growing season. Soil samples were collected from the top 10 cm using a 0.4-ha (1 ac) grid system for a total of 29 soil samples. Each soil sample was a composite sample constituted by four subsamples collected within a 30-cm (1 ft) radius from a center point for a total of five subsamples combined and mixed for each composite soil sample. An additional set of five soil samples was collected with a 4.8-cm-diameter, stainless steel core chamber and slide hammer from five random locations within the field from the top 10 cm for bulk density (BD) determination.

A 1:2 soil mass:water volume suspension was used to determine soil electrical conductivity (EC) and pH, while SOM concentration was determined by weight-loss-on-ignition following combustion at 360°C for 2 hours. Extraction in a 1:10 soil mass:extractant volume ratio and analysis by inductively coupled, argon-plasma spectrophotometry were used to determine Mehlich-3-extractable soil nutrient concentrations (*i.e.*, P, K, Ca, Mg, Fe, Mn, Na, S, and Zn) [34]. Measured BD, averaged across replicates, was used to convert measured SOM and extractable nutrient concentrations to contents (kg or Mg·ha⁻¹) for data reporting and statistical analyses.

2.4. Poultry Litter Analysis

Poultry litter was analyzed for each off-season application in 2021, 2022, and 2023. The litter sample was weighed before and after drying for 24 hours at 105°C to determine gravimetric moisture content. Chemical PL analyses were conducted on fresh (*i.e.*, wet) material; thus, the resulting properties are reported on an as-is basis. Litter pH was determined using a pH electrode on a 1:10 litter mass-to-water volume mixture. Total N (TN) was determined by high-temperature combustion using a Vario Max CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ). Soluble P and K were extracted with a 1:10 litter mass-to-water volume mixture and analyzed by inductively coupled optical emission spectroscopy according to [35].

2.5. Water Sample Collection and Analysis

An automated runoff water quality monitoring station was installed at the lower end of the furrow-irrigated field next to the drainage outlet and was positioned directly next to an existing discharge point where all runoff water flowed through a 20-cm wide, fiberglass, pre-calibrated, trapezoidal flume equipped with a stilling well (Tracom Inc., Jasper, GA) that was installed at the drainage outlet. An autosampler (6712 Teledyne-ISCO, Lincoln, NE) enclosed in a weather-resistant shelter was installed next to the trapezoidal flume and integrated with the well. The autosampler system was equipped with a Flowlink interface (Teledyne-ISCO, Lincoln, NE) to allow remote data downloading. A submerged probe (720 Teledyne-ISCO) was inserted in the well to measure the hydraulic head at a flow-calibrated point. The probe was programmed to record hydraulic-head data every minute. The autosampler was programmed to collect 100-mL aliquots based on flow pacing for each runoff discharge event, up to a total of 10 L [27]. A runoff event was classified and categorized as a flow increment above 6.9 cm of the hydraulic head [26] [27]. Runoff discharge (Q) was calculated by computing the hydraulic head (H) according to Equation (1):

$$Q = (373.6H^{1.5}) + (809.9H^{2.5}) \quad (1)$$

where H was expressed in meters (m) and Q in $L \cdot s^{-1}$ [26].

At each sampling interval, two 125-mL water samples were collected from the autosampler and mixed. The autosampler was then emptied and reset to collect water for upcoming runoff events. Water samples were stored on ice and analyzed for NO_3^- , nitrite (NO_2^-), TN, TP, SRP, K, SO_4^{2-} , and TSS concentrations according to protocols set by the US Environmental Protection Agency and the American Public Health Association [27] [36]. Water samples were collected from the monitoring station on 17 and 22 February; 22 March; 4, 8, 15, 22, and 27 April; 2 and 5 May; 13 June; 6, 15, 17, 20, and 26 July; 2, 8, 13, 18, 20, 23, and 26 August; and 22 September 2022; on 24 April; 12, 16, 27, and 29 June; 7, 17, 20, and 27 July; 7, 14, and 22 August; and 31 October 2023; and on 12 and 24 January; 1, 10, 18, and 29 July; and 7 and 13 August 2024, for a total of 45 sampling dates over the 3-

year study period. The frequency of sampling was dictated by rainfall events during the off-season months and by rainfall events and irrigation practices during the growing season, resulting in a more concentrated sampling frequency between April and August each year than during the other months. Precipitation data were retrieved from a local weather station within 6 km of the study area [37].

2.6. Statistical Analyses

Regression analyses were conducted in JMP (version 17.0, SAS Institute, Inc., Cary, NC) on NO_3^- and NO_2^- , TN, TP, SRP, K, SO_4^{2-} , and TSS concentrations using total rainfall (TR, in mm) between consecutive sampling dates as the predictor variable. Linear and quadratic regression models were tested to determine the best fit based on the resulting R^2 value and root mean square error (RMSE). Influential values and outliers were assessed through leverage plots and externally studentized residuals, respectively. If the response variable was characterized by a large degree of variability (*i.e.*, numerous influential values), a Cauchy distribution was used instead of a normal distribution [38]. If the response variable was characterized by a skewed distribution, a log transformation was performed on the response variable [39]. Only the best-fit model was reported.

Elemental NO_3^- , NO_2^- , TN, TP, SRP, K, SO_4^{2-} , and TSS concentrations ($\text{mg}\cdot\text{L}^{-1}$) were converted to flow-weighted concentrations or mass loads ($\text{kg}\cdot\text{ha}^{-1}$) using the total flow (L) measured from the automated runoff water quality monitoring station at each sampling date. Due to a temporary malfunction of the sensor measuring the flow across the drainage outlet (*i.e.*, from 4 April to 27 April in 2022 and from 18 July to 29 July in 2024), the dataset on total flow had numerous missing values (*i.e.*, 9 in total).

A simple linear regression analysis in JMP was performed using TR as the predictor to establish a predictive equation to generate total flow estimations for the sampling dates when total flow was not recorded. The resulting simple linear model, characterized by $P < 0.01$ and $R^2 = 0.46$, resulted in Equation (2):

$$\text{Total flow} = 2016921 + 21075 * \text{TR} \quad (2)$$

The relatively low R^2 in the Total Flow model might have led to a partial misrepresentation of the trend and magnitude of the volume of runoff water across the field. Nonlinear models and/or additional predictors should be considered in future studies to validate the role of TR in modeling analysis to explain runoff flows. The Root Mean Square Error for the Total Flow model (*i.e.*, 2×10^6 L) suggested that an overestimation of the predictions most likely occurred.

A budget approach was used to evaluate P and K across the study area. Fertilizer and PL applications were considered additions, while runoff and grain uptake represented removal processes from the field. Grain uptake was estimated from yield data, while vegetative nutrient uptake was not measured nor included in the budget approach, as the non-grain vegetative material was returned to the field. Soil pH and soil nutrient content ($\text{kg}\cdot\text{ha}^{-1}$) differences over time were calculated

as end-of-the-season minus beginning-of-the-season to estimate the change in storage for the budget. A 95% confidence interval was used to determine if the changes in soil properties were significantly different from zero. Nutrient budgets were estimated on a year-to-year basis and for the entire 3-year study period. No outliers were detected among the response variables. Significance for all data analyses was judged at the 0.05 level.

3. Results and Discussion

3.1. Initial Soil Properties and PL Analyses

Soil properties were measured at the beginning of the study after land leveling was implemented, but before the first PL application, to determine the initial soil fertility level across the study area and possible changes that would occur in response to PL applications (**Table 1**).

Table 1. Summary of soil physical and chemical properties means and standard errors (SE) ($n = 29$) in the top 10 cm at the end of the 2021 growing season (27 October) in a furrow-irrigated rice field near Newport, AR.

Soil Property	Mean (\pm SE)
Bulk density ($\text{g}\cdot\text{cm}^{-3}$)	1.30 (0.1)
pH	5.8 (<0.1)
Extractable nutrients ($\text{mg}\cdot\text{kg}^{-1}$)	
P	23.1 (0.61)
K	114.6 (2.2)
Ca	1619 (41.1)
Mg	276.9 (6.5)
S	15.8 (0.5)
Na	18.2 (0.4)
Fe	157.7 (2.2)
Mn	203.2 (7.6)
Zn	4.9 (0.2)
Soil organic matter (%)	2.4 (0.1)

After land leveling, an overall reduction in near-surface SOM and an increase in BD are commonly expected due to the passage of heavy machinery and the redistribution of the topsoil [40]. Land leveling creates a uniform slight slope gradient that improves irrigation and drainage across the entire field, but can also disrupt soil fertility levels, particularly in the areas where the topsoil is cut and redistributed to fill low and depressional areas [40]. Substantial additions of nutrients are often required in freshly land-leveled fields to re-establish a soil environment to support plant growth [40]. The UA-DA-CES recommends the addition of 2.25 to 4.5 $\text{Mg}\cdot\text{ha}^{-1}$ of PL following the implementation of precision land-leveling to restore soil productivity after exposing unproductive subsoil [32].

Soil BD was numerically greater than BDs measured in FIR fields under reduced or NT management practices in a silt-loam soil in east-central Arkansas (*i.e.*, 1.2 g·cm⁻³) [41]. Soil pH was at the lower limit of the optimal range for rice production systems (*i.e.*, 5 to 6.5) [42]. According to University of Arkansas recommendations for rice production systems, soil nutrient concentrations were within the medium level for P (17 to 25 mg·kg⁻¹) and K (91 to 130 mg·kg⁻¹) and above optimum for Zn (>4.1 mg·kg⁻¹), Mn (>40 mg·kg⁻¹), Ca (>400 mg·kg⁻¹), Mg (>30 mg·kg⁻¹), and S (>10 mg·kg⁻¹) (**Table 1**) [32] [33]. Initial soil physical and chemical properties highlighted the potential disruptive effect of land leveling and the necessity for organic soil amendments, such as PL, to restore or improve soil fertility and subsequent crop growth and productivity [40].

Poultry litter analyses demonstrated how PL's physical and chemical properties can vary substantially, even among batches of the same material [6]. The pH of the PL applied for the 2022 and 2023 growing seasons was highly alkaline and within the range (*i.e.*, 7.9 to 8.7) reported by the University of Arkansas Diagnostic Laboratory over many PL samples ($n > 500$) produced in Arkansas [33]. The pH of the PL applied for the 2024 growing season was slightly acidic and was outside what has been commonly reported for Arkansas-produced PL [33]. Total N, P, and K were numerically similar for the 2022 and 2024 growing seasons, while the PL applied for the 2023 growing season had numerically lower nutrient concentrations (**Table 2**).

Table 2. Summarizes the physical and chemical properties of the poultry Litter used in the 2022, 2023, and 2024 growing seasons in a furrow—An irrigated rice field near Newport, AR.

Poultry Litter Property	2022	2023	2024
pH	8.8	8.2	6.5
Moisture (%)	41.8	37.3	20.8
Total N (%)	4.58	2.57	3.49
Total P (%)	1.36	0.86	1.13
Total K (%)	3.12	2.62	3.44

The PL material applied for the 2024 growing season was drier than the PL applied for the 2022 and 2023 growing seasons (**Table 2**). The PL applied for the 2022 and 2024 growing seasons had numerically similar nutrient concentrations to those of other Arkansas-produced PL [3], while the PL applied for the 2023 growing season had numerically lower nutrient concentrations than the average reported for Arkansas-produced PL [33].

3.2. Runoff Water Analysis

3.2.1. Total Flow

The measured total flow indicated that the three years were characterized by substantially different conditions, resulting in temporally variable runoff (**Figure 1**).

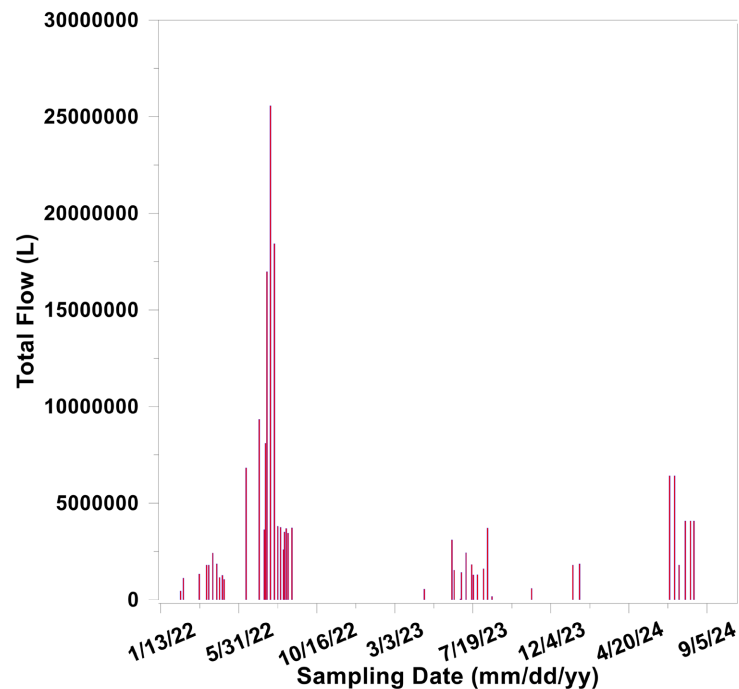


Figure 1. Shows the total flow measured during 2022, 2023, and 2024 from an automated runoff water quality monitoring station located at the lower end of a furrow-irrigated rice field near Newport, AR.

Although the total flow was a combination of measured and modeled data, the measured data represented more than 80% of the total observations. Therefore, individual event volumes and temporal trends in total flow over time were considered representative of the environmental conditions experienced by the field over the course of the three growing seasons (**Figure 1**). The no-flow periods recorded mainly between the end of one and the beginning of the subsequent growing seasons indicated that runoff from the FI field was negligible or below the detection limit of the sensor (*i.e.*, $1 \text{ m}^3\text{-s}^{-1}$), although missing values due to equipment malfunctions cannot be excluded as a cause of no-flow measurements (**Figure 1**).

In 2022, 127 million L of total flow was recorded, while 19.6 and 30.5 million L of total flow were recorded in 2023 and 2024, respectively (**Figure 1**). Local rainfall data recorded were 1262, 1473, and 1312 mm for the 2022, 2023, and 2024 calendar years, respectively (**Figure 1**). The differences in total flow among the three years may also have been related to differences in applied irrigation that were not consistently quantified over the course of the study and thus were not reportable. Although the lack of irrigation-application quantification was a study limitation, the total measured runoff was assumed to be the result of a combination of precipitation and irrigation, thereby reinforcing the validity and applicability of the results of the current study. The partitioning of the measured total flow between irrigation and precipitation should be evaluated in future studies to more accurately categorize the dynamics related to runoff processes.

3.2.2. Nutrient Concentrations

Runoff concentrations were graphically represented with total rainfall between sampling dates to highlight the association of rainfall with the runoff process (**Figure 2**). Runoff concentration showed various trends, although common patterns can be recognized among all measured runoff parameters (**Figure 2**). During 2022, runoff concentrations appeared to closely follow total rainfall trends between sampling dates, while in 2023 and 2024, the correlation between rainfall in the sampling intervals and runoff concentrations appeared to be weaker, which supported the original hypothesis (**Figure 2**). Over the whole 3-year period, the numeric concentration peaks for $\text{NO}_3^- + \text{NO}_2^-$ ($6.9 \text{ mg}\cdot\text{L}^{-1}$) and TN ($22.9 \text{ mg}\cdot\text{L}^{-1}$) occurred on 13 June 2022; for SO_4^{2-} ($39 \text{ mg}\cdot\text{L}^{-1}$) occurred on 12 June 2023; and for SRP ($3.5 \text{ mg}\cdot\text{L}^{-1}$), TP ($4.3 \text{ mg}\cdot\text{L}^{-1}$), and K ($36 \text{ mg}\cdot\text{L}^{-1}$) occurred on 31 October 2023, right after rice harvest (**Figure 2**). Peak $\text{NO}_3^- + \text{NO}_2^-$ and TN concentrations were likely related to the fertilizer-N applications that occurred weeks before the measured concentration peaks in each growing season, while peaks in SRP, TP, and K concentrations were likely related to the decomposition of crop residues left on the soil surface after harvest and the fact that the rice crop was actively removing P and K from the soil during the growing season (**Figure 2**). In two adjacent rice fields where flood-irrigated rice was being grown, concentration peaks for $\text{NO}_3^- + \text{NO}_2^-$ and TN were not observed during the growing season (Daniels, Personal Communication, 2026). Furrow irrigation of rice often keeps the soil moist but not saturated, unlike the saturated soil in flood irrigation, which may imply a lack of denitrification of nitrate in FIR, which could make $\text{NO}_3^- + \text{NO}_2^-$ more susceptible to loss in runoff.

Nitrate + NO_2^- concentration trends closely followed the TN concentration trends during 2022, while a weaker temporal connection between $\text{NO}_3^- + \text{NO}_2^-$ and TN concentration trends occurred during 2023 and 2024 (**Figure 2**). The runoff $\text{NO}_3^- + \text{NO}_2^-$ concentration represented, on average, 33% of the TN concentration in 2022, but only 16% and 18% in 2023 and 2024, respectively (**Figure 2**).

The potential soil compaction from land-leveling processes may have limited infiltration and increased horizontal runoff during 2022, resulting in numerically greater $\text{NO}_3^- + \text{NO}_2^-$ concentrations and a numerically greater $\text{NO}_3^- + \text{NO}_2^-$ proportion of the TN concentration compared to 2023 and 2024, one and two complete years, respectively, after land leveling (**Figure 2**). Rice root development during and after the 2022 growing season likely at least partially alleviated topsoil compaction, thus enhancing vertical water infiltration and percolation, resulting in numerically lower runoff $\text{NO}_3^- + \text{NO}_2^-$ concentrations and a numerically lower $\text{NO}_3^- + \text{NO}_2^-$ proportion of the TN concentration in 2023 and 2024 (**Figure 2**). Organic matter addition from root decomposition can also increase water retention in the topsoil and reduce runoff [43].

Similar to the results of the current study, water quality assessments in the Little River Ditches and Lower St. Francis Basins during the 2015 growing season, where the current study area was located, reported mean $\text{NO}_3^- + \text{NO}_2^-$ concentrations

of 6.9 and 10.4 mg·L⁻¹, respectively, highlighting the potential contribution of agricultural activities to N inputs in the proximal tributary systems [44]. A national study conducted between 1992 and 2004 by the United States Geological Survey (USGS) reported NO₃⁻ + NO₂⁻ concentrations ranging between 2.9 and 14 mg·L⁻¹ in sampled streams and groundwater in northeast Arkansas [45].

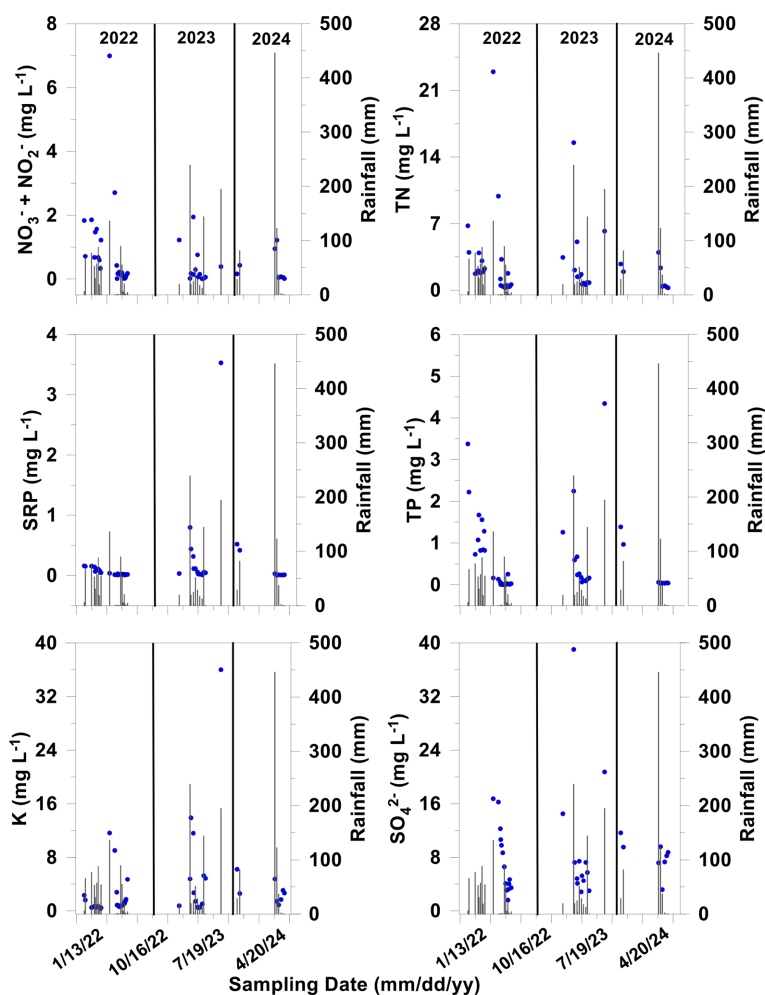


Figure 2. Visual representation of nitrate and nitrite ($\text{NO}_3^- + \text{NO}_2^-$), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), potassium (K), and sulfate (SO_4^{2-}) concentrations (blue dots) in runoff water and rainfall (vertical bars) amount calculated as total rainfall received between consecutive sampling dates throughout 2022, 2023, and 2024 from a furrow-irrigated rice field near Newport, AR. Vertical lines from the bottom to the top axes separate the years. Note the different y-axis scales across runoff properties.

During each of the three years, wider fluctuations of $\text{NO}_3^- + \text{NO}_2^-$ and TN concentrations occurred from March to ~June, after which N concentrations started to decrease with narrower fluctuations (Figure 2). Fertilization practices that occur early in the growing season likely played a fundamental role in runoff-N losses during early runoff events (Figure 2). A significant effect of fertilizer-N

rate on runoff $\text{NO}_3^- + \text{NO}_2^-$ and TN concentrations has been reported in rice paddies (*i.e.*, flood-irrigated) in the Fujian Province in China, where increasing fertilizer-N rate was associated with a concomitant increase in runoff-N losses [46].

Both runoff SRP and TP concentrations showed substantially different temporal trends (Figure 2). During 2023 and 2024, runoff SRP and TP concentrations had similar temporal fluctuations, while in 2022, runoff SRP and TP concentrations had contrasting temporal trends (Figure 2). In 2022, runoff SRP concentrations were relatively stable over time, ranging between 0.01 and 0.16 $\text{mg}\cdot\text{L}^{-1}$, with no visual correlation with rainfall events and/or fluctuations of total flow (Figure 1 and Figure 2). In contrast to SRP, runoff TP concentrations in 2022 initially decreased sharply, then stabilized toward the end of the growing season, with concentrations of 3.4 $\text{mg}\cdot\text{L}^{-1}$ on 17 February and 0.03 $\text{mg}\cdot\text{L}^{-1}$ on 2 September (Figure 2). In 2023, both runoff SRP and TP concentrations visually matched the trend in total rainfall between sampling dates, with increasing concentrations to 12 June, then decreasing concentrations to 20 July, followed by increasing concentrations again to 31 October (Figure 2). In 2024, both SRP and TP runoff concentrations decreased to 10 July, after which increasing concentrations occurred (Figure 2). Over the course of the three years, runoff SRP and TP concentrations were, on average, ~3 times numerically greater than field-scale runoff SRP and TP concentrations from cotton fields in northeast Arkansas between 2011 and 2014 [27]. The relatively large runoff-P concentrations reported in the current study were likely at least partially due to P release dependent on factors that affect mineralization and transport from P-containing PL (Figure 2).

Runoff SRP concentrations represented, on average, 51%, 38%, and 30% of TP concentrations in 2022, 2023, and 2024, respectively (Figure 2). Runoff SRP represented the majority of runoff TP when total rainfall between sampling dates was relatively low (*i.e.*, small spikes), as in 2022. In contrast, in 2023 and 2024, when total rainfall was greater (*i.e.*, larger spikes), SRP represented a minority of the runoff TP concentration, suggesting that particulate-P may have represented much of the runoff P when rainfall was more abundant (Figure 2). Runoff SRP losses from agricultural fields have been shown to be strongly correlated with dissolved-reactive P (DRP), to the point that both parameters can be considered interchangeable [47]. Previous studies conducted in an agricultural watershed in Ohio reported a DRP:TP ratio ranging from 0.29 to 0.35, with a maximum ratio of 0.60 [48], which is similar to the current study. Previous studies at the watershed level determined an inverse relationship between runoff discharge and the DRP:TP ratio, linking strong rainfall events (*i.e.*, >25 mm) to TP mobilization and transport, specifically in the particulate form [47] [49] [50]. While SRP originates from organic material and is transported through water flow after desorption and dissolution, particulate P is usually sorbed to soil particles and/or other organic compounds and is transported via erosion processes [51].

Runoff K concentrations over the course of the three years closely followed the

trend of total rainfall between sampling dates, likely due to K's solubility (K remains soluble in plant tissue as it is not incorporated into the cell structure, unlike other nutrients) and mobility [52] (Figure 2). Although runoff K does not represent a threat to water quality, runoff K losses from agricultural fields constitute an agronomic and economic issue [26]. Runoff K loss at the field scale has been identified as the principal K-loss mechanism from agroecosystems in the eastern Arkansas portion of the Lower Mississippi River Valley [53]. Few studies have assessed and reported runoff K losses from agricultural fields, especially from FIR production [26]. In FI-soybean fields in Brazil under conventional tillage and NT, runoff K concentrations ranged from 1.3 to 9.0 mg·L⁻¹, which are similar to those reported in the current study [54].

Runoff SO₄²⁻ originates from fertilizer-S additions and rainfall deposition. Fertilizer-S additions in agricultural production systems are commonly low and often associated with the input of more critical nutrients, such as Zn as zinc sulfate or N as ammonium sulfate [55]. Excluding the first few months of 2022 when no runoff SO₄²⁻ was detected, runoff SO₄²⁻ concentrations generally matched the trend of rainfall between sampling dates, suggesting that precipitation and atmospheric deposition may represent the main mechanism that adds S into the soil surface that can subsequently succumb to runoff (Figure 2). In a field-scale study in Oklahoma and Texas, runoff SO₄²⁻ concentrations ranged from 8.3 mg·L⁻¹ from a sorghum (*Sorghum bicolor*)-fallow rotation to 14.8 mg·L⁻¹ from a peanut (*Arachis hypogaea*)-sorghum rotation [55], closely matching the upper runoff SO₄²⁻ concentration range reported in the current study (Figure 2).

The runoff nutrient concentration ranges measured in the current study (Figure 2) highlight the variable nature of runoff processes, where synergistic mechanisms can operate simultaneously and result in substantial nutrient losses at the field scale. Runoff nutrient concentration ranges from FIR treated with PL suggest that the addition of organic amendments can increase the probability of N, P, and/or K loss that could otherwise benefit plant growth and contribute to soil nutrient buildup. Management practices need to be implemented to limit off-site transport of essential nutrients from agricultural fields to maximize plant growth, nutrient uptake, and productivity.

3.2.3. Regression Analyses

The significant relationships between total flow and total rainfall between sampling dates identified in the current study, in conjunction with the well-established correlations between total flow and runoff nutrient concentrations in agricultural fields [26], raised the question of whether total rainfall between sampling dates can be used as a predictor of runoff nutrient concentrations over time. Regression analyses were kept as simple as possible to obtain results that could potentially be generalized to other agroecosystems in the region. Runoff TN, SRP, K, and SO₄²⁻ concentrations were best described by a linear model with a normal distribution, NO₃⁻ + NO₂⁻ by a linear model with a Cauchy distribution, and TP by a quadratic model (Table 3). Runoff TSS concentration was best described

by a log-transformed linear model with a Cauchy distribution (**Table 3**).

All regression models were significant ($P < 0.05$), suggesting that total rainfall between sampling dates can be used as a relevant predictor of runoff nutrient concentrations (**Table 3**). However, the ability of the predictor to explain the variability of the response variables was weak, as indicated by low R^2 values (**Table 3**). With the models able to capture between 10% (K) and 26% (TSS) of the variability, the results indicated that total rainfall between sampling dates needed to be associated with other relevant predictors, such as antecedent soil moisture, to achieve reliable and useful predictions (**Table 3**). While TR represented a significant and substantial contributor to the prediction of nutrient runoff, the use of TR alone in prediction models can lead to considerable over- and/or under-estimation of nutrient concentration trends and magnitude. The predictive equations showed that the linear coefficients (*i.e.*, slopes) for total rain (TR) as the predictor were 0.01 for $\text{NO}_3^- + \text{NO}_2^-$, SRP, and TSS; 0.02 for TN and K; and 0.03 for SO_4^{2-} concentrations (**Table 3**). The numerically similar linear coefficients for TR across all response variables suggested that an increase in rainfall would result in a numerically similar increase in runoff concentrations (**Table 3**).

Table 3. Summary of regression models for nitrate and nitrite ($\text{NO}_3^- + \text{NO}_2^-$), total nitrogen (TN), soluble-reactive phosphorus (SRP), total phosphorus (TP), potassium (K), sulfate (SO_4^{2-}), and total suspended solids (TSS) concentrations ($\text{mg}\cdot\text{L}^{-1}$) from runoff water with total rain (mm) measured between consecutive sampling dates as the predictor variable ($n = 45$) throughout 2022, 2023, and 2024 in a furrow-irrigated rice field near Newport, AR.

Response Variable	Model	R^2	P -value	Predictive Equation
$\text{NO}_3^- + \text{NO}_2^-$	Cauchy	0.14	<0.01	$0.10 + 0.01*\text{TR}^\ddagger$
TN	Linear	0.16	<0.01	$1.78 + 0.02*\text{TR}$
SRP	Linear	0.11	0.02	$0.07 + 0.01*\text{TR}$
TP	Quadratic	0.18	0.01	$0.33 + 0.01\text{TR} - (2.59 \times 10^{-5})*(\text{TR} - 49.44)^2$
K	Linear	0.10	0.03	$2.26 + 0.02*\text{TR}$
SO_4^{2-}	Linear	0.18	0.01	$6.86 + 0.03*\text{TR}$
TSS	Log-Cauchy	0.26	<0.01	$2.14 + 0.01*\text{TR}$

[‡]Total rain measured between consecutive sampling dates.

The effect of TR on the response variables did not appear to be associated with the chemical characteristics of the nutrients, but more likely with the physical impact rainfall events can have on nutrient transport at the soil surface (**Table 3**). A significant relationship between rainfall intensity and runoff nutrient concentrations has been reported in previous studies in agricultural settings [47] [52] [56]. A laboratory study assessing rainfall intensity effects on nutrient runoff from agricultural soils, which also occurred in the current study, but, in contrast to the results of the current study, identified a negative relationship between rainfall and runoff NO_3^- concentration [56]. A quadratic relationship between runoff TP concentration and rainfall was reported in previous laboratory studies, where an ini-

tial increase in runoff TP concentration occurred as rainfall increased, followed by a decrease in runoff TP concentration with further increases in rainfall [57]. The kinetic energy of raindrops can solubilize soil-adsorbed P in the topsoil and detach soil aggregates with adsorbed P, resulting in a rapid increase in runoff P concentration [57]. As rainfall increases, a dilution effect may also result in an apparent decrease in runoff TP concentration [57].

Erosion and dilution processes associated with runoff events are influenced by field topography, field position in the landscape, and near-surface soil hydraulic properties [58] [59]. Differential runoff trends in response to rainfall events have been reported for the up-, mid-, and down-slope portions within the same field [60]. However, in the current study, runoff nutrient concentrations were the result of runoff processes occurring along the entire predominant and uniform slope of the field, which likely affected the power of rainfall to predict runoff nutrient concentrations (Table 3).

3.2.4. Nutrient Loads

Across the 3-year study period, the magnitude of the various runoff loads varied, although some common trends were visible (Figure 3).

A steep increase in all nutrient runoff loads occurred over time in 2022, followed by a more moderate increase over time in 2023, and another steep increase over time in 2024 (Figure 3). Runoff loads were likely related to fertilizer and PL additions that caused discrete spikes over the course of the 3-year study period (Figure 3).

Runoff nutrient loads were likely correlated with the temporal trends in total flow. Increasing total flow over time in 2022, in combination with the recent land-leveling that had occurred, contributed to all runoff nutrient loads, except for K, where 2022 runoff load rates were numerically lower than in 2024 (Figure 3). The soluble nature of K likely resulted in a substantial portion of K being lost in the short term after land-leveling and before the runoff measurements began [26] (Figure 3). The homogeneous total flow measured in 2023 contributed to a relatively low rate of nutrient loss for all nutrients, except for SRP, TP, and TN, where three distinct changes in slope (*i.e.*, the change in load per unit change in time) are visible (Figure 3). Total flow in 2023 was characterized by three numerically large spikes that likely controlled the magnitude of SRP, TP, and TN loads (Figure 3). The relatively low N, P, and K concentrations in the PL applied for the 2023 growing season likely contributed to the reduced nutrient loss rate in 2023 compared to 2022 and 2024 (Table 2; Figure 3).

Temporal trends in nutrient loads reflect the dynamic nature of FIR systems, where environmental conditions are spatially variable, resulting in variable nutrient losses even when management practices and soil amendments are similar. The results appear to indicate that managing total flow across a FIR field would be an efficient option to regulate and potentially limit nutrient losses over time (Figure 3). The results also highlight how critical management practices are during the off-season when substantial nutrient losses can occur, reducing soil fertility for

the next growing season (**Figure 3**). Practices such as cover crops and levees, maintained between growing seasons, have been suggested as useful options to decrease nutrient runoff losses [26] [61]. Cover crops and levees strategically positioned at the end of a FI field can slow water flow along the predominant field slope and at the field edge, respectively, allowing PL-applied nutrients more time to mineralize and be assimilated into the topsoil [61] [62].

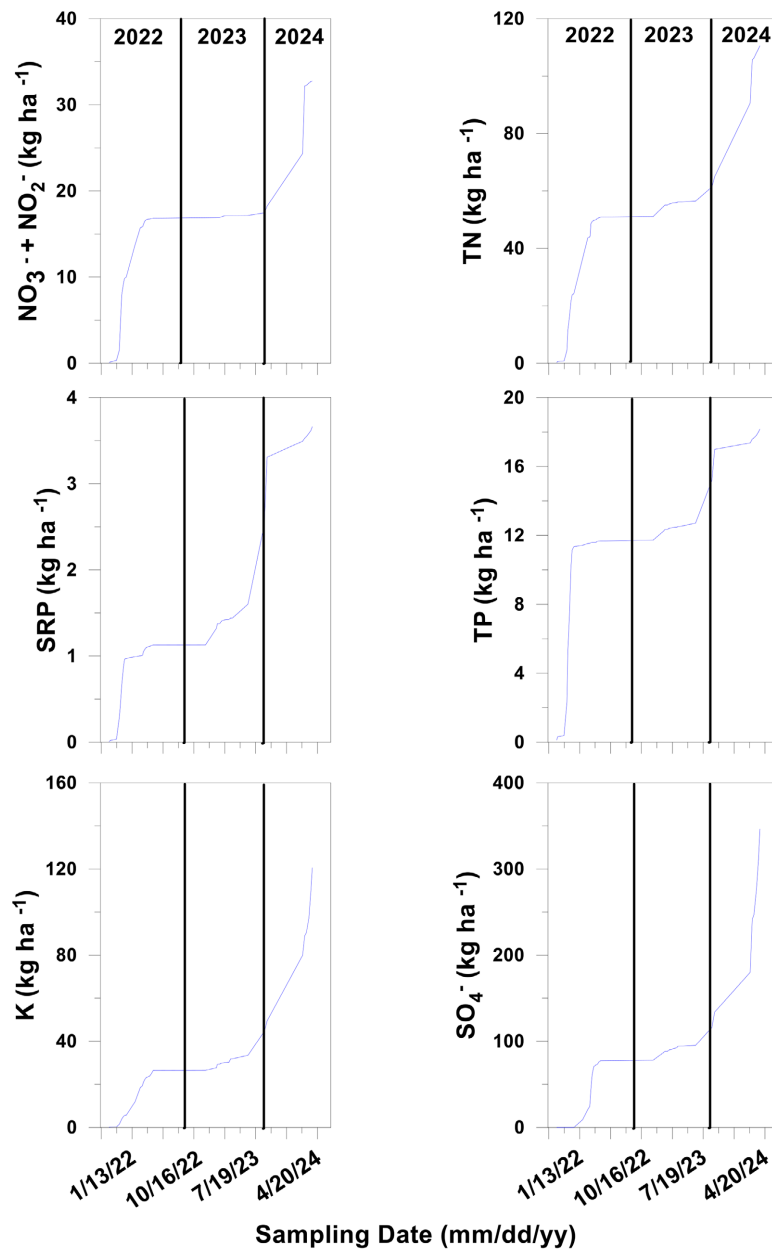


Figure 3. Visual representation of the cumulative nitrate and nitrite ($\text{NO}_3^- + \text{NO}_2^-$), total nitrogen (TN), soluble-reactive phosphorus (SRP), total phosphorus (TP), potassium (K), and sulfate (SO_4^{2-}) runoff loads throughout 2022, 2023, and 2024 from a furrow-irrigated rice field near Newport, AR. Vertical lines from the bottom to the top axes separate the years. Note the different y-axis scales across runoff properties.

3.2.5. TSS Concentrations and Loads

Total suspended solids in agricultural runoff are composed mostly of sediment particles detached from soil-surface aggregates by raindrop splash and slaking from irrigation events, but also partly of dissolved materials [63]. The analysis of TSS does not provide information on the composition of the particles suspended in the runoff, but TSS can be used as a proxy to assess the degree of in-field soil erosion [63]. The evaluation of runoff TSS temporal trends can represent an essential tool to determine what mechanisms are enhancing soil erosion during the growing season [64].

Runoff TSS concentrations followed a negative exponential trend within each of the three study years, with an apparent correlation between TSS and rainfall that decreased over the course of the 3-year study period, as hypothesized (Figure 4).

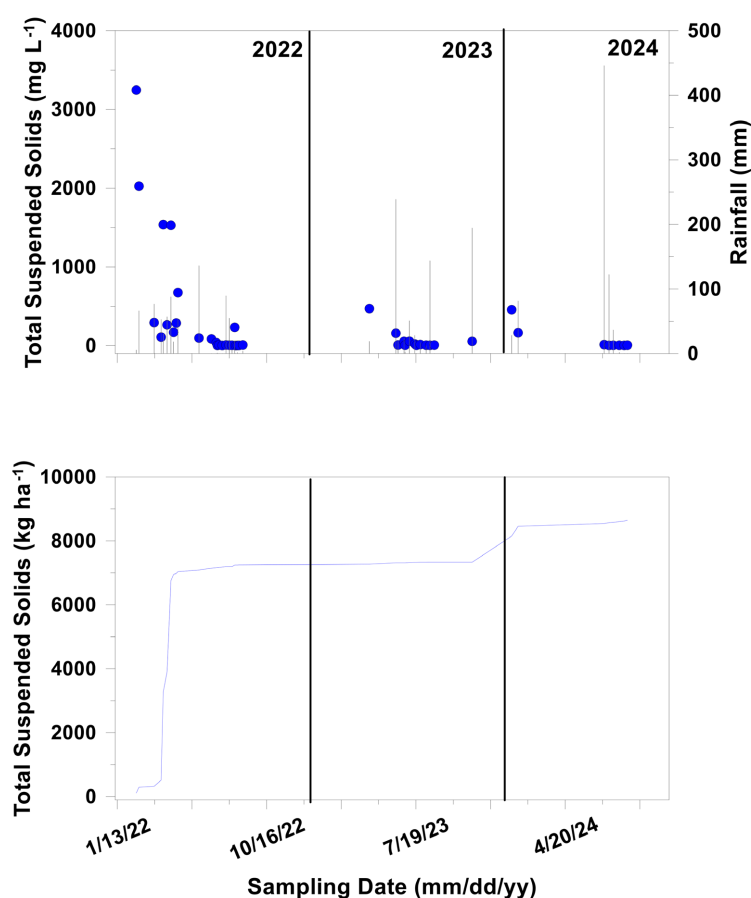


Figure 4. Visual representation of total suspended solids concentration in runoff water and rainfall (vertical bars) amount calculated as total rainfall received between consecutive sampling dates (top panel) and cumulative total suspended solids load (bottom panel) throughout 2022, 2023, and 2024 for a furrow-irrigated rice field near Newport, AR. Vertical lines from the bottom to the top axes separate the years.

The numeric peak runoff TSS concentration occurred on 17 February (3245 mg·L⁻¹), 24 April (470 mg·L⁻¹), and 12 January (457 mg·L⁻¹) in 2022, 2023, and 2024, respectively (Figure 4). The lack of observations during the first three

months of 2023 and between February and June 2024 may have resulted in an incomplete representation of the temporal trend of TSS, although some temporal patterns are still visible (**Figure 4**). The temporal trend of runoff TSS concentrations closely resembled the runoff TP trend over the course of the 3-year study period (**Figure 2** and **Figure 4**). A strong, significant relationship between runoff TSS and runoff TP concentrations has been identified on clayey soils due to the predominant contribution of particulate P to runoff P concentrations [50].

Each of the three study years was characterized by numerically greater TSS concentrations during the early runoff events, followed by a decreasing trend that stabilized towards the last observations (**Figure 4**). Runoff TSS concentrations were numerically greater during the first half of 2022 compared to the first half of 2023 and 2024, while the second half of each year produced similar runoff TSS concentration magnitudes and temporal trends (**Figure 4**). Runoff TSS concentrations stabilized around 13 June 2022, 16 June 2023, and 1 July 2024, suggesting that environmental conditions during the growing season substantially impacted rainfall and irrigation effects on soil erosion (**Figure 4**).

The land-leveling that occurred in 2021 substantially disturbed the soil surface, resulting in loose soil and increased erosion potential, along with the potential for nutrient and organic matter loss [65] (**Figure 4**). A substantial increase in soil erosion and TSS loads was reported from a recently land-leveled area being reclaimed for agricultural activities in southern Italy [65]. Macropore disaggregation and sub-soil exposure caused by land-leveling processes can result in detached soil particles and soil crusting that can reduce infiltration and enhance runoff and soil erosion [65]. The numerically lower runoff TSS concentrations in 2023 and 2024 compared to 2022 could have been related to the soil surface stabilizing over time to allow more infiltration and reduce runoff (**Figure 4**). The periods of no measured TSS concentration that occurred each year were likely related to rice plants that, between June and July, achieved enough vegetative growth and root development to limit the erosive action of rainfall and irrigation (**Figure 4**) [66]. An exponential decrease in water erosion rate has been associated with increasing vegetative cover in agricultural fields [66]. Root exudates provide organic compounds that stabilize rhizosphere soil to enhance soil aggregation and reduce the erosive potential of water at the soil surface [66].

Runoff TSS load assessments over time can provide additional complementary information to runoff TSS concentration trends (**Figure 4**). At the end of 2022, the cumulative TSS load was 7251 kg·ha⁻¹, which represented almost 84% of the total runoff TSS load recorded for the whole 3-year study period (8649 kg·ha⁻¹; **Figure 4**). In 2023, only 80.9 kg TSS ha⁻¹ was estimated, while in 2024, runoff TSS amounted to 1317 kg·ha⁻¹ (**Figure 4**). Although a more intense and frequent water sampling scheme might have provided more detailed trends, the results clearly indicate the negative but short-lived effect land leveling had on topsoil erodibility.

Soil losses exceeding 1000 kg·ha⁻¹ have been classified as irreversible and typical of desertification processes [65]. While the risk of desertification is not applicable to the current study, the large cumulative runoff TSS load in 2022 (**Figure 4**)

clearly indicated that land leveling can be a severe soil-surface disturbance and that land-leveling management practices must be implemented to limit soil erosion [65]. Cover crops have been suggested as a management option following land leveling to prevent, or at least minimize, runoff [62]. The increasing runoff TSS loads at the end of 2023 represent the only indication that the PL application in the fall may contribute to soil erosion (Figure 4). Poultry litter additions have often been associated with increased runoff nutrient losses, but also with a reduction in particle losses due to the ground cover and increased water-holding capacity provided by the organic amendment itself [67].

3.3. P and K Budget Analysis

Poultry litter applications in agricultural fields are often used as an N, P, and K source, which are also elements prone to runoff. Estimating a simplified nutrient budget with fertilizers and PL as inputs and runoff and grain uptake and removal as outputs can provide important insight regarding nutrient cycling among the pedosphere, hydrosphere, and biosphere. Removal processes like leaching, particularly relevant for soluble elements like K and N, and gaseous losses from the pedosphere, which can be significant for elements like N, were not considered in the current study, leading to potential overestimation of the resulting nutrient budgets. Grain-P and -K uptake was not directly measured but was estimated using the combine-harvested yield and the average grain-P (*i.e.*, 0.23%) and -K (*i.e.*, 0.27%) concentration measured in a similar hybrid cultivar grown in FI conditions on a silt-loam soil [41] [68]. The combine-harvested yield for the entire field was 10.3, 11.8, and 7.9 Mg·ha⁻¹ in 2022, 2023, and 2024, respectively.

In 2022, grain removal represented 39% of the total P additions that were entirely sourced from the PL application, as no fertilizer-P application occurred (Table 4).

Table 4. Summary of phosphorus (P) and potassium (K) additions and losses and estimated budgets (*i.e.*, additions minus losses) over the course of the 2022, 2023, and 2024 growing seasons individually and overall for the 3-year study period from a poultry-litter (PL)-amended, furrow-irrigated rice field near Newport, AR.

Element	Period	Additions (In)		Losses (Out)		Budget
		Fertilizer (kg·ha ⁻¹)	PL (kg·ha ⁻¹)	Grain Removal (kg·ha ⁻¹)	Runoff (kg·ha ⁻¹)	Δ(In-Out) (kg·ha ⁻¹)
P	2022	0	61	23.7	11.7	+25.6
	2023	0	38.6	27.0	1.0	+10.6
	2024	0	50.7	18.3	5.5	+26.9
	Overall	0	150.3	69.0	18.2	+63.1
K	2022	93.4	139.9	27.8	26.5	+179.0
	2023	93.4	117.5	31.7	7.0	+172.2
	2024	93.4	154.3	21.5	87.1	+139.1
	Overall	280.2	411.7	81.0	120.6	+490.3

Similar to that hypothesized, runoff P loss constituted 19% of the total P added, for a cumulative P loss from the field equal to 58% of the total P added (**Table 4**). In 2023, grain removal, runoff P loss, and total removals/losses accounted for 70, 3, and 73%, respectively, of the total P added. In 2024, grain removal, runoff P loss, and total removals/losses amounted to 46, 12, and 58% of the total P added, respectively (**Table 4**). Over the three years, the simplified P budget showed that 46 and 12% of the 150.3 kg total P·ha⁻¹ added to the field were removed as grain uptake and lost as runoff, respectively (**Table 4**).

Results indicated a positive budget (*i.e.*, greater inputs than outputs) for the three years, suggesting that, in the absence of other P-loss processes from the field, soil-P accumulation was expected. The positive budgets in 2022 and 2024 were numerically similar, whereas in 2023, the numerically lower PL-P addition and the numerically greater yield likely resulted in a numerically lower P budget (**Table 4**). Similar results were reported by [69] in row-crop and grazed-pasture systems on various soil textures and treated with various PL rates, where a positive P budget was estimated on a yearly basis using a budget approach similar to that in the current study. Contrary to [69], which used DRP as a runoff-P concentration predictor, the percentage of runoff P lost in the current study was numerically greater than that reported by [69]. Runoff P losses relative to total P additions in the current study suggest that management practices in land-leveled, FI rice need to be considered to limit edge-of-field P losses.

Similar estimated budgets over the course of the three years occurred for K as for P (**Table 4**). Grain-K removal accounted for 12, 14, and 9%, while runoff K losses accounted for 11, 3, and 37% of the total K added in 2022, 2023, and 2024, respectively (**Table 4**). Somewhat similar to that hypothesized, K loss amounted to 23, 45, and 46% of the total K added in 2022, 2023, and 2024, respectively, suggesting that a substantial portion of K is removed and lost from the field each year (**Table 4**). Combined over the three years, 12 and 17% of the total K added was removed in grain and lost through runoff, respectively (**Table 4**). While adequate nutrient uptake is necessary to maintain optimal crop production, runoff K losses can significantly impact the economic return of agricultural enterprises [26] [70].

Similar to P, the K budget estimated a K surplus and soil K accumulation if no other loss mechanisms were considered (**Table 4**). A meta-analysis evaluating conventional and conservation management practices with and without the addition of cow slurry estimated K budgets from root and cereal cultivations, calculated with a similar approach as in the current study, with magnitudes roughly half of the K budget components estimated in the current study [71] (**Table 4**). However, [71] included nutrients removed from the vegetative crop biomass as an additional output that was not considered in the current study.

In rice production, more than 60% of the aboveground plant residues are returned to the soil during the harvest process and, if residues are not burned, the nutrients stored in the vegetative tissues can potentially be returned to the soil [72]. Plant residue decomposition can result in nutrient release from vegetative

tissues that can be lost through runoff and/or leaching or immobilized and fixed in the soil [72] [73]. Nutrients that accumulate in the soil can then be used by a subsequent crop [72]. Therefore, assessment of changes in soil nutrients between the main growing seasons can provide additional insight into the fate and transport of nutrients and improve nutrient budget estimates.

3.4. Changes in Soil Properties

The change in soil properties for each growing season and over the 3-year study period was determined for several soil properties to assess the effects on soil fertility and chemical parameters over time and to provide an additional comparison for the K and P budgets (Table 4 and Table 5). The change in soil properties for each single year reflects the change that occurred over an entire calendar year. Therefore, the annual change included the effects of one PL application and one full growing season (Table 5).

Table 5. Summary of the mean ($n = 29$) change (Δ) in soil properties, calculated as the end-of-the-season value minus the beginning-of-the-season value, with standard errors in parentheses, for the 2022, 2023, and 2024 growing seasons individually and overall for the 3-year study period in a furrow-irrigated rice field near Newport, AR.

Soil property	$\Delta 2022$	$\Delta 2023$	$\Delta 2024$	$\Delta 3\text{-year Period}$
pH	+0.5 (0.1)	-0.1* (0.1)	+0.1* (0.1)	+0.5 (0.1)
P (kg·ha ⁻¹)	+1.6* (1)	+18.8 (3)	-15.2 (3)	+5.2 (1)
K (kg·ha ⁻¹)	+60.4 (6)	+64.3 (8)	-36.3 (9)	+88.5 (8)
Ca (kg·ha ⁻¹)	+367 (56)	-29.4* (79)	-9.1* (96)	+329 (70)
Mg (kg·ha ⁻¹)	+78.6 (20)	+33.1 (15)	-29.3* (16)	+82.4 (12)
Na (kg·ha ⁻¹)	-0.8* (1)	+8.1 (1)	+1.6* (1)	+8.9 (1)
S (kg·ha ⁻¹)	-5.1 (1)	+13.2 (2)	-6.4 (2)	+1.7* (1)
Fe (kg·ha ⁻¹)	+80.8 (8)	-35.1 (12)	-6.4* (10)	+39.4 (7)
Mn (kg·ha ⁻¹)	+48.7 (13)	-56.7 (11)	-6.9* (11)	-15.0* (13)
Zn (kg·ha ⁻¹)	-0.2* (0.5)	+1.8 (0.4)	-0.6* (0.4)	+0.9* (0.5)
Soil organic matter (Mg·ha ⁻¹)	-2.2* (1)	+4.9 (1)	+2.8 (1)	+5.6 (1)

An asterisk () indicates the mean does not differ from zero ($P > 0.05$).

In 2022, except for Na, S, Zn, and SOM, which at least numerically decreased over time, all other soil properties at least numerically increased over time in the top 10 cm, although the soil P change did not differ ($P > 0.05$) from zero (Table 5). Among the soil properties that decreased in 2022 (*i.e.*, Na, S, Zn, and SOM), only the soil S change did not differ ($P > 0.05$) from zero (Table 5). During 2023, except for soil pH, Ca, Fe, and Mn, which at least numerically decreased over time, all other soil properties at least numerically increased over time (Table 5). Among the soil properties that decreased over time in 2023 (*i.e.*, pH, Ca, Fe, and Mn), only soil pH and Ca changes did not differ ($P > 0.05$) from zero (Table 5). During 2024, except for soil pH, Na, and SOM, which at least numerically increased over time,

all other soil properties at least numerically decreased over time, while the change in soil pH, Ca, Mg, Na, Fe, Mn, and Zn did not differ ($P > 0.05$) from zero (**Table 5**). Over the 3-year study period, none of the soil property differences over time showed a constant trend, although management and field practices were identical across the three growing seasons (**Table 5**).

Following land leveling, PL and inorganic fertilizer applications likely raised the soil pH and facilitated nutrient fixation in the exposed subsoil, thus improving many soil properties (**Table 5**). The results of the current study support previous reports that PL can be used as an effective option to increase soil fertility levels after land leveling [3] [11] [74] (**Table 5**). Similar results were reported by [75], who conducted a meta-analysis on PL effects on nutrient availability in plant-soil systems. Continuous PL application in agroecosystems increased SOM and soil C, N, P, K, Ca, and Mg in the topsoil [11] [76] [77].

The numeric and significant soil P and K changes on a yearly basis, when combined with the simplified annual P and K budget estimates, provide a more precise picture of the fate and transport of P and K (**Table 4** and **Table 5**). Soil P and K accumulation on a yearly basis (*i.e.*, positive change) suggested that a portion of the P and K additions was assimilated into the topsoil, thus reducing the annual P and K budget estimates by the amount of soil P and K increase. An annual soil P and K decrease suggested soil P and K removal, the fate of which could not be precisely accounted for; thus, the P and K budgets were increased by the amount of soil P and K decrease. Consequently, updating the P budget with the soil P change resulted in +24, -8.2, and +42.1 kg·ha⁻¹ in 2022, 2023, and 2024, respectively, and an overall 3-year P budget of +62.6 kg·ha⁻¹, which corresponded, on average, to a positive P budget of 20.9 kg·P·ha⁻¹·yr⁻¹ (**Table 4** and **Table 5**). Updating the K budget with soil K changes resulted in +119, +108, and +175 kg·ha⁻¹ in 2022, 2023, and 2024, respectively, and an overall 3-year K budget of +402 kg·ha⁻¹, which corresponded, on average, to a positive K budget of 134 kg·K·ha⁻¹·yr⁻¹ (**Table 4** and **Table 5**). The estimated P and K budgets, accounting for soil storage changes, suggest that continuous annual PL application could result in a nutrient surplus that requires additional inputs that were not considered in the current study to fully understand nutrient fates. If a neutral budget (*i.e.*, inputs = outputs) is considered the best management practice to reduce nutrient losses through runoff, according to the current results, PL application should be reduced to two out of three and three out of four years if PL is used as a P and K source, respectively. Similar conclusions were reached in a study conducted in the Blackland Prairie ecoregion in Texas on long-term PL effects on P balance and runoff in various crop production systems [69].

Results indicated that the variability among annual nutrient budgets makes it difficult to pinpoint which mechanisms and processes should have been considered in the analytical approach. Multiple years in the current study were necessary to determine long-term trends in soil P and K fate and transport and to determine which nutrient budget components needed to be accounted for. In a 2-year study

in FI rice on a silt-loam soil in east-central Arkansas, [68] reported vegetative P uptake that ranged from 5.7 to 14.7 kg-ha⁻¹ and vegetative K uptake that ranged from 111 to 299 kg-ha⁻¹, which approximated the updated 3-year average P and K budgets estimated in the current study. Consideration of rice residue left on the soil surface after each harvest could provide another important input to account for, in addition to inputs from amendments and fertilizers and outputs from runoff and grain nutrient removal, to more reliably track nutrients in an agroecosystem. The estimated SOM accumulation over time (Table 5) indicated that continuous annual PL application can be a useful management option to enhance soil health toward optimal levels in degraded, land-leveled fields to increase agricultural sustainability.

4. Conclusions

Poultry litter has often been recommended for application to intensively cultivated agricultural fields to enhance soil fertility and health. Furrow-irrigated rice production systems represent an increasingly adopted cultivation method in Arkansas that can increase water-use efficiency while maintaining yields. Although the combination of furrow-irrigation and PL application in rice fields can lead to substantial runoff and nutrient losses, to date, few studies have assessed nutrient runoff from FI rice systems in Arkansas.

Results supported the hypothesis that the relationship between rainfall and runoff was visually weaker over time for each of the three growing seasons. Results supported the hypothesis that cumulative rainfall between sampling dates can be used as a predictor of runoff nutrient concentrations, although additional predictors need to be considered to improve the predictive ability of the models. Results partially supported the hypothesis that runoff P and K loads represented 20% of the total nutrient additions, where, on average, over the course of the 3-year study period, P and K accounted for only 11 and 17% of total nutrient inputs. Results supported the hypothesis that positive P and K budgets calculated over the 3-year course of the study were associated with nutrient accumulation in the topsoil, although a great degree of variability occurred from year to year. Results also supported the hypothesis that PL application can increase soil fertility and soil health levels over time.

The current study clearly indicated that continuous annual PL applications can be used as an organic amendment and nutrient source in agricultural fields that have experienced severe disruptions due to land-leveling. However, this study also highlighted the potential risk that PL can stimulate increased runoff nutrient losses. Management practices should be implemented during the growing season and during the off-season to reduce runoff, erosion, and nutrient losses. Cover crops during the off-season and calibrated irrigation regimes during the growing season are potentially effective management practices that have been implemented with the specific purpose of limiting erosion and runoff. Future studies should aim to develop calibrated mitigation practices for PL-amended rice fields

to establish optimal rates and application timings to enhance agricultural sustainability in the Lower Mississippi River Valley and beyond.

Conflicts of Interest

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

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