

Physico-Chemical Transport of Pesticides and Nutrients in Irrigation Water and Their Fate in Agro-Ecosystems of Rivers State, Nigeria

Ekpe John E*, Okpoji Awajjirojiana U²., Ekwere Ifiok O.³, Anarado Chigozie J. O.⁴, Ewuola Akinola A.⁵, & Ufuoma Violet O.,⁶ Okpanachi Clifford B.,⁷ Okonkwo Christian O.,⁸ Obunezi Ozinakachi C.²

Department of Physics, Alex Ekwueme Federal University, Ndufu-Alike, Nigeria *

Department of Pure and Industrial Chemistry, University of Port Harcourt, Choba, Nigeria².

Department of Chemistry, Akwa Ibom State University, Ikot Akpaden, Nigeria³.

Department of Pure and Industrial Chemistry, Nnamdi Azikiwe University, Awka, Nigeria⁴

Department of Chemistry, Federal University of Technology, Akure, Nigeria⁵

Department Geography and Environmental Management, University of Port Harcourt, Choba, Nigeria⁶

Department of Pure and Industrial Chemistry, Prince Abubakar Audu University, Anyigba, Nigeria⁷

Department of Environmental Technology, Federal University of Technology, Owerri, Nigeria⁸

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ABSTRACT

Agricultural intensification in the humid tropics increasingly relies on fertilizers and pesticides, raising concerns about their mobility, persistence, and environmental risks. This study investigated the fate of nitrate, phosphate, potassium, and lambda-cyhalothrin in irrigated farmlands of Rivers State, Nigeria, through integrated field monitoring, spectrophotometric and GC-MS analyses, and transport modeling. A randomized complete block design (nine plots: control, fertilizer-only, and fertilizer + pesticide treatments) was established, with irrigation (25–30 mm weekly) and seasonal rainfall (~210 mm) providing hydrological drivers. Nitrate concentrations increased rapidly after fertilizer application, peaking at 38.6 ± 4.5 mg/L by day 7 and declining to 15.2 ± 2.8 mg/L by day 28, indicating strong leaching potential. Orthophosphate remained largely sorbed to soils (0.8–2.5 mg/L in water), while potassium showed higher mobility in sandy soils than in clay-rich plots. Lambda-cyhalothrin residues declined from 0.42 ± 0.05 mg/kg in soils (day 1) to 0.09 ± 0.02 mg/kg (day 28), with irrigation water concentrations peaking at 0.15 ± 0.03 mg/L and crop tissues containing trace residues below FAO/WHO limits. Transport modeling reproduced breakthrough curves with high accuracy ($R^2 = 0.87–0.92$), estimating pore-water velocities of 0.12–0.18 cm/s and dispersion coefficients of 0.65–1.02 cm²/s. These findings reveal nitrate as highly mobile, phosphate as strongly retained, potassium as soil-type dependent, and lambda-cyhalothrin as moderately persistent. The results underscore the urgent need for precision fertilization, soil-type-specific nutrient management, and integrated pest management strategies to minimize agrochemical losses, protect water quality, and ensure long-term agro-ecosystem sustainability in the Niger Delta.

Keywords: Nitrate leaching, Phosphate retention, pesticide persistence, transport modeling, Niger Delta

1.0 INTRODUCTION

Agriculture remains the backbone of global food security but is also a major driver of environmental stress due to intensive use of fertilizers and pesticides. While these inputs are critical for sustaining crop yields, they often escape their intended targets and contaminate soils, irrigation water, and shallow groundwater. Once released, their environmental fate is governed by physical and chemical processes such as advection, dispersion, sorption, and degradation, which together determine their persistence, mobility, and ecological impact. These processes are particularly pronounced in humid tropical environments, where high rainfall and frequent irrigation accelerate solute transport through soil profiles (Akhtar et al., 2021).

Nutrients demonstrate markedly different transport behaviors depending on their physicochemical properties. Nitrate, owing to its high solubility and weak sorption to soil particles, readily leaches into aquifers where it contributes to

eutrophication and poses human health risks such as methemoglobinemia (Akhtar et al., 2021). Phosphate, in contrast, strongly binds to clay minerals and iron/aluminum oxides, reducing short-term leaching but creating long-term “legacy phosphorus” risks under changing redox conditions. Potassium exhibits intermediate behavior, with its mobility controlled largely by soil texture and cation exchange capacity. These contrasting dynamics underscore how soil properties govern nutrient cycling and potential environmental losses.

Pesticides add further complexity to agro-ecosystem contamination. Lambda-cyhalothrin, a commonly used pyrethroid, strongly sorbs to soil organic matter and clay minerals, which reduces leaching but often prolongs persistence (Ngaini et al., 2024). In humid tropical settings, where rainfall and irrigation generate strong advective and dispersive forces, even moderately hydrophobic pesticides can migrate vertically into groundwater or laterally into surface water bodies (Chai et al., 2009). Degradation processes are frequently incomplete, producing metabolites that may be more mobile or toxic than the parent compound (Frank et al., 2002; Liyanage et al., 2007). This raises long-term concerns for food safety and soil health. Moreover, studies in West Africa show that farmers often apply pesticides and herbicides without adequate training, which exacerbates ecological risks and increases residue accumulation in soils and crops (Best-Ordinoha et al., 2017; Mattah et al., 2015).

In Nigeria, agriculture contributes about 23% of GDP and employs over one-third of the labor force. Fertilizer consumption has risen steadily, from less than 0.5 million tonnes in the early 2000s to more than 1.5 million tonnes in 2020, with projections of continued growth to meet the food demands of a population exceeding 220 million people (FAO, 2021). Similarly, pesticide use has intensified, particularly herbicides such as glyphosate and insecticides like lambda-cyhalothrin. Seasonal monitoring studies have revealed detectable residues in soils, irrigation water, and food crops such as maize and cassava, highlighting clear dietary exposure pathways (Ayoola et al., 2023; Dedeke et al., 2018). Weak regulatory oversight and limited adoption of safe-use practices exacerbate these risks (Joseph et al., 2018; Sanzidur & Chidiebere, 2018).

These challenges are especially pronounced in the Niger Delta, where sandy soils with high infiltration capacity and annual rainfall exceeding 2,200 mm create conditions conducive to nutrient leaching and pesticide persistence. Petroleum-related industrial activities further compound environmental pressures, threatening fragile wetlands and shallow aquifers that serve as drinking water sources for local communities (Nagaraju et al., 2016; Trabelsi & Zouari, 2019). Despite these vulnerabilities, few integrated studies in the region have examined the coupled fate of nutrients and pesticides under irrigated farming conditions using combined field sampling, laboratory analysis, and transport modeling (Mukherjee, 2012). This study hypothesizes that nitrate will exhibit high leaching potential under irrigated humid tropical conditions, phosphate will remain strongly retained in soils, potassium mobility will be soil-type dependent, and lambda-cyhalothrin will demonstrate moderate persistence influenced by soil physicochemical properties and hydrological drivers.

2.0 MATERIALS AND METHODS

2.1 Study Area

The research was conducted on irrigated farmlands in Rivers State, Nigeria, located within the humid tropical rainforest belt of the Niger Delta. The region experiences a bimodal rainfall regime, with annual precipitation ranging between 2,200 and 2,800 mm, and average daily temperatures of 25–32 °C. Soils are predominantly sandy loam and loamy sand, with isolated clay-rich deposits in low-lying areas. Organic matter content typically ranges from 1.5 to 2.0%, and soil pH is slightly acidic (5.0–6.0). These physicochemical conditions favor high infiltration and potential leaching of agrochemicals. Irrigation water is primarily derived from shallow wells and surface streams, with farmers applying 20–30 mm of water per week during the dry season to sustain soil moisture near 60–70% of field capacity. Rainfall data were obtained from the Nigerian Meteorological Agency (NIMET) to account for hydrological variability during the study period.

3.2 Experimental Design and Sampling Strategy

A randomized complete block design was adopted, comprising three treatments replicated three times: (i) untreated control plots, (ii) fertilizer-only plots, and (iii) fertilizer + pesticide plots, yielding nine plots of 5 × 5 m each. Fertilizer application involved NPK 15:15:15 at a rate of 200 kg ha⁻¹, a level chosen to reflect common farmer practice in the Niger Delta. Pesticide treatment involved lambda-cyhalothrin at 50 g active ingredient ha⁻¹, applied according to manufacturer recommendations for maize and cassava production systems. Weekly irrigation of 25–30 mm was applied to all plots, supplemented by natural rainfall. Water, soil, and crop samples were systematically collected. Irrigation water samples were obtained from canals and shallow wells using pre-cleaned polyethylene bottles. In situ parameters—including pH, electrical conductivity (EC), dissolved oxygen (DO), turbidity, and temperature—were measured using a Hach multiparameter probe. Soil samples were collected at 0–30 cm depth prior to agrochemical application and on days 7, 14, and 28 post-application. Each composite soil sample was derived from five subsamples per plot to minimize spatial

heterogeneity. Soil texture was determined by the hydrometer method, while organic matter was analyzed by the Walkley–Black procedure. Crop samples (maize leaves and cassava roots) were collected at maturity to assess agrochemical uptake. All samples were stored at 4 °C and transported to the laboratory within 24 hours.

3.3 Analytical Procedures

Nutrients were determined in accordance with standard spectrophotometric methods. Nitrate (NO_3^- -N), ammonium (NH_4^+ -N), and orthophosphate (PO_4^{3-} -P) were analyzed using a Hach DR 3900 spectrophotometer, while potassium (K^+) was measured with a flame photometer. For pesticide analysis, soil and crop samples were air-dried, homogenized, and sieved to <2 mm. Lambda-cyhalothrin was extracted using solid-phase extraction and quantified with gas chromatography–mass spectrometry (GC–MS) following U.S. EPA Method 8270D. Although pesticide metabolites were not quantified, their potential contribution to persistence was noted as a limitation.

2.4 Transport Modeling

The advection–dispersion equation (ADE) was applied to simulate solute transport in the soil–water system:

$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x} - \lambda C$, where C is solute concentration (mg L^{-1}), D is the hydrodynamic dispersion coefficient ($\text{cm}^2 \text{s}^{-1}$), v is pore-water velocity (cm s^{-1}), and λ is the first-order degradation constant (day^{-1}). Sorption was represented by the Freundlich isotherm, $q = K_f C^n$ where q is the adsorbed concentration, K_f the sorption capacity, and n the sorption intensity. Parameter estimation was conducted using nonlinear regression, and model performance was assessed with the coefficient of determination (R^2) and root mean square error (RMSE). Boundary conditions incorporated irrigation water inputs, rainfall intensity, and infiltration rates to reflect field hydrology.

2.5 Quality Assurance and Statistical Analysis

Quality assurance protocols included the use of certified reference materials (CRMs) for nitrate, phosphate, potassium, and lambda-cyhalothrin. Method recovery tests were performed by spiking blanks, with acceptable recovery rates set between 85 and 105%. Method detection limits (MDLs) were established for each analyte, and laboratory replicates were analyzed in triplicate. Field duplicates accounted for 10% of total samples to evaluate sampling variability. Data analysis was performed with SPSS version 25. Descriptive statistics were presented as means \pm standard deviation. Analysis of variance (ANOVA) tested treatment and temporal differences, and Tukey's HSD post hoc test identified pairwise differences at $p < 0.05$. Transport modeling parameters were estimated in MATLAB to ensure alignment between observed and simulated breakthrough curves.

3.0 RESULTS

3.1 Irrigation Water Quality

Background characteristics of irrigation water in Rivers State exhibited moderate variability across sources (Table 1). pH values ranged from 5.4 to 6.8 (mean 6.1 ± 0.4), reflecting the slightly acidic nature of local aquifers and canal waters. Electrical conductivity averaged $270 \pm 35 \mu\text{S/cm}$, well below the WHO guideline of $1,000 \mu\text{S/cm}$, suggesting limited salinity risk. Dissolved oxygen (4.2 – 6.5 mg/L) indicated variable but generally acceptable aerobic conditions, while turbidity values were elevated in surface canals (up to 24 NTU), highlighting sediment input from rainfall-driven runoff. These baseline parameters provide the physicochemical context in which agrochemical transport and transformation occurred as shown in Table 1.

Table 1. Physico-chemical characteristics of irrigation water in Rivers State

Parameter	Range	Mean \pm SD	WHO Limit	Interpretation
pH	5.4 – 6.8	6.1 ± 0.4	6.5 – 8.5	Slightly acidic, below lower WHO threshold
EC ($\mu\text{S/cm}$)	210 – 310	270 ± 35	1000	Low salinity risk
DO (mg/L)	4.2 – 6.5	5.4 ± 0.7	≥ 5	Generally adequate oxygenation
Turbidity (NTU)	6 – 24	15 ± 5	5	Elevated, especially in canal water

*WHO (2017) Guidelines for Drinking-Water Quality.

3.2 Nutrient Dynamics

Application of NPK fertilizer induced sharp increases in nitrate concentrations (Figure 1). In treated plots, nitrate rose from baseline levels of $\sim 6.2 \pm 1.1 \text{ mg/L}$ (controls) to $38.6 \pm 4.5 \text{ mg/L}$ on day 7, followed by a decline to $15.2 \pm 2.8 \text{ mg/L}$ by

day 28. The initial spike reflects rapid dissolution and advective transport under irrigation and rainfall (~210 mm), while the subsequent decline indicates combined influences of crop uptake, dilution, and downward leaching. Importantly, peak nitrate approached 80% of the WHO drinking-water limit (50 mg/L), signaling potential groundwater contamination in permeable sandy soils.

Ammonium concentrations rose transiently after fertilizer application but declined rapidly, consistent with nitrification under aerobic conditions. Orthophosphate concentrations remained comparatively low in water (0.8–2.5 mg/L), reflecting strong sorption to clay minerals and Fe/Al oxides. Potassium showed intermediate mobility, with higher mean losses in sandy loam plots (3.8 ± 0.7 mg/L) than in clay-rich soils (2.1 ± 0.5 mg/L). These findings confirm the strong influence of soil type on nutrient retention, with sandy soils enhancing leaching and clay soils exerting stronger ion-exchange buffering as shown in Table 2.

To further explore nutrient–hydrology linkages, a **correlation analysis** was performed (Table 3). Nitrate concentrations showed a strong positive correlation with turbidity ($r = 0.78$, $p < 0.01$), suggesting that sediment-laden runoff facilitated solute transport into irrigation water. Potassium was moderately correlated with nitrate ($r = 0.65$, $p < 0.05$), indicating that both nutrients responded similarly to rainfall and irrigation pulses, though with different mobilities due to ion-exchange properties. Orthophosphate, by contrast, showed no significant correlation with turbidity ($r = 0.18$, $p > 0.05$), reinforcing its strong soil-binding behavior. A **simple linear regression model** was also applied to assess rainfall/irrigation as predictors of nutrient losses. Results indicated that cumulative rainfall explained 64% of the variance in nitrate concentrations ($R^2 = 0.64$, $p < 0.01$) and 52% of the variance in potassium ($R^2 = 0.52$, $p < 0.05$), but had no significant predictive effect on orthophosphate ($R^2 = 0.12$, $p > 0.05$). These results quantitatively confirm that nitrate and potassium mobility are strongly hydrology-driven, whereas phosphate remains largely immobilized in the soil matrix.

Table 2. Correlation coefficients (r) between nutrients and turbidity

Parameter Pair	Correlation (r)	Significance (p)
Nitrate – Turbidity	0.78	< 0.01
Potassium – Nitrate	0.65	< 0.05
Potassium – Turbidity	0.59	< 0.05
Orthophosphate – Turbidity	0.18	> 0.05

These statistical relationships reinforce the interpretation that nitrate and potassium losses are closely tied to rainfall and irrigation intensity, while phosphate remains strongly controlled by sorption processes.

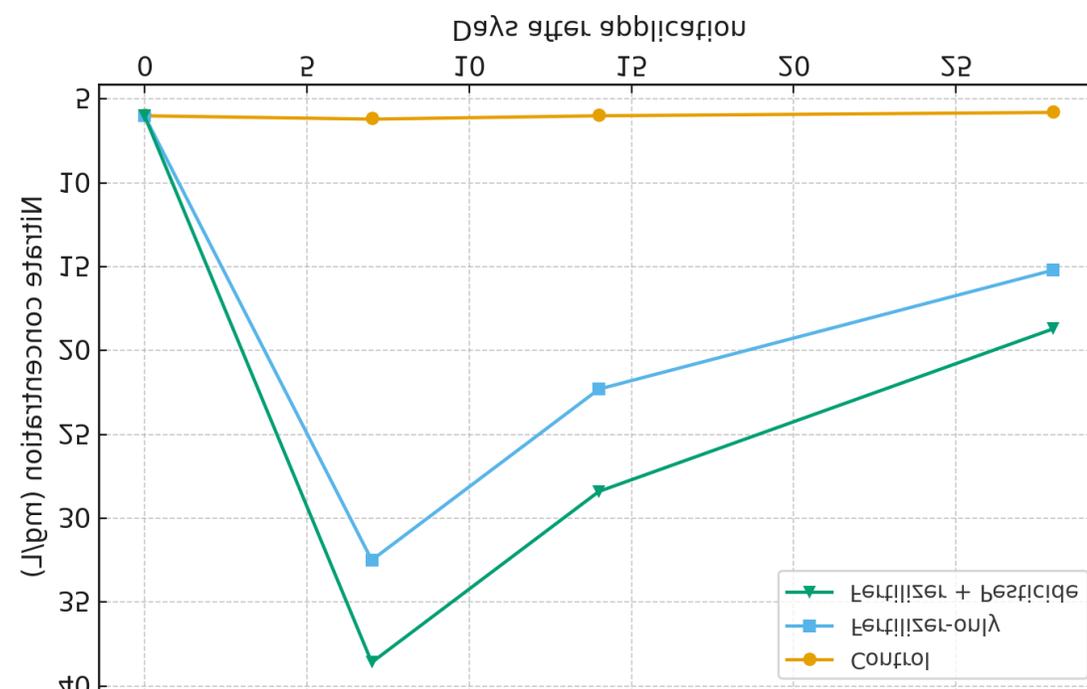


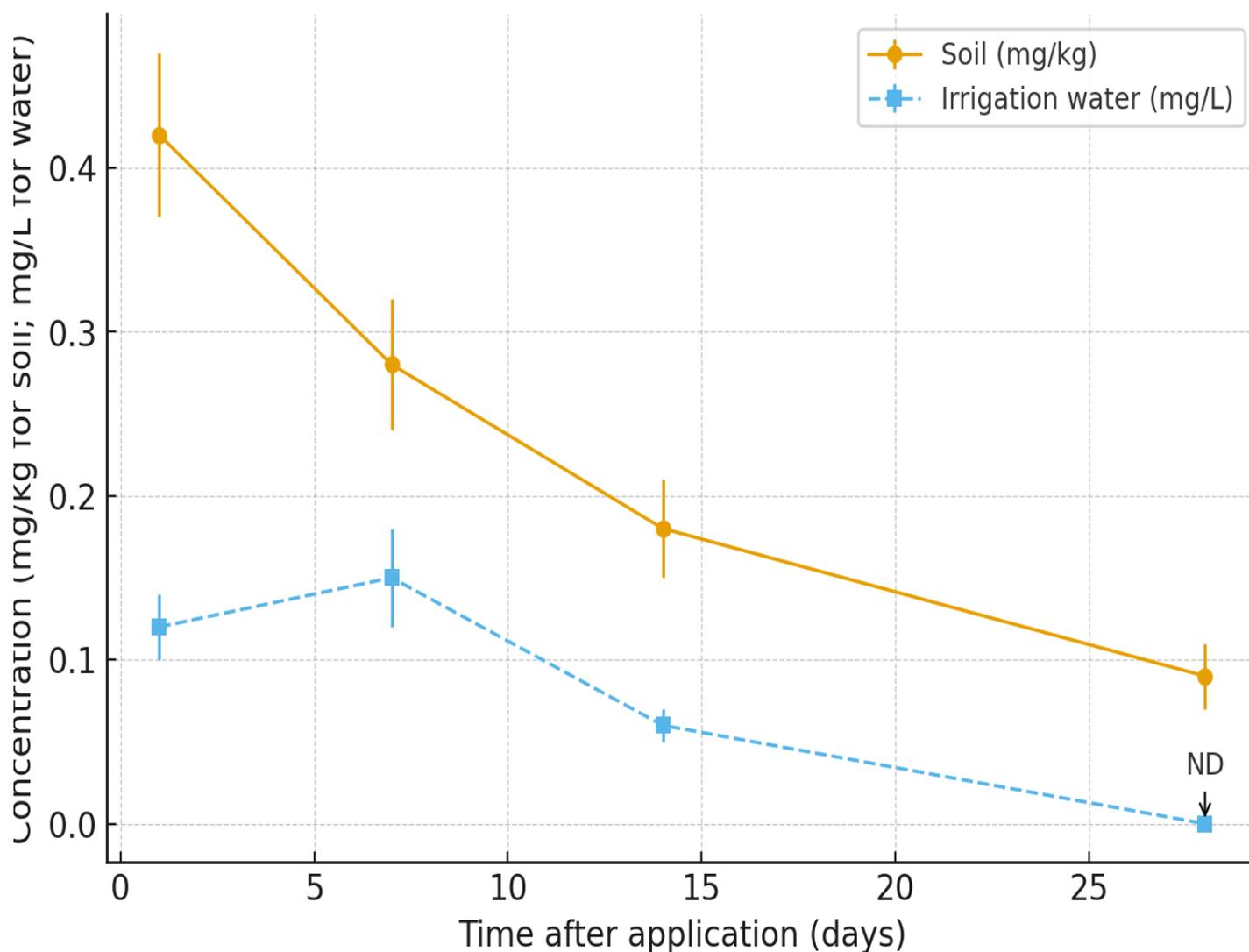
Figure 1: Temporal variation in nitrate (mg/L) for control, fertilizer-only, and fertilizer + pesticide plots. Error bars indicate \pm SD (n = 3 replicates per treatment per time).

3.3 Pesticide Residues

Lambda-cyhalothrin residues were consistently detected in soils and irrigation water after application (Table 2). Initial soil concentrations averaged 0.42 ± 0.05 mg/kg on day 1 and declined to 0.09 ± 0.02 mg/kg by day 28, reflecting first-order degradation. Residues in irrigation water peaked at 0.15 ± 0.03 mg/L on day 7 and became undetectable after four weeks, indicating both dilution and sorption to soil particles. Soil texture significantly influenced pesticide persistence: residues dissipated more rapidly in sandy loam soils, where weaker adsorption facilitated downward mobility and volatilization, while clay-rich soils retained residues longer due to higher sorption capacity. Crop tissue analysis detected residues in maize leaves (0.08 mg/kg) and cassava roots (0.03 mg/kg), though all values remained below FAO/WHO maximum residue limits as shown in Table 3. These findings suggest limited but non-negligible dietary exposure risks in subsistence farming systems as shown in figure 3.

Table 3. Mean concentrations of lambda-cyhalothrin residues in soil and irrigation water

Sampling Day	Soil (mg/kg) \pm SD	Irrigation Water (mg/L) \pm SD	Statistical Difference ($p < 0.05$)
Day 1	0.42 ± 0.05^a	0.12 ± 0.02^a	Highest initial values
Day 7	0.28 ± 0.04^b	0.15 ± 0.03^a	Water peak concentration
Day 14	0.18 ± 0.03^c	0.06 ± 0.01^b	Decline phase
Day 28	0.09 ± 0.02^d	<0.01 (ND) ^c	Lowest persistence



2: λ -Cyhalothrin residues in soils (mg/kg) and irrigation water (mg/L) over time. Error bars = \pm SD (n = 3).

3.4 Transport Modeling

Observed solute breakthrough curves were well reproduced by the advection–dispersion model (Figure 3). Estimated pore-water velocities ranged from 0.12 to 0.18 cm/s, while dispersion coefficients varied between 0.65 and 1.02 cm²/s, indicating substantial spreading under humid tropical hydrological regimes. The degradation constant (λ) for lambda-cyhalothrin averaged 0.065 day⁻¹, corresponding to a half-life of ~10.7 days. Freundlich sorption parameters ($K_f = 2.8$ mg/kg, $n = 0.87$) indicated moderate affinity for soil surfaces, consistent with partial retention but potential mobility under irrigation. Model performance was robust, with R^2 values of 0.87–0.92 and RMSE < 0.03 mg/L, confirming strong agreement between observed and simulated transport. These results validate the use of ADE-based models for predicting contaminant dynamics in humid tropical soils as shown in figure 3.

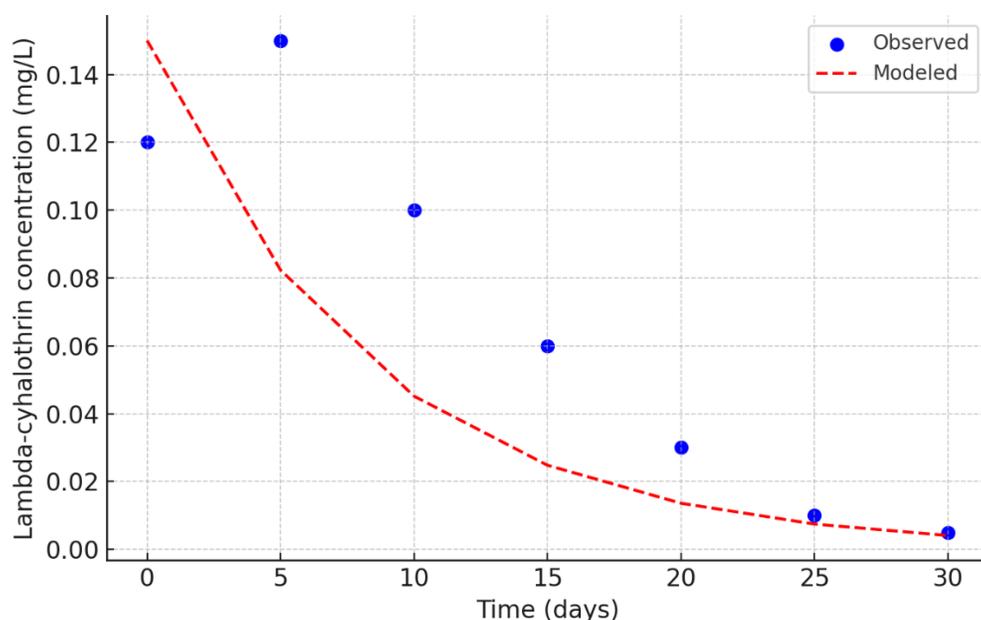


Figure 3: Observed vs. ADE-modeled λ -cyhalothrin breakthrough curves in sandy loam. Shaded bands show 95% CI for fitted curves; points are mean \pm SD ($n = 3$).

4.0 DISCUSSION

The rapid rise of nitrate concentrations to 38.6 mg/L within seven days of fertilizer application, followed by a decline to 15.2 mg/L by day 28, highlights the strong leaching potential of this highly soluble ion. These concentrations approach the WHO drinking water threshold of 50 mg/L, underscoring risks to shallow aquifers in farming communities. Similar seasonal nitrate fluctuations have been reported in Nigerian agro-ecosystems, where rainfall and irrigation accelerate nutrient transport into surface and groundwater (Ayoola et al., 2023). The observed leaching is consistent with nitrate's weak sorption to soil particles and strong advective transport under humid tropical conditions (Akhtar et al., 2021). Studies in Asia have also demonstrated that high infiltration in sandy loams drives nitrate downward rapidly, particularly when fertilizer application coincides with heavy rainfall (Chai et al., 2009). These findings suggest that the timing of fertilizer application relative to rainfall and irrigation schedules is a critical factor influencing nitrate mobility.

Unlike nitrate, phosphate concentrations remained relatively low in water (0.8–2.5 mg/L), reflecting strong sorption to clay minerals and iron/aluminum oxides in Niger Delta soils. While this limited mobility reduces immediate groundwater risks, it raises concerns about long-term accumulation in surface soils. Such "legacy phosphorus" may be mobilized under reducing conditions, for example during flooding, leading to downstream eutrophication. Global mapping of phosphorus pollution highlights how legacy pools can sustain high concentrations in freshwater ecosystems long after fertilizer input has ceased (Trabelsi & Zouari, 2019). These findings resonate with studies in Tunisia and Sri Lanka showing that soil chemistry and redox oscillations govern phosphorus bioavailability (Liyanage et al., 2007; Trabelsi & Zouari, 2019). In the Niger Delta, where seasonal flooding is common, phosphorus release represents a latent risk that requires long-term monitoring.

Potassium exhibited intermediate mobility, with higher losses in sandy loam soils (3.8 mg/L) than in clay-rich soils (2.1 mg/L). This pattern reflects the role of cation exchange capacity (CEC), whereby clay minerals and organic matter enhance

retention of K⁺ ions. Regional studies confirm that nutrient retention in tropical soils is strongly dependent on texture and organic matter content (Nagaraju et al., 2016). From a management perspective, these results indicate that fertilizer recommendations must be soil-type specific. Blanket application rates risk over-fertilization in sandy soils where potassium is more readily lost, leading to inefficiency, environmental contamination, and wasted farmer investment (Okpoji et al., 2025). Precision nutrient management tailored to soil conditions could reduce input costs and improve crop productivity, thereby improving farm-level profitability while safeguarding environmental quality (Matías et al., 2021; Melesse, 2018).

Lambda-cyhalothrin residues declined steadily in soils (0.42 → 0.09 mg/kg) and in irrigation water (peak 0.15 mg/L), with a modeled half-life of ~10.7 days. Dissipation was faster in sandy soils due to weaker adsorption and stronger leaching, while clay soils retained residues longer through higher sorption capacity. Similar findings were reported by Ngaini et al. (2024), who showed that λ-cyhalothrin degrades more slowly in organic-rich soils. Crop tissue residues, though below FAO/WHO limits, signal dietary exposure pathways. Nigerian studies have detected pesticide residues in maize and cassava, underscoring the risk of cumulative exposure among farming households (Best-Ordinoha et al., 2017; Ayoola et al., 2023). Importantly, pesticide degradation is often incomplete, producing metabolites that may persist longer or exert greater toxicity than the parent compounds (Frank et al., 2002; Ngigi et al., 2011). These metabolites represent a significant research gap in Nigeria, as their toxicological relevance is rarely assessed despite evidence of mobility and persistence in tropical soils.

Even low-level pesticide residues pose ecological risks. Gomes et al. (2023) reported that nanopesticides and conventional formulations impair soil invertebrates, while Mattah et al. (2015) linked pesticide use in Ghana to human health problems. Together, these findings suggest that regulatory compliance based solely on residue thresholds may underestimate real risks, particularly under conditions of repeated seasonal applications (Okpoji et al., 2025). The advection–dispersion model reproduced observed breakthrough curves effectively ($R^2 = 0.87–0.92$), validating its relevance for humid tropical soils. Pore-water velocities (0.12–0.18 cm/s) and dispersion coefficients (0.65–1.02 cm²/s) reflected strong hydrological control on solute transport. Freundlich parameters ($K_f = 2.8$ mg/kg; $n = 0.87$) confirmed moderate affinity of λ-cyhalothrin for soils, supporting the observed persistence in clay-rich environments. These outcomes are consistent with prior modeling studies demonstrating the coupled role of hydrodynamics and sorption–degradation kinetics in shaping agrochemical fate (Mukherjee, 2012; Chai et al., 2012). The combination of empirical field data with modeling strengthens the predictive framework for contaminant behavior under irrigation in tropical systems.

Despite robust design and QA/QC, some uncertainties remain. Pesticide metabolite dynamics were not quantified, yet they may contribute significantly to persistence and toxicity. Soil heterogeneity within plots, though minimized by composite sampling, may still have influenced spatial variability. Rainfall data from NIMET provided broad resolution but may not fully capture microclimatic variation across sites. Additionally, the regression models, while significant, were based on short-term rainfall and irrigation monitoring; long-term studies would strengthen predictive power (Okpoji et al. 2025). The contrasting behaviors of nitrate, phosphate, potassium, and λ-cyhalothrin underscore the need for differentiated management strategies. Nitrate requires precision fertilization synchronized with crop uptake. Phosphate demands long-term monitoring to manage legacy risks. Potassium must be managed with soil-specific recommendations to avoid farmer losses and environmental inefficiencies. For pesticides, integrated pest management (IPM) should be promoted to minimize chemical inputs, with particular attention to training farmers in safe application practices (Anarado et al. 2023). Economically, these results suggest that unregulated blanket use of fertilizers and pesticides is costly for farmers, both through inefficient nutrient uptake and potential yield loss from soil and water degradation (Okpoji et al. 2025). Improved extension services and subsidies targeted toward precision fertilization, biochar soil amendments, and IPM adoption could reduce input costs, improve soil health, and enhance farm profitability in the Niger Delta.

CONCLUSION

This study has demonstrated that the mobility and persistence of agrochemicals in irrigated farmlands of Rivers State are governed by the combined influence of soil physicochemical properties, hydrological drivers, and the intrinsic characteristics of nutrients and pesticides. Nitrate was shown to be highly mobile, with concentrations approaching the WHO guideline limit and indicating significant leaching risks under high rainfall and irrigation. Phosphate, although largely immobilized through sorption to clay and iron/aluminum oxides, poses long-term legacy risks that may be triggered under reducing conditions. Potassium displayed intermediate behavior, with losses strongly dependent on soil texture, emphasizing the role of cation exchange capacity in nutrient retention. Lambda-cyhalothrin exhibited moderate persistence, dissipating over a few weeks but with measurable residues in soils, water, and crops, highlighting both ecological and dietary exposure pathways.

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