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Water Regime Effects on Phosphorus Mobility and the Performance of Liquid Phosphorus Fertilizers in Contrasting Soils

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Abstract

The behavior of phosphorus (P) fertilizers in soil is governed not only by fertilizer solubility, but also by P mobility and vertical redistribution within the soil profile under contrasting water regime. This study aimed to investigate the combined effects of water regime, fertilizer type, and soil properties on the vertical redistribution of ammonium acetate–lactate extractable phosphorus (P-AL) in the surface soil layer under controlled pot conditions. Experiments were conducted using three soils with contrasting chemical properties: AC-LO (acidic loam, pH 5.9), NE-CL (neutral clay loam, pH 6.8), and AL-SL (alkaline sandy loam, pH 8.0). Four simulated rainfall regimes were applied at a constant rate of 25 mm day^{-1}, corresponding to cumulative water inputs of 0 mm (W0), 50 mm (W50), 100 mm (W100), and 150 mm (W150). Fertilizer treatments included an unfertilized control (NF), a liquid NP 4–18 fertilizer applied at a low dose (L1), a liquid NP 4–18 fertilizer applied at a high dose (L2), and a solid NPK 15–15–15 fertilizer (S). Water regime exerted the strongest control on P mobility, with P-AL increasing by approximately 40–60% from W0 to W150, depending on soil type. In AC-LO, strong P fixation under low moisture minimized differences among fertilizer treatments, whereas under higher moisture (W100–W150), liquid fertilizers—particularly L2—resulted in P-AL levels approximately 10–30% higher than those of the solid fertilizer. In NE-CL, P mobility was moderate and, under W100–W150, L2 produced P-AL values approximately 10–15% higher than the solid fertilizer, promoting a more uniform P redistribution within the 2–8 cm layer. In AL-SL, the response under wet conditions depended on the water regime: at W100, L2 generated P-AL values comparable to the solid fertilizer, whereas at W150, L2 increased P-AL by approximately 11% relative to the solid form. Overall, the results indicate that soil chemical properties primarily regulate the extent of phosphorus redistribution, while water regime controls its intensity and fertilizer form influences the initial spatial configuration of P within the surface soil layer. The findings provide mechanistic insight into short-range phosphorus transport in soil, without allowing direct inferences regarding agronomic efficiency or crop response.

Keywords: soil phosphorus dynamics; nutrient stratification; phosphorus redistribution indices; fertilizer formulation; soil chemical buffering; ammonium acetate–lactate extraction

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1. Introduction

Phosphorus (P) is one of the least mobile nutrients in soil. Its movement is controlled by adsorption, precipitation, and chemical fixation processes, and it is most effectively

accessed when roots proliferate near the fertilizer placement zone [1,2]. In mineral fertilizers, reactions occurring immediately after application reduce P mobility and limit the amount that remains available to plants [3], which largely explains the low efficiency of phosphorus use in many agricultural systems [4].

The concentration of extractable phosphorus is particularly constrained in acidic and alkaline soils, where fixation occurs rapidly, either through adsorption onto Fe and Al oxides or through the formation of stable Ca phosphates [1,5–9]. These equilibria between adsorption/desorption and precipitation/dissolution determine the concentration of P in the soil solution and its chemical mobility [1,9,10].

Soil texture, clay content, and organic matter further influence phosphorus behavior by regulating sorption capacity and diffusion pathways [9,11–14]. Overall, phosphorus distribution within the soil profile and its accessibility to plants are governed by the combined chemical and physical properties of the soil [4,9,13–16].

Phosphorus mobility also depends strongly on soil moisture and water movement through the soil profile. In contrast to highly mobile nutrients such as nitrate, phosphorus exhibits a dynamic governed primarily by diffusion processes and by sorption–desorption reactions at the solid–solution interface [17–19]. In this context, the vertical movement of water through the soil profile does not act as a direct transporter via mass flow, but rather influences phosphorus mobility mainly in an indirect way, by modifying the continuity of water films and the kinetics of physicochemical reactions [17,19,20].

This dependence on soil water regime means that, under dry conditions, phosphate diffusion is severely restricted, markedly limiting root phosphorus supply [1,14,21–23]. Conversely, as soil moisture increases, phosphorus mobility is enhanced, allowing its redistribution within surface soil layers [1,9,17,24,25].

Although phosphorus movement is generally confined to shallow depths, intense rainfall events or conditions in soils with low fixation capacity can amplify the downward displacement of applied phosphorus, thereby altering its vertical distribution [5,6,9,26].

Superimposed on these physicochemical mechanisms are biological factors, including microbial activity, mycorrhizal symbioses, and the release of root-derived organic acids, which facilitate phosphorus solubilization in the rhizosphere [1,2].

Overall, the synergy among these processes determines phosphorus distribution and mobility, an aspect that is particularly relevant in regions with pronounced hydrological variability, such as Central and Eastern Europe, where the alternation of dry periods and intense precipitation governs fertilization efficiency.

Although phosphorus mobility in soil has been widely studied, much less attention has been given to its vertical distribution within narrow surface layers. Most studies assess phosphorus over broader depth intervals (e.g., 0–10 or 0–20 cm), which can obscure rapid adsorption, diffusion, and water redistribution processes occurring in the first centimeters after fertilizer application [1,27,28].

Data on phosphorus behavior at fine depth intervals (2–4, 4–6, and 6–8 cm) remain limited, despite the relevance of these layers for characterizing early redistribution and availability within the surface soil layer [29].

Moreover, relatively few studies have examined soil type, fertilizer form, and water regime simultaneously within a controlled factorial design, even though interactions among these factors directly influence phosphorus mobility and use efficiency [1,14,23,24,29]. This lack of integrated approaches limits the development of fertilization strategies adapted to specific soil and climatic conditions [23,30,31].

Chemical fertilizers supply soluble forms of phosphorus that increase their immediate availability; however, once introduced into the soil, these forms may rapidly undergo adsorp-

tion or precipitation reactions. Consequently, fertilizer efficiency is strongly influenced by soil pH, fertilizer form, and the soil's capacity to retain or release phosphorus [1,2,4,5,32–34].

Solid fertilizers dissolve gradually and create localized zones of high phosphorus concentration, which are rapidly exposed to fixation processes, particularly in acidic and alkaline soils [4,5,30,31]. By contrast, liquid fertilizers mix more rapidly with the soil solution, penetrate soil micropores more uniformly, and may reduce immediate fixation, thereby maintaining higher concentrations of mobile phosphorus for a longer period [16,30,34–37].

These differences between liquid and solid formulations are therefore critical for understanding phosphorus mobility and optimizing fertilization strategies under variable soil and water regimes [4,5,29,32,38,39].

In regions with a highly continental temperate climate in Central and Eastern Europe, P-AL concentrations in the surface soil layer at the resumption of vegetation are particularly relevant under autumn-sown cropping systems. This is particularly evident in southern and eastern Romania, where high interannual variability in precipitation and frequent drought episodes directly affect the efficiency of basal fertilization. In years when drought at sowing prevents fertilizer activation, crops depend largely on the phosphorus present in the surface soil layer at the beginning of spring. Under such conditions, liquid phosphorus fertilizers may influence phosphorus redistribution patterns during early vegetative regrowth [30,31,40].

The aim of this study was to evaluate how soil type, phosphate fertilizer form, and water regime interact to influence short-range phosphorus redistribution and P-AL distribution within surface soil layers under controlled conditions representative of Central and Eastern Europe. By comparing liquid and solid fertilizers in soils with contrasting chemical properties and under variable water regimes, the study provides a mechanistic framework for interpreting phosphorus redistribution patterns following surface application, without directly assessing crop response or fertilizer use efficiency.

2. Materials and Methods

2.1. General Conditions and Experimental Setup

The experiment was carried out in 2025 at the Laboratory of Plant Nutrition and Soil Fertility, "Ion Ionescu de la Brad" University of Life Sciences, Iași, Romania. The primary objective of the study was to evaluate the vertical redistribution of phosphorus within the soil profile as influenced by fertilizer type and dose, soil properties, and controlled water input. Vegetation pots were used to establish soil columns for simulating the effects of contrasting water regimes on phosphorus redistribution within the soil profile. Each pot represented an individual experimental unit defined by a specific combination of soil type, fertilizer treatment, and water regime. As the experimental design focused on within-profile redistribution processes, leachate water was not analyzed for phosphorus content, since the study did not aim to quantify phosphorus losses through leaching.

2.2. Experimental Design

The experiment followed a three-factor factorial design in a completely randomized block system, with three replicates per treatment combination. The experimental factors were:

(1) Soil reaction and texture, with three levels: AC-LO (acidic loam, pH 5.9), NE-CL (neutral clay loam, pH 6.8), and AL-SL (alkaline sandy loam, pH 8.0);
(2) Fertilizer type, with four variants: NF (unfertilized control), L1 (liquid NP 4–18 fertilizer with 0.12% Zn and 0.12% B, low dose), L2 (same liquid fertilizer, high dose), and S (granular NPK 15–15–15);

(3) Water input applied as simulated rainfall: 0 mm (W0, no precipitation), 50 mm applied over two consecutive days (W50), 100 mm applied over four days (W100), and 150 mm applied over six days (W150), all delivered at a constant daily rate of 25 mm.

Each treatment combination was replicated three times, resulting in a total of 144 experimental units (3 soils × 4 fertilizers × 4 water regimes × 3 replicates).

Vegetation pots were used to establish soil columns for the simulation of water percolation and phosphorus movement through the soil profile. The pots were 25 cm high and 20 cm in inner diameter and were equipped with drainage holes at the bottom. Each pot was placed on an individual container to allow separate collection of leachates. Prior to filling, soils were air-dried and sieved through a 2 mm mesh to remove coarse fragments. The processed soils were then gradually added to the pots and uniformly compacted using the same procedure across all treatments, resulting in soil columns with a final height of 24 cm (soil volume ≈ 7.5 L). Although the same compaction procedure was applied to all pots, slight differences in bulk density among soils reflected inherent differences in soil texture. Soil mass per pot varied among soils due to differences in texture and bulk density. All pots were maintained under controlled laboratory conditions at a constant temperature (18 ± 2 °C) in a closed room without natural light, minimizing biological activity.

2.3. Soil Characterization

Soils were collected from agricultural areas of the Moldavian Plateau (northeastern Romania) to represent contrasting conditions for phosphorus mobility in terms of soil reaction, texture, and background phosphorus status. Samples were taken from the 0–20 cm layer and prepared following standard procedures for pot experiments [41].

Chemical analyses performed prior to pot filling revealed clear differences among soils in pH, cation exchange capacity (CEC), and levels of ammonium lactate–extractable phosphorus and potassium (Table 1).

Table 1. Chemical properties of the soils used in the experiment.

Parameter	AC-LO	NE-CL	AL-SL
pH (H_2O)	5.9	6.8	8.0
SOC (%)	0.99	1.68	1.8
Ha (meq 100 g^{-1})	2.3	1.4	0.2
SB (meq 100 g^{-1})	9.8	24.9	41.4
CEC (meq 100 g^{-1})	12.1	26.3	41.7
V (%)	80.9	94.6	99.5
$CaCO_3$ (%)	-	-	1.8
Al^{3+} (meq 100 g^{-1})	0.06	-	-
Na^+ (mg L^{-1})	15.0	-	-
TSS (mg L^{-1})	0.011	0.033	0.048
IN	1.4	2.7	3.1
Total P (mg kg^{-1})	270.0	460.0	2900.0
P-AL (mg kg^{-1})	5.4	45.1	178.1
K-AL (mg kg^{-1})	107.0	250.0	580.0

P-AL and K-AL represent ammonium lactate–extractable phosphorus and potassium. AC-LO, acidic loam soil; NE-CL, neutral clay loam soil; AL-SL, alkaline sandy loam soil.

Soil physical properties were determined after pot assembly to characterize the actual experimental conditions. Data on soil texture, clay content, bulk density (BD), wilting point (WP), field capacity (FC), available water (AW), total porosity (TP), and air-filled porosity (AP) are presented in Table 2.

Table 2. Physical properties of soils determined in soil columns.

Parameter	AC-LO	NE-CL	AL-SL
Clay content (%)	25.0	33.0	15.0
BD (g cm^{-3})	1.34	1.31	1.40
Soil mass/pot (kg)	10.1	9.9	10.5
WP (% vol)	9.1	12.7	6.9
FC (% vol)	22.6	24.2	19.3
AW (% vol)	16.2	1.0	15.3
TP (% vol)	49.4	50.5	47.2
AP (% vol)	26.8	26.3	27.9

AC-LO, acidic loam soil; NE-CL, neutral clay loam soil; AL-SL, alkaline sandy loam soil.

The AC-LO soil is an acidic loam derived from an acidic brown soil. Its acidic reaction and loamy texture result in a modest nutrient retention capacity and low levels of plant-available phosphorus. The moderate clay content and balanced structure provide an average ability to retain water while maintaining aeration, conditions that tend to limit both extractable phosphorus levels and its downward movement within the soil profile.

The NE-CL soil is a neutral clay loam corresponding to a cambic chernozem. By combining a neutral pH with a higher clay content, it presents a more stable chemical environment and a stronger buffering capacity. Although total porosity is high, the amount of water readily available to plants is low, suggesting that the finer texture retains water more tightly. This combination supports nutrient retention but may restrict phosphorus mobility under the experimental conditions.

The AL-SL soil is an alkaline sandy loam originating from a sandy carbonatic chernozem with residual phosphorus accumulation. It is characterized by an alkaline reaction and sandy loam texture and contains elevated phosphorus reserves resulting from long-term fertilization. Despite its lighter texture, it maintains a relatively favorable level of plant-available water. In combination with its chemical properties, these physical traits suggest a higher potential for vertical phosphorus movement under irrigation.

2.4. Soil Analytical Methods

Soil chemical and physical analyses were performed using standard pedological and agrochemical methods recommended by the National Research-Development Institute for Pedology, Agrochemistry and Environmental Protection (ICPA), as documented in Romanian methodological literature [42], and complemented by internationally recognized procedures. Soil pH was measured potentiometrically in a 1:2.5 soil-to-water suspension following widely accepted procedures for soil reaction assessment.

Organic carbon was determined by the modified Walkley–Black method, and humus content was calculated using the standard conversion factor (1.724). Hydrolytic acidity and exchangeable bases were assessed by the Kappen method, and the results were used to calculate cation exchange capacity (CEC) and base saturation (V%). Calcium carbonate ($CaCO_3$) was quantified using the Dronineanu method, while exchangeable aluminum (Al^{3+}) was determined following the Sokolov procedure.

Ammonium acetate–lactate extractable phosphorus (P-AL) and potassium (K-AL) were extracted using the Egner–Riehm method, with phosphorus measured spectrophotometrically (UV 1700, Shimadzu, Shimadzu Corporation, Kyoto, Japan) and potassium by flame photometry (Flame photometer 410, Sherwood, Sherwood Scientific Ltd., Cambridge, UK). Total phosphorus was determined by wet acid digestion followed by colorimetric detection of orthophosphate.

Physical and hydro-physical parameters were included to better interpret nutrient mobility under conditions of simulated precipitation. Particle-size distribution (clay content)

was determined by sedimentation using the Stokes principle. Bulk density was measured gravimetrically on oven-dried soil samples collected from vegetation pots, reflecting the physical condition of the analyzed 2–8 cm soil layer. Hydro-physical indices—field capacity (FC), wilting point (WP), available water (AW), total porosity (TP), and air-filled porosity (AP)—were estimated using pedotransfer functions based on clay content, soil texture, and bulk density, following the approach described by Canarache [41,43].

2.5. Fertilizer Treatments

Phosphorus fertilization treatments included a liquid NP 4–18 fertilizer (SynerTech 418 Pro, Timac Agro, Bucharest, Romania) applied at two rates (L1 and L2) and a granular NPK 15–15–15 fertilizer (S), used as a reference. Fertilizer rates were defined based on common agronomic field applications (L ha^{-1} or kg ha^{-1}) of the respective commercial products and were converted to the surface area of each vegetation pot. The corresponding quantities of P_2O_5 and elemental phosphorus (P) applied per pot were then calculated according to the declared fertilizer composition (Table 3).

Table 3. Equivalent phosphorus dose applied per fertilizer treatment.

Variant	Fertilizer	Applied Rate	Application Form	P_2O_5 (mg Pot^{-1})	P (mg Pot^{-1})
NF	No fertilization	–	–	0	0
L1	NP 4-18	50 L ha^{-1} fertilizer + 150 L ha^{-1} water	Solution 1:3	31.67	13.9
L2	NP 4-18	100 L ha^{-1} fertilizer + 100 L ha^{-1} water	Solution 1:1	63.34	27.9
S	NPK 15-15-15	250 kg ha^{-1} fertilizer	Solid (granular)	117.8	51.8

Phosphorus doses per pot were calculated by accounting for the surface area of each pot and, in the case of liquid formulations, the fertilizer density (1.12 g cm^{-3}). Conversion from P_2O_5 to elemental phosphorus (P) was performed using the standard stoichiometric factor. The resulting values represent the amount of phosphorus applied per experimental unit and provide a consistent basis for assessing its redistribution within the soil profile.

This experimental design was not intended to compare agronomic efficiency at equivalent phosphorus rates, but to analyze fertilizer-specific phosphorus redistribution patterns associated with contrasting application systems. Consequently, fertilizer form, application rate, and application pathway are inherently linked in the present study, and the results describe soil-level redistribution processes rather than formulation efficiency.

The liquid fertilizer NP 4-18 + 0.12% Zn + 0.12% B was applied as a diluted solution, in a 1:3 ratio for L1 (50 L ha^{-1} fertilizer + 150 L ha^{-1} water) and 1:1 for L2 (100 L ha^{-1} fertilizer + 100 L ha^{-1} water), resulting in the same total volume of 200 L ha^{-1} in both treatments. This dilution allowed for uniform surface application via dripping, simulating controlled-flow liquid fertilization and ensuring a realistic distribution of phosphorus in the upper soil layer. Before irrigation treatments, all pots were adjusted to field capacity to ensure uniform initial moisture conditions.

The solid fertilizer (S) was applied uniformly to the soil surface of each pot and was not mixed with the soil, in order to simulate the standard surface broadcasting practice used for phosphorus fertilization during the growing season in wheat cultivation. Fertilizer incorporation occurred only through subsequent simulated rainfall events. These treatments were designed as alternatives for spring phosphorus fertilization, aiming to increase the immediate availability of phosphorus for autumn-sown crops at the onset of vegetative regrowth. Accordingly, differences in phosphorus behavior between solid and

liquid fertilizers reflect contrasting application pathways under realistic surface application conditions rather than intrinsic formulation effects.

2.6. Simulation of Precipitation

To reproduce the hydro-climatic conditions of the Moldavian Plateau (northeastern Romania), the irrigation regime was designed based on meteorological data recorded between 2010 and 2024 by the Romanian National Meteorological Administration. This region is characterized by a high interannual variability in spring rainfall, alternating between dry years and wet springs with frequent episodes of 60–80 mm accumulated over 2–3 consecutive days, particularly in March and April.

Based on the regional climatic pattern, four simulated precipitation regimes were established to reproduce realistic rainfall scenarios: 0 mm (W0, no precipitation), 50 mm applied over two consecutive days (W50), 100 mm applied over four days (W100), and 150 mm applied over six days (W150), all delivered at a constant daily rate of 25 mm.

Water volumes were adjusted to pot surface area, and distilled water was used to avoid external chemical inputs. Precipitation was applied by slow surface dripping 24 h after fertilizer application. Following the final irrigation, soil columns were maintained at 22 ± 2 °C for 14 days to allow water redistribution and stabilization of phosphorus forms.

2.7. Sampling and Phosphorus Determination

Soil sampling was carried out 14 days after treatment application. This interval was selected to allow water-driven redistribution processes of labile phosphorus along the soil depth to develop, prior to longer-term stabilization processes in the soil. The experiment was conducted without plants; therefore, phosphorus uptake was not considered.

Columns were sectioned and samples collected from three depth intervals: 2–4, 4–6, and 6–8 cm. This zone corresponds to the period of intensive root development in winter wheat during early spring, when phosphorus demand is critical for root initiation and elongation.

Ammonium acetate–lactate extractable phosphorus (P-AL) was determined using the Egner–Riehm extraction followed by spectrophotometric measurement. Results were expressed as mg P kg^{-1} dry soil.

2.8. Calculation and Interpretation of Vertical Phosphorus Redistribution Indices

To characterize the vertical redistribution of mobile phosphorus within the surface soil layer (2–8 cm), two synthetic indices were used, designed to describe the direction of redistribution and the degree of vertical uniformity of phosphorus distribution between soil layers. The indices were derived from concentrations of P-AL determined at three depth intervals (2–4, 4–6, and 6–8 cm) and are conceptually based on indicators reported in the international literature for assessing nutrient stratification and distribution uniformity within soil profiles [44–46].

The mean content of mobile phosphorus within the analyzed soil layer ($Mean_{2–8}$) was calculated as the arithmetic average of P-AL values determined for the 2–4, 4–6, and 6–8 cm depth intervals:

$$Mean_{2–8} = (P_{2–4} + P_{4–6} + P_{6–8})/3$$

The Vertical Distribution Index (VDI), conceptually derived from nutrient stratification indicators and nutrient distribution ratios used for soil management assessment [45], was calculated according to the following equation:

$$VDI = P_{6–8}/Mean_{2–8}$$

where $P_{6–8}$ represents the content of mobile phosphorus in the lower soil layer (6–8 cm), and $Mean_{2–8}$ represents the mean phosphorus content of the analyzed profile (2–8 cm).

By its construction, VDI functions as a directional indicator of vertical redistribution, allowing assessment of the relative tendency of phosphorus to migrate toward the lower portion of the investigated soil layer. Values close to unity indicate a relatively balanced vertical distribution of phosphorus, subunitary values reflect predominant accumulation in the upper portion of investigated soil layer, whereas supraunitary values suggest a relatively more pronounced redistribution toward the lower layer. VDI was used exclusively for relative comparisons among treatments and does not imply phosphorus losses beyond examined profile section or interpretations related to plant phosphorus availability.

Coefficient of Vertical Uniformity (CVU) is inspired by uniformity coefficients originally developed to assess irrigation water distribution [46] and subsequently adapted for the analysis of nutrient distribution in soils, including phosphorus. CUV was calculated according to the following equation:

$$CVU = 1 - |P_{6–8} - P_{2–4}| / (P_{2–4} + P_{4–6} + P_{6–8})$$

where $P_{2–4}$ and $P_{6–8}$ represent phosphorus concentrations in the marginal segments of the investigated soil layer, and the denominator represents the cumulative phosphorus content across the entire 2–8 cm profile.

This coefficient quantifies the degree of vertical homogeneity of phosphorus distribution between the upper (2–4 cm) and lower (6–8 cm) portions of the analyzed soil layer and is sensitive to extreme differences between layers. Higher CUV values indicate a more uniform vertical distribution of phosphorus, whereas lower values reflect a heterogeneous distribution within the analyzed profile.

Both indices were calculated at the level of individual experimental units (vegetation pots) and subsequently averaged by treatment. The indices were used as descriptive and comparative tools to interpret soil-level phosphorus redistribution processes and do not represent indicators of agronomic efficiency, plant phosphorus uptake, or fertilizer performance.

2.9. Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) to evaluate the main effects of fertilizer treatment (F), water regime (W), and soil depth (D), as well as their interactions (W × F, W × D, F × D, and W × F × D) on phosphorus distribution within the soil profile. Each vegetation pot was considered the experimental unit, with three independent replicates per treatment combination.

Soil P-AL concentrations at each depth were determined using replicate laboratory measurements to improve analytical precision; these replicates were used to reduce measurement error and were not treated as independent experimental replicates in the statistical analysis.

Given the factorial structure of the experiment and the level of replication, the statistical analysis was primarily intended to identify main effects and consistent interaction trends. Higher-order interactions were evaluated in an exploratory manner and interpreted with caution. Results are presented as means ± standard deviation. Treatment means were compared using Tukey's HSD test at $p < 0.05$, and Bonferroni correction was applied when evaluating interaction effects. All statistical analyses were performed using SPSS v.22 (IBM Corp., Armonk, NY, USA).

3. Results

Phosphorus content was analyzed across successive soil layers, with results presented for individual depths and cumulatively for the 2–8 cm interval. This approach allows

evaluation of how fertilizer form and water regime influence the vertical redistribution of extractable phosphorus within the analyzed soil layer.

3.1. Acid, Low-Phosphorus Soil (AC-LO)

The three-way ANOVA (W × F × D) revealed significant main effects of water regime, fertilizer type, and soil depth on phosphorus distribution in the acidic soil ($p < 0.001$; Table 4). The significance of the W × F × D interaction indicates that fertilizer-related differences in P-AL distribution were not uniform across soil depths, but were expressed only under specific water regimes, reflecting a strong water-dependent modulation of vertical phosphorus redistribution in this acidic soil. All interaction terms were significant, confirming that phosphorus responses varied according to the combined effects of water regime, fertilization, and depth. High partial η^2 values indicate that both individual factors and their interactions contributed substantially to variability in phosphorus distribution, highlighting the dominant role of water regime and fertilizer form in controlling phosphorus mobility in AC-LO soil.

Table 4. ANOVA summary for AC-LO soil.

Source of Variation	df	F Value	*p* Value	Partial η^2
Water regime (W)	3	186.08	<0.001	0.853
Fertilizer (F)	3	136.37	<0.001	0.810
Soil depth (D)	2	254.50	<0.001	0.841
W × F	9	23.64	<0.001	0.689
W × D	6	56.87	<0.001	0.780
F × D	6	66.32	<0.001	0.806
W × F × D	18	10.811	<0.001	0.670

$R^2 = 0.965$ (Adjusted $R^2 = 0.947$).

3.1.1. Effect of the Water Regime on Phosphorus Distribution in AC-LO Soil

In the acidic soil, soil moisture strongly controlled phosphorus redistribution. The P-AL content measured in the 2–8 cm layer under W0 (approximately 5 mg kg^{-1}) represents the baseline level of mobile phosphorus in the soil, whereas increasing water input led to a progressive increase in P-AL, reaching more than 8 mg kg^{-1} under the highest water regime (W150).

Under W0, differences among treatments were negligible, and P-AL values remained uniformly low throughout the profile with no significant effects of the F × D interaction ($p > 0.05$). The lack of moisture limited phosphorus dissolution and diffusion, resulting in similar behavior of L1, L2, and the solid fertilizer (S) across all depths (Figure 1). This absence of treatment differentiation under W0 explains the lack of a significant F × D interaction, indicating that limited soil moisture prevented the vertical expression of fertilizer-specific effects.

At moderate moisture (W50), available phosphorus in the 2–4 cm layer increased markedly for the liquid fertilizers, with significant differences relative to the control and the solid fertilizer ($p < 0.001$) and a strong F × D interaction being observed ($\eta^2_p = 0.84$). At the same time, S showed a smaller increase but a more uniform vertical distribution. Increasing water input to W100 further enhanced phosphorus mobility, and differences among fertilizer treatments became more pronounced in the upper soil layers ($p < 0.001$), as reflected by high η^2_p values for the F × D interaction (0.90). The emergence of strong F × D interactions under these water regimes indicates that increasing soil moisture enabled fertilizer-specific redistribution patterns to develop along the soil profile, particularly in the surface layers.

Under excess moisture (W150), liquid fertilizers produced the highest P-AL values in the surface layer and promoted redistribution toward deeper layers. In contrast, the solid fertilizer maintained a comparatively uniform profile, with smaller variations among depths even under high water input. These patterns are illustrated in Figure 1 and supported by the corresponding interaction effects (η^2_p = 0.92). These contrasting responses between liquid and solid fertilizers under the highest water regime are consistent with a depth-dependent redistribution process driven by water availability, as reflected by the high magnitude of the interaction effects.

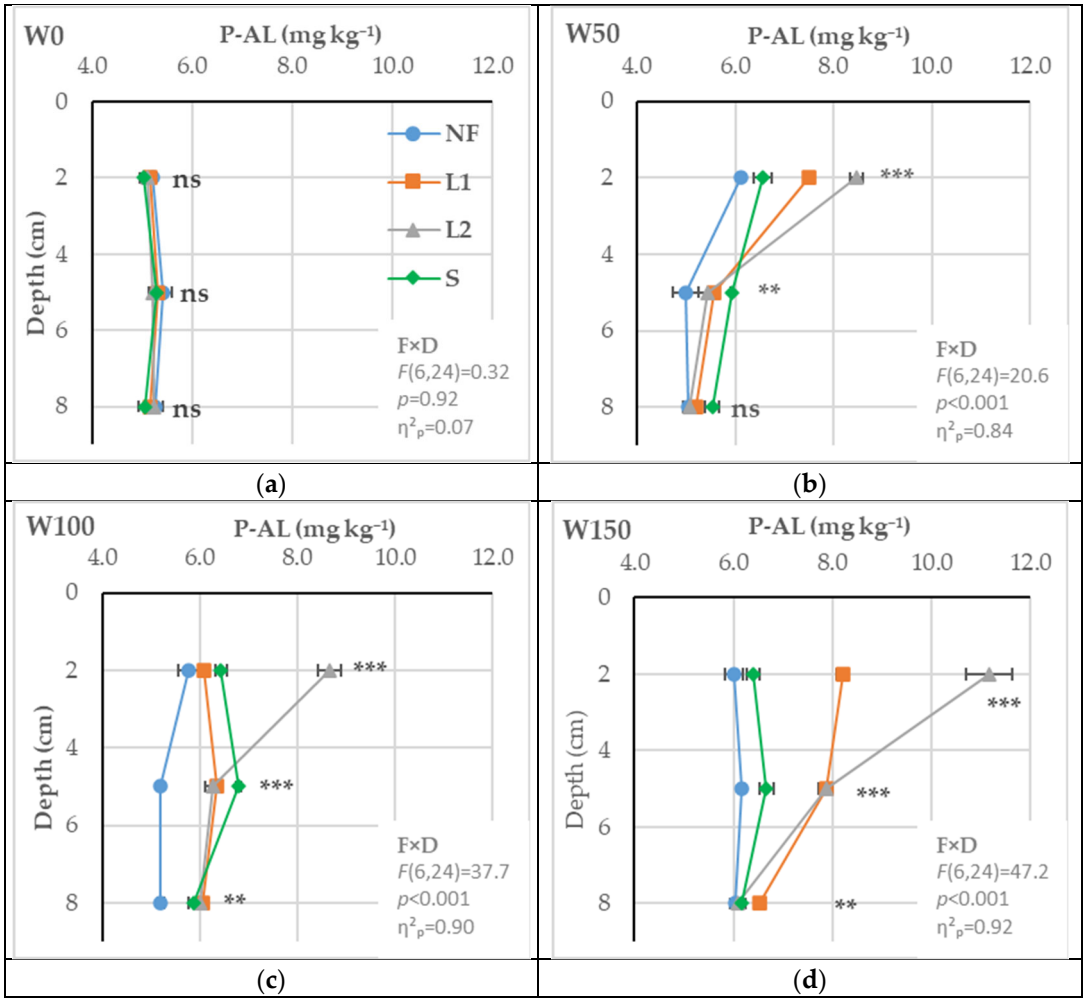

Figure 1. Distribution of phosphorus content (P-AL, mg kg^{-1}) along the soil profile in AC-LO under different water regimes: (**a**) W0, (**b**) W50, (**c**) W100, and (**d**) W150 (25 mm day^{-1}). NF, unfertilized control; L1, liquid NP fertilizer applied at low dose; L2, liquid NP fertilizer applied at high dose; S, solid NPK fertilizer. Values are means of three replicates ± standard error of the mean (±SE). Symbols "ns", "**" and "***" denote non-significant or significant differences at $p < 0.01$ and $p < 0.001$, respectively (Bonferroni test). F and η^2_p values shown in boxes correspond to the F × D (Fertilizer × Depth) interaction.

3.1.2. Effect of Fertilizer Type on Phosphorus Distribution in the AC-LO Soil

Depth-specific data show that the liquid fertilizer L2 (100 L ha^{-1}) achieved the highest phosphorus availability in the surface layers (2–4 and 4–6 cm) under W50–W150, with P-AL values ranging from 8.5 to 11.2 mg kg^{-1} (Table 5). These results indicate a rapid increase in extractable phosphorus within the 2–8 cm soil layer. Under W150, elevated values in the 2–4 cm layer (11.2 mg kg^{-1}) were accompanied by redistribution toward 4–6 cm (7.9 mg kg^{-1}), where differences between L2 and L1 were no longer significant.

Table 5. Mean content of mobile phosphorus (P-AL, mg kg^{-1}) as affected by water regime, fertilizer type, and soil depth in the AC-LO soil.

Water Regime (L m^{-2})	Depth (cm)	P-AL (mg kg^{-1})			
		NF	L1	L2	S
W0	2–4	5.2 a	5.2 a	5.1 a	5.0 a
	4–6	5.4 a	5.3 a	5.2 a	5.3 a
	6–8	5.3 a	5.2 a	5.2 a	5.1 a
W50	2–4	6.1 c	7.5 b	8.5 a	6.6 c
	4–6	5.0 b	5.6 ab	5.4 ab	5.9 a
	6–8	5.0 a	5.2 a	5.1 a	5.5 a
W100	2–4	5.8 c	6.1 b	8.7 a	6.4 b
	4–6	5.2 c	6.3 ab	6.3 a	6.8 b
	6–8	5.2 c	6.1 a	6.0 a	5.9 b
W150	2–4	6.0 c	8.2 b	11.2 a	6.4 c
	4–6	6.2 b	7.9 a	7.9 a	6.7 ab
	6–8	6.0 b	6.5 a	6.1 a	6.2 a

Values represent means (n = 3). Within each water regime, different lowercase letters indicate significant differences among fertilizer × depth combinations (Bonferroni test, $p < 0.05$).

The lower liquid dose (L1) showed an intermediate response, with P-AL values consistently higher than those of the unfertilized control but lower than those obtained with L2 in the surface layer. For example, at W50 and W100, L1 reached 7.5 and 6.1 mg kg^{-1}, respectively, in the 2–4 cm layer, with differences relative to NF being significant, while statistical separation from L2 was maintained (Table 5). A more balanced vertical distribution of phosphorus was observed, indicating moderate mobility and greater stability within the soil profile.

The solid fertilizer exhibited a more conservative vertical behavior. Although P-AL values in the 2–4 cm layer were slightly higher than those of the control (6.4–6.6 mg kg^{-1} at W50–W150), they remained lower than those obtained with L2. In deeper layers, S showed values comparable to those of the liquid treatments under certain water regimes, resulting in a relatively uniform distribution with depth. This relatively uniform distribution reflects a slow and steady release of phosphorus.

Overall, the statistically significant differences observed among fertilizer treatments indicate that L2 resulted in the highest P-AL concentrations in the surface layer compared with the unfertilized control (NF), L1 produced a moderate and stable increase in extractable phosphorus, and the solid fertilizer (S) ensured a more uniform vertical distribution within the 2–8 cm interval, with smaller differences relative to NF in the deeper layers.

3.1.3. Total Mobilized Phosphorus in the 2–8 cm Layer and Vertical Dispersion Indices in AC-LO

Total mobile phosphorus in the 2–8 cm layer differed clearly among water regimes and fertilizer treatments (Table 6). Under drought conditions (W0), P-AL values were similar across treatments, and VDI and CUV values close to 1.0 indicate a stable vertical distribution.

At moderate moisture levels (W50–W100), fertilized treatments showed significant increases in total P-AL compared with the unfertilized control, with the highest values recorded for L2 ($p < 0.05$). Subunitary VDI values (0.8–0.9) and increasing CUV values (1.6) indicate moderate vertical dispersion and a more uniform distribution of phosphorus within the profile.

Under excess moisture (W150), phosphorus mobilization was maximal for liquid fertilizers, particularly L2, which reached the highest P-AL value across the 2–8 cm layer (8.38 mg kg^{-1}). Low VDI (0.7) and high CUV values (1.6) confirm pronounced vertical

redistribution, whereas the solid fertilizer-maintained dispersion indices close to unity, indicating greater vertical stability.

Table 6. Mean P-AL concentration (mg kg^{-1}) in the 2–8 cm layer and the VDI and CUV indices as affected by water regime and fertilizer type in the AC-LO soil.

Water Regime (L m^{-2})	Fertilizer	P-AL (mg kg^{-1}) 2–8 cm	VDI	CUV
W0	NF	5.30 ± 0.11 a	1.0	1.0
	L1	5.21 ± 0.08 ab	1.0	1.0
	L2	5.18 ± 0.07 ab	1.0	1.0
	S	5.13 ± 0.15 b	1.0	1.0
W50	NF	5.38 ± 0.63 b	0.9	1.2
	L1	6.09 ± 1.24 a	0.9	1.4
	L2	6.32 ± 1.87 a	0.8	1.5
	S	6.01 ± 0.52 a	0.9	1.2
W100	NF	5.39 ± 0.34 d	1.0	1.1
	L1	6.16 ± 0.15 c	1.0	1.0
	L2	6.98 ± 1.47 a	0.9	1.4
	S	6.37 ± 0.47 b	0.9	1.1
W150	NF	6.07 ± 0.09 b	1.0	1.0
	L1	7.53 ± 0.88 a	0.9	1.2
	L2	8.38 ± 2.57 a	0.7	1.6
	S	6.41 ± 0.25 b	1.0	1.0

Values represent mean ± standard deviation (n = 3). Different lowercase letters indicate significant differences among fertilizers within the same water regime (Tukey's HSD, $p < 0.05$). VDI: <1 = upper-layer accumulation; ≈1 = balanced; >1 = lower-layer redistribution. CUV: higher values = greater vertical uniformity (2–8 cm).

3.2. Neutral, Moderately Supplied Soil (NE-CL)

The three-way ANOVA (W × F × D) revealed significant main effects of water regime, fertilizer type, and soil depth on phosphorus distribution in the neutral soil ($p < 0.001$; Table 7). All interaction terms were also significant, indicating that phosphorus responses depended on the combined effects of moisture, fertilization, and depth within the profile. The significance of these interaction terms indicates that fertilizer-related differences in P-AL distribution were progressively expressed with increasing water input and varied across soil depths, reflecting a moisture-dependent differentiation of vertical phosphorus redistribution in the NE-CL soil.

Table 7. Summary of the ANOVA results for the NE-CL soil.

Source of Variation	df	F Value	*p* Value	Partial η^2
Water regime (W)	3	80.72	<0.001	0.716
Fertilizer (F)	3	84.25	<0.001	0.725
Soil depth (D)	2	148.64	<0.001	0.756
W × F	9	16.44	<0.001	0.606
W × D	6	8.48	<0.001	0.346
F × D	6	15.58	<0.001	0.493
W × F × D	18	3.58	<0.001	0.402

R^2 = 0.923 (Adjusted R^2 = 0.885).

3.2.1. Effect of the Water Regime on Phosphorus Distribution in the NE-CL Soil

In the NE-CL soil, water input strongly affected phosphorus mobility. Under drought (W0), limited moisture restricted phosphorus dissolution and diffusion, and P-AL remained concentrated in the surface layer (2–4 cm), with similar values among fertilized treatments and the unfertilized control (42–46 mg kg^{-1}). The Fertilizer × Depth interaction was

not significant (p = 0.548), indicating a stable vertical distribution regardless of fertilizer form (Figure 2). This lack of interaction under W0 indicates that insufficient soil moisture prevented the vertical differentiation of fertilizer-specific phosphorus distribution patterns.

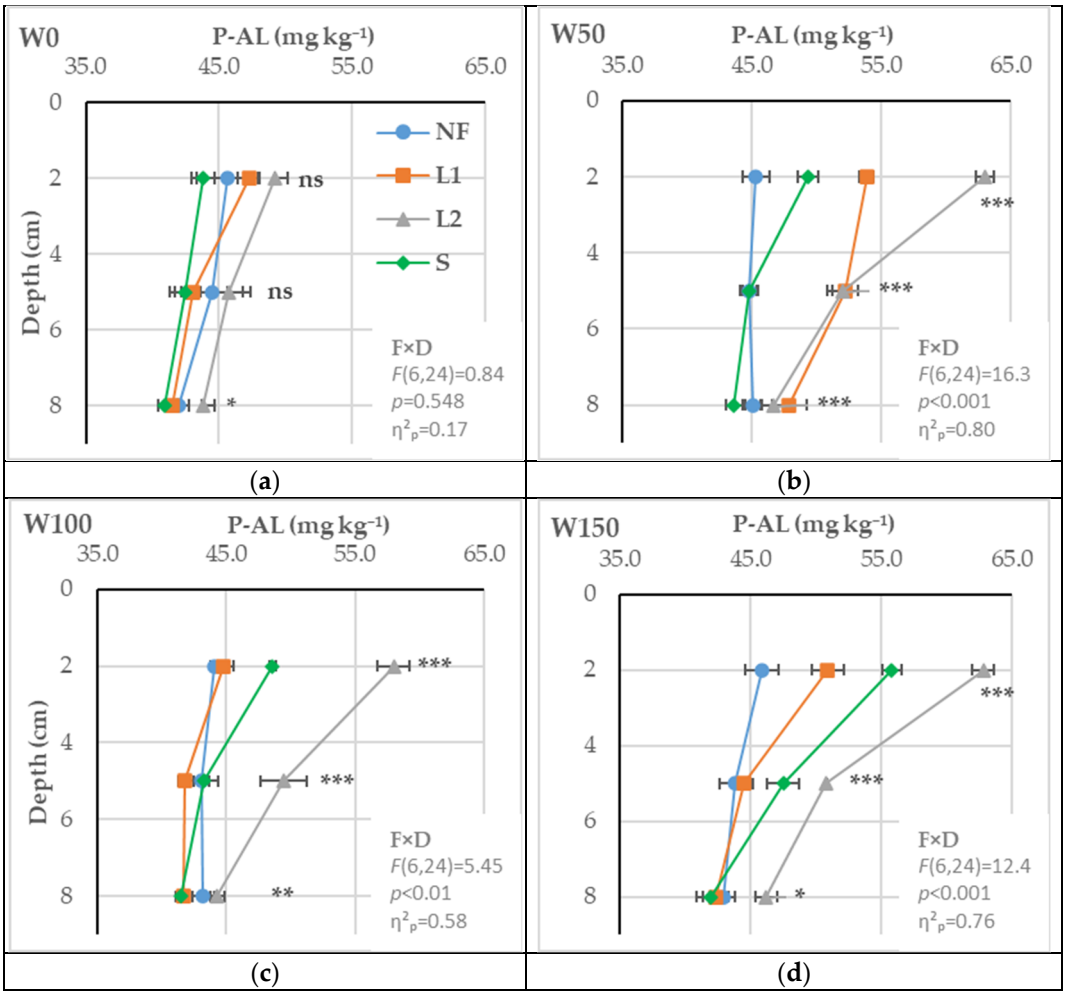

Figure 2. Distribution of phosphorus content (P-AL, mg kg^{-1}) along the soil profile in NE-CL under different water regimes: (**a**) W0, (**b**) W50, (**c**) W100, and (**d**) W150 (25 mm day^{-1}). NF, unfertilized control; L1, liquid NP fertilizer applied at low dose; L2, liquid NP fertilizer applied at high dose; S, solid NPK fertilizer. Values are means of three replicates ± standard error of the mean (±SE). Symbols "ns", "*", "**", and "***" denote non-significant or significant differences at $p > 0.05$, $p < 0.01$, and $p < 0.001$, respectively (Bonferroni test). F and η^2_p values shown in boxes correspond to the F × D (Fertilizer × Depth) interaction.

At moderate moisture (W50), treatment effects became clearer. The liquid fertilizer L2 produced the highest P-AL values in the 2–4 cm layer (63 mg kg^{-1}), significantly exceeding the control and the solid fertilizer ($p < 0.001$). Phosphorus was also detected in the 4–6 cm layer (52.5 mg kg^{-1}), indicating controlled vertical redistribution, and the Fertilizer × Depth interaction was strong (η^2_p = 0.80).

At higher moisture (W100), phosphorus mobility increased further, and liquid treatments maintained higher P-AL values in the surface layer (45–58 mg kg^{-1}), with phosphorus extending down to 6 cm. The solid fertilizer showed a slower response but a relatively uniform profile.

Under excess moisture (W150), vertical transport became more pronounced, particularly for L2, where high surface values (exceeded 60 mg kg^{-1}) were accompanied by redistribution toward 4–6 cm. Differences among depths were again significant

($p < 0.001$), and the contribution of the Fertilizer × Depth interaction increased ($\eta^2_p = 0.76$). In contrast, the solid fertilizer maintained a more stable profile with smaller depth-related variation. This pattern indicates that, under high water regimes, the expression of fertilizer-specific effects on phosphorus distribution becomes increasingly depth-dependent in the NE-CL soil.

3.2.2. Effect of Fertilizer Type on Phosphorus Distribution in the NE-CL Soil

Differences among fertilizers were most evident in the surface layer (2–4 cm), where treatment effects on P-AL concentration were most pronounced (Table 8). The liquid fertilizer L2 consistently produced the highest P-AL values, reaching 58–63 mg kg^{-1} in the 2–4 cm layer, significantly higher than the unfertilized control and the other fertilized treatments ($p < 0.05$). The liquid fertilizer L1 showed an intermediate response, with values above the control but below L2, and a relatively balanced depth distribution. Vertical distribution was relatively balanced, without excessive accumulation in the surface layer, indicating moderate phosphorus mobility within the soil profile.

Table 8. Mean content of mobile phosphorus (P-AL, mg kg^{-1}) as affected by water regime, fertilizer type, and soil depth in the NE-CL soil.

Water Regime (L m^{-2})	Depth (cm)	P-AL (mg kg^{-1})			
		NF	L1	L2	S
W0	2–4	45.6 a	47.3 a	49.2 a	43.8 a
	4–6	44.5 a	43.0 a	45.7 a	42.5 a
	6–8	42.0 a	41.5 a	43.8 a	41.0 a
W50	2–4	45.3 c	53.9 b	63.0 a	49.3 bc
	4–6	44.8 b	52.2 a	52.0 a	44.8 b
	6–8	45.1 b	47.9 a	46.7 ab	43.6 c
W100	2–4	44.1 b	44.8 b	58.0 a	48.6 a
	4–6	43.1 b	41.7 b	49.5 a	43.2 b
	6–8	43.2 a	41.6 a	44.3 a	41.5 a
W150	2–4	45.9 d	50.9 c	62.8 a	55.8 b
	4–6	43.8 b	44.5 b	50.8 a	47.0 ab
	6–8	42.9 a	42.3 a	46.2 b	41.9 a

Values represent means (n = 3). Within each water regime, different lowercase letters indicate significant differences among fertilizer × depth combinations (Bonferroni test, $p < 0.05$).

The solid fertilizer exhibited a slower release and a more uniform distribution with depth. Surface-layer values (49–56 mg kg^{-1}) were moderate, while deeper-layer values were often comparable to those of the liquid treatments, suggesting more controlled redistribution and limited depth-related variability. Overall, direct comparison among treatments shows that L2 resulted in the highest P-AL concentrations in the surface layer, L1 produced intermediate values with relatively stable distribution patterns, and the solid fertilizer ensured a more uniform vertical distribution within the analyzed 2–8 cm interval.

3.2.3. Total Mobilized Phosphorus in the 2–8 cm Layer and Vertical Dispersion Indices in the NE-CL Soil

Total P-AL in the 2–8 cm layer differed among water regimes and fertilizer treatments (Table 9). Under W0, values were similar across treatments, and VDI and CUV values close to unity indicate a stable distribution. At W50, liquid fertilizers produced the highest P-AL values across the profile, particularly L2, which was significantly higher than the unfertilized control and the solid fertilizer ($p < 0.05$). Subunitary VDI values and higher CUV values indicate moderate vertical redistribution and a more uniform distribution

among layers. At W100 and W150, L2 remained the dominant treatment, maintaining the highest P-AL values across the analyzed profile. Dispersion indices confirm controlled vertical mobility without pronounced losses from the 2–8 cm zone. Overall, total P-AL values and the VDI/CUV indices indicate that, in NE-CL soil, L2 resulted in the highest degree of phosphorus mobilization within the 2–8 cm layer, whereas the solid fertilizer tended to maintain a more stable vertical profile.

Table 9. Mean P-AL concentration (mg kg^{-1}) in the 2–8 cm layer and the VDI and CUV indices as affected by water regime and fertilizer type in the NE-CL soil.

Water Regime (L m^{-2})	Fertilizer	P-AL (mg kg^{-1}) 2–8 cm	VDI	CUV
W0	NF	44.0 ± 1.8 a	1.0	1.1
	L1	43.9 ± 3.0 a	0.9	1.1
	L2	46.2 ± 2.8 a	0.9	1.1
	S	42.4 ± 1.4 a	1.0	1.1
W50	NF	45.3 ± 0.1 b	1.0	1.0
	L1	51.3 ± 3.1 a	0.9	1.1
	L2	53.9 ± 8.3 a	0.9	1.3
	S	45.9 ± 3.0 b	1.0	1.1
W100	NF	43.5 ± 0.5 b	1.0	1.0
	L1	42.7 ± 1.8 b	1.0	1.1
	L2	50.6 ± 6.9 a	0.9	1.3
	S	44.4 ± 3.7 ab	0.9	1.2
W150	NF	44.2 ± 1.5 b	1.0	1.1
	L1	45.9 ± 4.5 b	0.9	1.2
	L2	53.3 ± 8.6 a	0.9	1.3
	S	48.4 ± 7.0 b	0.9	1.3

Values represent mean ± standard deviation (n = 3). Different lowercase letters indicate significant differences among fertilizers within the same water regime (Tukey's HSD, $p < 0.05$). VDI: <1 = upper-layer accumulation; ≈1 = balanced; >1 = lower-layer redistribution. CUV: higher values = greater vertical uniformity (2–8 cm).

3.3. Alkaline, Very Well Phosphorus-Supplied Soil (AL-SL)

The three-way ANOVA showed significant main effects of water regime, fertilizer type, and soil depth on phosphorus distribution in the alkaline soil ($p < 0.001$; Table 10). Interaction terms were also significant, indicating that phosphorus mobility depended on the combined influence of water regime, fertilizer form, and depth within the soil profile.

Table 10. Summary of the ANOVA results for the AL-SL soil.

Source of Variation	df	F Value	*p* Value	Partial η^2
Water regime (W)	3	203.81	<0.001	0.864
Fertilizer (F)	3	11.15	<0.001	0.258
Soil depth (D)	2	38.01	<0.001	0.442
W × F	9	27.70	<0.001	0.722
W × D	6	9.32	<0.001	0.368
F × D	6	19.86	<0.001	0.554
W × F × D	18	5.64	<0.001	0.514

R^2 = 0.929 (Adjusted R^2 = 0.893).

The significance of these interactions indicates that fertilizer-related differences in phosphorus distribution were expressed differently across soil depths as water input increased, reflecting a strong modulation of vertical redistribution by moisture under alkaline soil conditions. Partial η^2 values highlight the dominant role of the water regime, with fertilizer type and soil depth exerting secondary but consistent effects.

3.3.1. Effect of the Water Regime on Phosphorus Distribution in the AL-SL Soil

In the AL-SL soil, soil moisture strongly controlled phosphorus redistribution, an effect amplified by the alkaline reaction and high background phosphorus reserves (Figure 3).

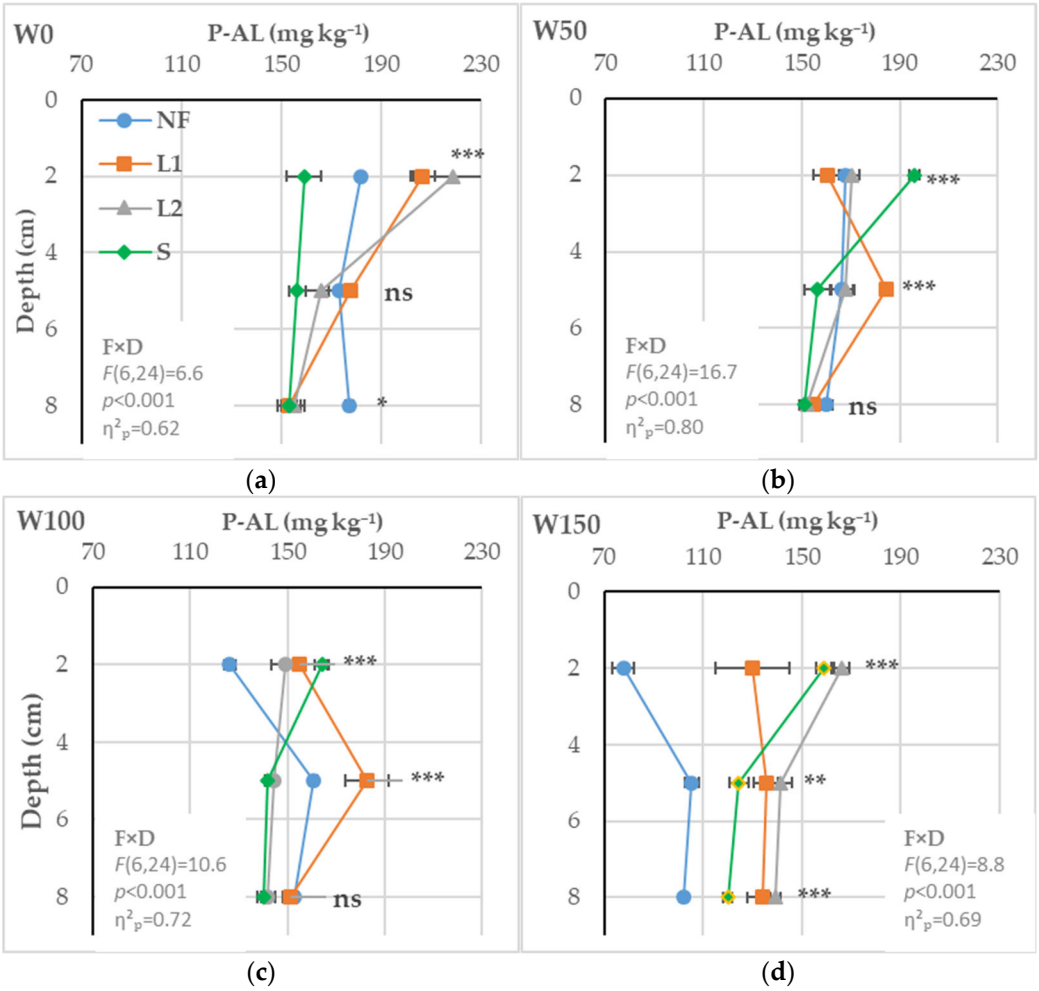

Figure 3. Distribution of phosphorus content (P-AL, mg kg^{-1}) along the soil profile in AL-SL under different water regimes: (**a**) W0, (**b**) W50, (**c**) W100, and (**d**) W150 (25 mm day^{-1}). NF, unfertilized control; L1, liquid NP fertilizer applied at low dose; L2, liquid NP fertilizer applied at high dose; S, solid NPK fertilizer. Values are means of three replicates ± standard error of the mean (±SE). Symbols "ns", "*", "**", and "***" denote non-significant or significant differences at $p > 0.05$, $p < 0.01$, and $p < 0.001$, respectively (Bonferroni test). F and η^2_p values shown in boxes correspond to the F × D (Fertilizer × Depth) interaction.

Under drought conditions (W0), phosphorus remained largely concentrated in the surface layer (2–4 cm), where liquid fertilizers produced high P-AL values (180–210 mg kg^{-1}), while the solid fertilizer showed lower surface accumulation and limited downward movement.

The significant Fertilizer × Depth interaction indicates that differences among treatments were already evident along the profile under dry conditions. This early expression of the Fertilizer × Depth interaction under W0 reflects the high background phosphorus status of the soil, allowing fertilizer-specific distribution patterns to be detected even under the lowest water regime.

At moderate moisture (W50), dissolution of liquid fertilizers was enhanced and phosphorus redistribution extended to the 4–6 cm layer. Differences among treatments became more pronounced, with L2 recording the highest surface P-AL values exceeded 200 mg kg^{-1}

and a strong Fertilizer × Depth interaction ($\eta^2_p \approx 0.80$), reflecting controlled but evident vertical mobility.

At higher moisture (W100), phosphorus mobility increased further. Liquid fertilizers maintained high surface concentrations while available phosphorus extended down to 6 cm (185–168 mg kg^{-1}). Differences among fertilizers remained significant, and interaction effects indicate sustained vertical redistribution. The solid fertilizer displayed a more uniform profile, but with lower overall mobility.

Under excess water conditions (W150), vertical redistribution of phosphorus became more pronounced. For L2, P-AL values in the 2–4 cm layer remained high (≈160–170 mg kg^{-1}) and were accompanied by a visible migration toward the 4–6 cm layer. Differences among depths were significant ($p < 0.001$), and the Fertilizer × Depth interaction explained a substantial proportion of the observed variability ($\eta^2_p = 0.69$).

By contrast, the solid fertilizer maintained a more stable profile, with smaller variations among layers, indicating a lower risk of excessive phosphorus redistribution under high water input. This pattern indicates that, even under excess moisture, vertical phosphorus redistribution in the AL-SL soil remains strongly constrained by soil chemical buffering, resulting in depth-dependent but limited fertilizer-specific effects.

3.3.2. Effect of Fertilizer Type on Phosphorus Distribution in the AL-SL Soil

Fertilizer type significantly influenced phosphorus distribution in the alkaline soil, particularly in the surface layer (2–4 cm), where differences among treatments were most evident (Table 11). The liquid fertilizer L2 consistently produced the highest P-AL values under most water regimes, indicating rapid phosphorus mobilization within the 2–8 cm soil layer.

Table 11. Mean content of mobile phosphorus (P-AL, mg kg^{-1}) as affected by water regime, fertilizer type, and soil depth in the alkaline soil (AL-SL).

Water Regime (L m^{-2})	Depth (cm)	P-AL (mg kg^{-1})			
		NF	L1	L2	S
W0	2–4	182 b	206 b	218 a	159 c
	4–6	173 a	178 a	166 a	156 a
	6–8	177 a	153 a	155 a	153 a
W50	2–4	168 b	161 b	170 b	190 a
	4–6	166 b	185 a	168 b	157 b
	6–8	160 a	155 a	152 a	151 a
W100	2–4	126 b	155 a	149 ab	164 a
	4–6	161 b	183 a	144 b	142 b
	6–8	153 a	151 a	142 a	140 a
W150	2–4	78 c	130 b	166 a	159 a
	4–6	105 b	136 a	141 a	124 ab
	6–8	102 b	134 a	139 a	120 ab

Values represent means (n = 3). Within each water regime, different lowercase letters indicate significant differences among fertilizer × depth combinations (Bonferroni test, $p < 0.05$).

The liquid fertilizer L1 showed an intermediate response, with P-AL values consistently exceeding those of the unfertilized control but generally remaining below those recorded for L2 in the surface layer. For example, at W150, L1 reached 130 mg kg^{-1} in the 2–4 cm layer, significantly higher than NF (78 mg kg^{-1}) but lower than L2 (166 mg kg^{-1}). Phosphorus distribution with depth was relatively balanced, suggesting moderate mobility without excessive accumulation in deeper layers.

The solid fertilizer exhibited a distinct behavior characterized by a more uniform vertical distribution. In some cases, particularly under moderate moisture, surface-layer P-AL values exceeded those of the liquid treatments, while deeper-layer values were comparable across fertilizers. This pattern reflects a slower release and greater vertical stability of phosphorus.

Overall, comparison among treatments shows that L2 resulted in the highest P-AL concentrations, L1 provides an intermediate and more controlled response, and the solid fertilizer ensures a more uniform distribution with depth, reducing vertical variability. The differences highlighted statistically by the Bonferroni test ($p < 0.05$) confirm the role of fertilizer form on the vertical distribution and concentration of extractable phosphorus.

3.3.3. Total Mobilized Phosphorus in the 2–8 cm Layer and Vertical Dispersion Indices in the AL-SL Soil

Total mobilized phosphorus in the 2–8 cm layer varied with both fertilizer type and water regime (Table 12). Under drought conditions (W0), P-AL values were high and similar for the unfertilized control and liquid fertilizers (177–180 mg kg^{-1}), whereas the solid fertilizer showed lower total values (156 mg kg^{-1}, $p < 0.05$). VDI values close to 1.0 and CUV values of approximately 1.0–1.4 indicate a relatively stable distribution along the soil profile.

Table 12. Mean P-AL concentration (mg kg^{-1}) in the 2–8 cm soil layer and the VDI and CUV indices as affected by water regime and fertilizer type (AL-SL).

Water Regime (L m^{-2})	Fertilizer	P-AL (mg kg^{-1}) 2–8 cm	VDI	CUV
W0	NF	177 ± 4 a	1.0	1.0
	L1	179 ± 27 a	0.9	1.3
	L2	180 ± 34 a	0.9	1.4
	S	156 ± 3 b	1.0	1.0
W50	NF	165 ± 5 a	1.0	1.0
	L1	167 ± 16 a	0.9	1.0
	L2	163 ± 10 a	0.9	1.1
	S	168 ± 25 a	0.9	1.3
W100	NF	147 ± 18 b	1.0	0.8
	L1	163 ± 17 a	0.9	1.0
	L2	145 ± 4 b	1.0	1.0
	S	149 ± 13 b	0.9	1.2
W150	NF	95 ± 15 c	1.1	0.7
	L1	133 ± 3 b	1.0	1.0
	L2	149 ± 15 a	0.9	1.2
	S	134 ± 21 ab	0.9	1.3

Values represent mean ± standard deviation (n = 3). Different lowercase letters indicate significant differences among fertilizers within the same water regime (Tukey's HSD, $p < 0.05$). VDI: <1 = upper-layer accumulation; ≈1 = balanced; >1 = lower-layer redistribution. CUV: higher values = greater vertical uniformity (2–8 cm).

At moderate moisture (W50), total P-AL values differed little among treatments, and dispersion indices indicate moderate but controlled redistribution. Under high moisture (W100), L1 recorded the highest total P-AL across the profile (163 mg kg^{-1}), indicating enhanced phosphorus mobilization within the 2–8 cm layer.

Under excess moisture (W150), L2 produced the highest total mobilized phosphorus (149 mg kg^{-1}), significantly exceeding the unfertilized control (95 mg kg^{-1}, $p < 0.05$). VDI and CUV values reflect increased vertical redistribution, whereas the solid fertilizer maintained a more stable distribution with lower variability.

Overall, in the AL-SL soil, fertilizer-specific differences in phosphorus mobilization varied with water regime, with L2 showing greater mobilization under high moisture, L1 under moderate moisture, and the solid fertilizer maintaining the greatest vertical stability within the analyzed soil layer (2–8 cm).

4. Discussion

The results highlight that phosphorus mobility is governed by a complex interaction between water regime, soil type, and fertilizer form. Variations in these factors account for the contrasting patterns observed in the vertical distribution of phosphorus. The discussion therefore focuses on the mechanisms underlying these responses and on the redistribution of phosphorus within the surface soil layers under controlled conditions.

Because fertilizer forms were applied at different rates and, in the case of liquid formulations, at different solution volumes, the interpretation of the results is restricted to soil phosphorus redistribution patterns.

Although the experiment was conducted in a plant-free system, fertilizer doses were selected to reflect inputs commonly used in agricultural practice in Romania. Thus, the identified migration patterns provide insight into the processes shaping the spatial architecture of phosphorus in soil.

4.1. Influence of Water Regime on Phosphorus Mobility

The water regime represented the dominant factor controlling phosphorus mobility across all soil types, irrespective of fertilizer form [1,18,19]. Under surface application and low soil moisture conditions, dissolution and diffusion processes were severely constrained, resulting in the retention of phosphorus in the surface layer, with only minimal vertical redistribution relative to the soil layer in which the tested fertilizers were applied [21,22,47].

As soil moisture and water input increased following the simulation of precipitation regimes, phosphorus redistribution along the analyzed soil profile increased. This response is consistent with findings reported in similar studies [20,48]. However, this response was not linear. Increased water availability primarily facilitated the transfer of phosphorus from the surface to the immediately underlying layer (2–4 cm), rather than promoting a uniform vertical redistribution throughout the analyzed depth.

Under moderate precipitation regimes, redistribution remained largely confined to the upper segment of soil layer (2–4 cm). This pattern suggests that adsorption processes and the soil's buffering capacity restricted further downward migration toward the base of the analyzed layer (6–8 cm), despite the increased water supply.

These findings indicate that, under such conditions, water acts as a triggering factor for redistribution, while soil chemical constraints regulate its vertical extent [5,14,20].

High water input intensified vertical redistribution toward the lower part of the examined profile section only in soils with lower buffering capacity or when readily soluble liquid fertilizers were applied. These formulations are rapidly incorporated into the soil solution, which facilitates phosphorus movement.

Previous studies indicate that enhanced redistribution under high soil moisture does not necessarily imply immediate phosphorus losses. Adsorption and secondary precipitation processes may temporarily retain phosphorus, depending on soil pH and other chemical properties [5,20,25,49]. This behavior is consistent with the results of the present study. Increased phosphorus mobility under the W100–W150 treatments was reflected by changes in its vertical distribution within the investigated soil layer.

Although increasing water input promoted phosphorus redistribution within the analyzed surface soil profile, this response was not uniform across soil types and was strongly constrained by soil-specific chemical buffering mechanisms. This limitation explains why

similar water regimes did not generate comparable patterns of vertical redistribution in all investigated soils.

4.2. Role of Soil Properties in Controlling Phosphorus Distribution

The physical and chemical properties of the soil significantly influenced phosphorus dynamics by regulating adsorption, precipitation, and retention processes within the soil matrix. Soil texture and reaction (pH) conditioned the response of applied phosphorus to variations in the water regime, generating distinct patterns of vertical redistribution, in agreement with data reported in the literature [1,5].

In the acidic soil (AC-LO), phosphorus mobility was primarily limited by soil reaction (pH 5.9) and by the retention properties of the edaphic matrix. The pronounced discrepancy between total phosphorus content (270 mg kg^{-1}) and the very low level of P-AL concentration (5.4 mg kg^{-1}) indicates a strong tendency toward phosphorus immobilization in less mobile forms.

Although the content of exchangeable Al^{3+} was low (0.06 meq 100 g^{-1}), previous studies show that, in acidic soils, soil reaction and the nature of reactive surfaces can govern phosphorus retention even in the absence of high concentrations of extractable Al or Fe [1,5,50].

The loamy texture contributed to reduced phosphorus diffusion [13,17,23], while the relatively low soil organic carbon content (SOC = 0.99%) limited mobilization processes associated with organic complexation, favoring phosphorus retention in the surface layer [51]. In this context, the reduced amount of organic matter enhanced the exposure of mineral colloids, intensifying phosphorus retention processes and further constraining vertical redistribution, a mechanism well documented in the literature [51].

In contrast to acidic and alkaline soils, the neutral soil (NE-CL) exhibited the strongest relationship between water input and phosphorus redistribution within the analyzed soil layer. The neutral to slightly acidic reaction (pH 6.8) and the high cation exchange capacity (CEC = 26.3 meq 100 g^{-1}), together with a high base saturation degree (V = 94.6%), created favorable conditions for balanced phosphorus retention. These properties also supported controlled redistribution within the profile. Such behavior is consistent with observations reported for soils with similar reactions and high buffering capacity. consistent with observations reported for soils with similar reactions and high buffering capacity [1,11,15].

The relatively high content of P-AL (45.1 mg kg^{-1}) in relation to total phosphorus (460 mg kg^{-1}) indicates moderate immobilization and a substantial proportion of phosphorus maintained in readily extractable forms, a characteristic feature of this soil type [5,30,52].

The clay loam texture (A = 33%) promoted phosphorus retention at the colloidal complex. This contributed to its stabilization within the soil matrix and limited excessive vertical redistribution [17,42], even under increased water input [13,52].

At the same time, the higher level of organic carbon (SOC = 1.68%) may support moderate mobilization processes through anion competition and complexation. However, this did not lead to uncontrolled phosphorus redistribution within the profile [30,51]. Under these conditions, the NE-CL soil allowed a progressive migration of phosphorus within defined surface interval, while the process remained tightly regulated by the balance among pH, buffering capacity, and texture [11,15,30].

Consequently, phosphorus mobility increased with water input without excessive redistribution, confirming the balanced behavior of this soil type [32,53,54].

The alkaline soil (AL-SL) exhibited limited vertical redistribution, despite physical properties favorable to water infiltration along the soil profile and very high initial phosphorus reserves. The analyzed soil has a history of intensive fertilization, which explains the very high total phosphorus content (2900 mg kg^{-1}).

The high level of P-AL (178.1 mg kg^{-1}) reflects this historical supply. It also indicates that a substantial fraction of phosphorus remained in extractable forms in the surface soil, a pattern associated with long-term management strategies described in the literature [55].

Although the lighter texture and high porosity could have favored physical transport processes, phosphorus redistribution remained limited [1,7,8,51]. In this case, phosphorus distribution was controlled primarily by the alkaline soil reaction (pH 8.0) and the presence of calcium carbonate ($CaCO_3$ = 1.8%). These factors promote phosphorus precipitation into sparingly soluble forms [1,56,57].

The very high cation exchange capacity (CEC = 41.7 meq 100 g^{-1}), together with an almost complete base saturation (V = 99.5%), indicates a strongly buffered chemical system. Such conditions limit the flexibility of phosphorus equilibria.

Under these conditions, phosphorus mobility is no longer dominated by simple diffusive processes, but by strict control exerted by precipitation–dissolution equilibria, which severely restrict vertical redistribution [1,8,58,59]. This behavior indicates that, in alkaline environments, chemical stabilization reactions exert a much stronger influence on phosphorus distribution than physical transport properties [1,12,53,60].

This tendency is further supported by comparison with the neutral soil (pH 6.8), where vertical redistribution was less chemically constrained. Alkaline reaction, carbonate presence, and high buffering capacity are the factors that enforce rapid phosphorus stabilization, effectively blocking vertical diffusion despite the massive reserves identified within the soil matrix [1,12,53].

In summary, the results obtained in this study show that differences in phosphorus redistribution were primarily determined by soil chemical properties, which conditioned how water input was translated into vertical phosphorus mobility.

In the acidic (AC-LO) and alkaline (AL-SL) soils, changes in vertical distribution remained limited even under high water regimes, as a consequence of retention through specific adsorption and precipitation as calcium phosphates, respectively.

By contrast, in the neutral soil (NE-CL), increased water input led to a more evident and more uniform redistribution of phosphorus within the surface layer.

These differences indicate that, under the applied experimental conditions, soil reaction and chemical stabilization capacity regulated the amplitude of phosphorus redistribution under the influence of water regime to a greater extent than physical transport properties or the initial level of phosphorus reserves [1,8,56].

4.3. Differences Between Liquid and Solid Fertilizers

Differences between liquid and solid phosphate fertilizers were evident across all soil types and depended on both the water regime and soil properties.

Liquid and solid formulations were applied using distinct methods, involving different physical mechanisms of phosphorus transport. Therefore, the observed differences reflect redistribution processes specific to the mode of application rather than intrinsic formulation effects. These variations were expressed primarily in the dispersion patterns and in the degree of vertical redistribution of phosphorus.

Although liquid formulations were applied at lower phosphorus concentrations, their mode of application favored a more uniform incorporation of phosphorus into the surface soil layer, a behavior widely documented in the literature [5,57]. Consequently, the results reflect distinct dispersion patterns under agronomically realistic application conditions, without implying differences in efficiency between fertilizer types [55,61].

A more rapid increase in P-AL in the surface layer was observed for liquid formulations, particularly under high water regimes [5]. In acidic and neutral soils, liquid formulations—especially at the higher dose (L2)—generated higher P-AL values than the

solid fertilizer, indicating an accelerated integration of phosphorus into the soil solution and into readily exchangeable fractions.

This response is consistent with previous studies showing that liquid fertilizers enhance phosphorus dissolution and short-range diffusion when soil moisture is sufficient [4,30,62]. However, under low water input, these differences diminished, reflecting the dominant limitation imposed by reduced soil moisture [5,53].

Liquid formulations ensured a more uniform incorporation within the soil matrix. In contrast, the solid fertilizer exhibited greater vertical stability, with smaller variations in mobile phosphorus between soil layers and across water regimes. This behavior aligns with previously described dispersion mechanisms [57,61] and indicates that fertilizer form influences the initial configuration of nutrients in soil.

The effect was particularly evident in the alkaline soil, where precipitation processes and secondary fixation strongly constrain the mobility of soluble phosphorus [1,54]. Under these conditions, the solid formulation tended to retain phosphorus closer to the application layer, thereby limiting its redistribution within the investigated depth interval [13,60].

In contrast to studies reporting pronounced downward movement of phosphorus under intense precipitation regimes, the redistribution observed in this study remained confined to the surface layer, emphasizing the dominant role of chemical phosphorus stabilization under controlled conditions.

Overall, the results indicate that liquid fertilizers facilitate a more consistent and uniform redistribution of phosphorus within the surface soil layers (2–8 cm), whereas solid fertilizers are associated with a more stable vertical distribution under variable water regimes. This difference highlights the role of fertilizer form in shaping nutrient redistribution patterns in soil [2,5,16,40].

The data demonstrate that fertilizer physical form influences phosphorus distribution and its interaction with the soil matrix under controlled conditions.

4.4. Context-Dependent Implications of Fertilizer Form for Phosphorus Redistribution

Although the study was conducted under controlled conditions in a plant-free system, the observed phosphorus redistribution patterns provide mechanistic insight into how water regime, soil type, and fertilizer application method influence short-range phosphorus movement within the surface soil layer.

The analysis was restricted to the 2–8 cm layer, which is particularly relevant where fertilizers are surface-applied and soil disturbance is minimal. Under these conditions, water acted primarily as a triggering or amplifying factor for nutrient dynamics, whereas soil chemical properties imposed the limits of these processes [3,4,14].

In the acidic soil (AC-LO), phosphorus mobility was severely constrained by acidic reaction and specific adsorption processes [8,11,12]. The results indicate that, under water-deficit conditions, no fertilizer form can overcome the physicochemical barriers inherent to this soil.

Differences between liquid and solid formulations became apparent only when soil moisture was sufficient to activate dissolution and diffusion processes [20,49]. Even under these conditions, the magnitude of redistribution remained strictly controlled by specific adsorption, rendering the influence of fertilizer type secondary. Nevertheless, under favorable soil moisture, liquid formulations were associated with a more uniform dispersion of phosphorus within the surface layer (2–8 cm).

This observation is consistent with reports indicating that liquid fertilizers can facilitate more rapid phosphorus redistribution in soils with high fixation capacity prior to chemical stabilization [28,30,37].

The neutral soil (NE-CL) exhibited the most balanced behavior and represented the context in which differences between fertilizer forms were most clearly expressed. The soil's specific chemical equilibrium allowed a more flexible phosphorus redistribution under the influence of the water regime, while the clay loam texture favored effective nutrient retention within the colloidal complex [17,42].

The data indicate that, under moderate moisture regimes, liquid formulations promote a more homogeneous dispersion of phosphorus within the 2–8 cm layer, whereas solid fertilizers tend to maintain a more stable vertical distribution [30,32,53,54].

This behavior aligns with previous observations [63]. It indicates that, in the absence of major chemical constraints, fertilizer form contributes significantly to configuring phosphorus redistribution patterns in the surface layer as a function of water dynamics.

In the alkaline soil (AL-SL), the influence of fertilizer form was strongly attenuated by the chemical properties of the soil matrix. Although the lighter texture and higher porosity could have favored water movement, the presence of carbonates and the high buffering capacity promoted rapid phosphorus stabilization in the application zone, even under favorable water regimes [64].

Differences between liquid and solid formulations remained minor, as precipitation and chemical adsorption processes dominated phosphorus behavior, outweighing the influence of fertilizer presentation [46]. Thus, in alkaline soils, application form plays a secondary role, with redistribution within the 2–8 cm layer being governed almost exclusively by stabilization reactions characteristic of this environment [64].

Taken together, the results indicate that fertilizer form can be meaningfully related to soil type and water regime insofar as these factors condition phosphorus redistribution within the surface layer.

However, these implications are strictly limited to the plant-free experimental system and refer specifically to the identified redistribution processes. They do not allow direct inferences regarding crop phosphorus uptake, agronomic fertilization efficiency, or nutrient losses beyond the analyzed zone.

As well documented in the literature [1], nutrient dynamics in the presence of roots are substantially more complex due to chemical and biological modifications within the rhizosphere. Consequently, processes such as plant phosphorus uptake and agronomic fertilization efficiency cannot be evaluated based on the present results and require dedicated experimental approaches that incorporate soil–plant systems.

5. Conclusions

Phosphorus redistribution within the surface soil layer (2–8 cm) is governed primarily by soil chemical properties. Water regime modulates redistribution intensity, while fertilizer form influences the initial spatial distribution of applied phosphorus.

Distinct patterns were observed among soil types, reflecting differences in buffering capacity, sorption mechanisms, and precipitation processes. The neutral soil exhibited the most balanced response, allowing a more flexible redistribution of phosphorus under the influence of moisture, in contrast to acidic and alkaline soils, where chemical fixation processes imposed severe constraints.

The difference between liquid and solid fertilizers lies in their mode of dispersion within the soil matrix. Liquid formulations facilitated a more rapid and more uniform incorporation of phosphorus into the surface layer under favorable soil moisture conditions, whereas solid fertilizers were associated with greater vertical stability, particularly in soils with pronounced chemical buffering capacity. These differences describe soil-level redistribution processes and should not be extrapolated to fertilizer efficiency or crop response.

Overall, the results highlight the importance of considering soil type and moisture regime when interpreting patterns of surface-applied phosphorus redistribution. The findings provide mechanistic clarity by demonstrating how established processes are differentially expressed under varying water regimes, soil properties, and fertilizer application pathways within a standardized experimental framework.

The conclusions provide a solid mechanistic basis for understanding short-range phosphorus transport in soil, without allowing direct inferences regarding root uptake or nutrient losses beyond the analyzed layer.

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