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Interrelationship Analysis of Agrochemical Properties of Southern Chernozem in Northern Kazakhstan

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ABSTRACT

The article is devoted to the study of the interrelationships between the structural characteristics of the soil, agrochemical regime and elemental composition. The object of the study was two variants: control (C_0) and fertilized (P_{20}). It has been established that the application of fertilizers helps to stabilize the granulometric composition, increase the content of humus and total nitrogen, as well as reduce electrical conductivity in the lower horizons. In the southern chernozems of the Akmola region of Northern Kazakhstan, where over the past 16 years' experience has been conducted using traditional technology for the region, two soil sections were laid and their morphological description was performed. The interrelations between the granulometric composition of the soil, the content of humus, nitrogen, electrical conductivity and the main cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) in the upper horizons have been studied. Correlation, regression, and variance analysis was performed for two experimental variants (C_0 and P_{20}). The results showed that the nitrogen content is closely related to humus (r = 0.91), and the electrical conductivity is related to the number of cations (r = 0.88). Regression models explained more than 80% of the variation in nitrogen content and 77% of the changes in electrical conductivity. The analysis of variance revealed statistically significant differences between the C_0 and P_{20} variants in key indicators. The results obtained confirm the influence of granulometric composition and fertilizers on soil fertility. The results demonstrate that fertilization ensures a more uniform distribution of exchange cations and prevents the accumulation of salts in the lower part of the profile, increasing the agrochemical stability of the soil.

Keywords: Granulometric composition of soils, Fertilizers, Humus, Nitrogen, Cations, Electrical conductivity, Correlation analysis.

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INTRODUCTION

The preservation and enhancement of soil fertility represent one of the key directions of sustainable agriculture. Irrational use of fertilizers and unbalanced tillage systems can lead to structural degradation, reduction of organic matter content, alteration of salt balance, and deterioration of soil physical properties (Zafar et al., 2023). In this regard, the assessment of major agrochemical indicators under different technological practices makes it possible to identify optimal strategies for managing soil fertility. Soil texture (particle size composition) is one of the fundamental physical parameters that determine the water–physical properties, sorption characteristics, biogeochemical processes, and resistance of soils to erosion (Nunes et al., 2021; Ketena et al., 2025). Recent studies indicate that tillage significantly affects the distribution of aggregates and textural fractions. For instance, minimum and zero tillage contribute to the increase in macroaggregates (>0.25 mm) and the stabilization of organic matter, whereas conventional plowing leads to structural breakdown and the accumulation of fine particles (Pereira et al., 2023; Huang et al., 2025). Furthermore, regional studies from Kazakhstan emphasize that tillage and fertilization practices on light-textured chernozems of the Steppe Zone

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alter aggregate stability and soil structure (Ramazanova et al., 2023). Long-term field observations also show that tillage systems alter the soil's mechanical resistance and porosity, which in turn regulate water retention, infiltration, and air diffusion in the root zone (Steponavičienė et al., 2023; Cakpo et al., 2025). Similar patterns have been observed in the distribution of sand, silt, and clay fractions: under conventional tillage, higher content of stable aggregates and more uniform distribution of organic carbon within textural fractions are reported (Cárceles Rodríguez et al., 2022).

These data confirm that soil texture is closely associated with agrochemical properties. In soils with a high proportion of sand, lower cation exchange capacity (CEC) and reduced availability of available phosphorus are observed compared to loamy and clay soils (Mattila & Rajala, 2021; Kabala et al., 2024). Moreover, erosion processes on light soils are often accompanied by the removal of fine particles enriched in clay and silt, resulting in additional nutrient losses (Zhu et al., 2024; Ye et al., 2024; Chrysanthopoulos et al., 2025). In Kazakhstan, for example, soils of the Northern and Central agro-regions often show phosphorus deficiency and structural loosening in sandy fractions under long-term cropping without replenishment (Ramazanova et al., 2023). Humus content is one of the principal indicators of soil fertility, since organic matter regulates the accumulation and transformation of nutrients, influences buffering capacity, and supports agronomically valuable soil structure. Modern research (Gonet et al., 2023; Lal, 2022) demonstrates that intensive tillage and unbalanced fertilization accelerate the mineralization of organic matter, leading to a decline in humus reserves and, consequently, deterioration of soil physical properties and productive potential. Kazakh studies have shown that application of organic amendments in Steppe chernozems significantly increased humus content and aggregate stability over a 5-year period (Nauanova et al., 2017; Bostubaeva et al., 2023).

Conversely, organic and organo-mineral amendments have been proven to enhance microbial biomass carbon, enzymatic activity, and aggregate stability, which collectively sustain soil fertility and reduce degradation risk (Cooper et al., 2025; Lustosa Filho et al., 2025). Soil electrical conductivity (EC) is an integral indicator of salinity, dissolved salts, and the overall ionic saturation of the soil solution. It is strongly associated with the balance of calcium, magnesium, sodium, and with processes of leaching and salt accumulation under different irrigation and fertilization regimes (Corwin & Lesch, 2023; Huang et al., 2025). Increasing EC values in arid and semi-arid conditions are now considered early warning signals of secondary salinization and anthropogenic degradation (Larkin et al., 2023; Wang et al., 2025). The relevance of studying the interrelations between soil texture and agrochemical properties is determined by contemporary challenges: climate change, increasing frequency of extreme rainfall events and droughts, the need to improve fertilizer use efficiency, and to mitigate environmental risks (Yanai et al., 2005; Shumenova et al., 2023; Zafar et al., 2025). According to FAO (2025), more than 45% of agricultural lands in regions at high risk of salinization show signs of cation imbalance, often associated with inadequate fertilizer use and irrigation practices. Under these conditions, methods that account for soil texture in predicting phosphorus mobility, cation migration, and water retention gain particular importance (Xing et al., 2025; Simon et al., 2025).

In Northern Kazakhstan, the key limiting factors for crop yield formation are low levels of available phosphorus and insufficient moisture. Uneven precipitation distribution and frequent droughts during the growing season reduce nutrient uptake efficiency, especially in light soils with low water-holding capacity. Therefore, investigating the relationship between soil texture and agrochemical properties remains scientifically and practically significant for developing regionally adapted reclamation and agronomic practices, optimizing fertilizer use, and reducing ecological risks. Modern tasks of sustainable agriculture require an integrated analysis of both chemical and physico-mechanical properties of the soil profile. Maintaining fertility while simultaneously reducing salinization and degradation risks represents one of the key challenges under conditions of agricultural intensification. Comparing the control (C_0) and fertilized (P_{20}) treatments makes it possible to reveal systemic relationships between soil texture, organic matter distribution, and cation migration. The aim of this study is to compare agrochemical indicators and soil texture under traditional technology with and without fertilizer application, and to identify structural factors determining nutrient distribution and cation migration.

MATERIALS & METHODS

The research was conducted in 2025 on southern chernozem soils in the Akmola Region of Northern Kazakhstan (51.6099935° N, 71.0425707° E), an area characterized by a sharply continental climate with strong seasonal contrasts. The mean annual temperature is approximately +2°C. Winters are long and severe, with minimum temperatures reaching -43.8°C and a stable snow cover lasting up to 165 days, while summers are hot and dry, with maximum temperatures up to +38.2°C and a frost-free period of 100 – 130 days. Mean precipitation during the growing season is about 235mm, reflecting limited moisture availability and a high risk of drought. The sum of positive temperatures ranges from 2400 to 2600°C, supporting the cultivation of thermophilic crops under moisture-conserving conditions.

The research was conducted in 2025 on southern chernozem soils in Akmola Region, Northern Kazakhstan, where a long-term field experiment under the region's traditional technology has been carried out for the past 16 years. The experiment began in 2009 and continues to the present. The main crop cultivated in the experimental plots was wheat. The traditional technology included deep non-moldboard tillage, cultivation or disking, followed by compaction. Double superphosphate was applied as fertilizer. Two soil profiles were established on the experimental fields:

- Control – C_0 (51.6099935° N, 71.0425707° E)
- P_{20}, 20kg/ha of active substance (51.6100266° N, 71.0426967° E)

The soil profiles were established on April 28, 2025. For each soil profile, a detailed morphological description was carried out, and samples were collected in triplicate from each genetic horizon at different depths. The samples were air-dried, carefully ground, sieved through 1mm and 2mm meshes depending on the component to be analyzed, then packed into special containers and labeled for subsequent physicochemical analysis.

The analyzed parameters included humus content, total nitrogen, available phosphorus, exchangeable calcium, magnesium, sodium, and potassium, electrical conductivity, and particle-size distribution by fractions. Soil texture was determined using the pipette method in accordance with ISO 11277:2020. Total nitrogen and humus content were analyzed with a vario MAX cube CNS elemental analyzer (Elementar) in accordance with ISO 10694 and ISO 13878. Given that southern Chernozems contain carbonates, available phosphorus was extracted using the Olsen alkaline method. Phosphorus was extracted with 0.5M $NaHCO_3$ (pH 8.5) at a soil-to-solution ratio of 1:20. Quantification of P was performed by MP-AES at the 213.6nm analytical emission line. The soil's specific electrical conductivity was determined at a 1:5 (soil:water) ratio using a conductometer, in accordance with ISO 11265:2025. Soil reaction, pH(H_2O), was determined in accordance with ISO 10390:2021 using a pH meter/ionometer equipped with a combined glass electrode. The method consists of preparing a 1:5 (soil:deionized water) suspension to extract water-soluble electrolytes, followed by potentiometric pH measurement. For pH(KCl), the determination was likewise performed according to ISO 10390:2021 using a 1:5 (soil:solution) suspension in 1mol L^{-1} KCl with the same instrumentation and procedure. Exchangeable potassium was extracted with 1 M ammonium acetate at a 1:10 (soil:extractant) ratio, followed by quantification by MP-AES at the 769.9nm analytical emission line. Exchangeable Ca, Mg, and Na were determined in accordance with ISO/TS 22171:2023, using extraction with 1M NH_4OAc (pH 7.0) at a 1:10 (soil:extractant) ratio. Quantification was performed by MP-AES at the analytical emission lines 422.67nm (Ca), 285.21nm (Mg), and 589.59nm (Na). Descriptive statistics were employed to summarize the baseline characteristics of soil physicochemical properties. Prior to further analysis, the dataset was subjected to a normality assessment, after which Spearman's rho correlation coefficients were calculated to examine the strength and direction of relationships among soil variables. The correlation structure was visualized using heatmaps and bubble plots. Hierarchical cluster analysis (HCA) was conducted using Ward's linkage method and Euclidean distance to classify soil attributes into similarity-based groups. A two-way ANOVA was performed in Minitab v17 to evaluate the main and interactive effects of treatment and soil depth, and post-hoc comparisons were conducted using Tukey's test at $P<0.05$. All graphical outputs were generated using the ggplot package in RStudio.

RESULTS

Morphological description of soil profiles

Profile No. 1 – Control. The morphological description of the soil profile was conducted in a field under traditional cultivation technology without fertilizer application (control) at the experimental site of the A.I. Baraev Scientific and Production Center for Grain Farming.

Relief. The study area is located within a steppe plain characterized by a flat surface. Microrelief is not expressed, and noticeable elevation variations are absent, which determines relatively uniform conditions of water and thermal regimes in soil formation.

Profile No. 2. Relief and vegetation cover of the area where the second soil profile (P_{20}) was established are generally similar to the conditions of the first profile. The site is represented by a leveled steppe plain with an unexpressed microrelief, which ensures uniform conditions of moisture distribution and matter accumulation. The similarity of the morphological relief features indicates the comparability of soil-forming conditions in both fields.

Granulometric Composition of Soils

The granulometric (particle size) composition of soils is a fundamental property that determines key physical characteristics such as porosity, water-holding capacity, infiltration, capillary rise, nutrient retention, as well as soil aeration and thermal regimes (Han et al., 2025).

The analysis of the control profile (C_0), where no fertilizer was applied, revealed a relatively homogeneous texture dominated by the loamy fraction (Table 1). The upper horizon (A; 0–32cm), sand, silt, and clay contents were 40.10±2.1%, 49.03±0.9%, and 10.87±2.8%, respectively, corresponding to a loamy texture according to the USDA classification. The illuvial horizons B_1 (32–58cm) and B_2 (58–80 cm) contained 53.50±1.4% and 50.40±1.0% sand, with clay fractions of 7.47±0.5% and 15.20±2.3%, respectively, both classified as loam. The BC_k horizon (80–100cm) had 49.80±1.3% sand, 34.13±1.1% silt, and 16.13±2.4% clay, also loam, whereas the parent material (C; 100–110cm) exhibited 46.73±0.3% sand, 50.53±0.7% silt, and 2.80±0.6% clay, corresponding to a silt loam texture.

In the phosphorus-treated profile (P_{20}), the upper horizon (A) showed 44.50±1.4% sand, 42.80±0.9% silt, and 12.67±2.3% clay, classed as loam. B_1 and B_2 horizons contained 49.70±1.1% and 47.77±1.5% sand, and 9.67±1.4% and 16.37±2.0% clay, respectively, both maintaining loamy textures. The BC_k and C horizons also remained loamy, with minor variation in particle proportions. Statistical analysis (two-way ANOVA) revealed that soil depth had a highly significant effect ($P<0.001$) on the distribution of sand, silt, and clay fractions, while fertilizer application influenced both silt and clay content. The interaction between soil depth and fertilizer was also significant for all fractions ($P<0.01$), indicating slight textural adjustments across horizons under fertilization.

Profile No. 1 – Control C_0

Horizon	Depth, cm	Thickness, cm	Description
A	0-32	32	Dark chestnut, loamy, fresh, cloddy, compacted, strongly effervescent with hydrochloric acid, porous, with abundant roots and plant residues; transition to the underlying horizon is distinct.
B_1	32-58	26	Dark chestnut, loamy, fresh, cloddy, dense, strongly effervescent with hydrochloric acid, finely porous, with few roots, containing plant residues and lime nodules; transition to the underlying horizon is gradual.
B_2	58-80	22	Dark brown, loamy, moist, cloddy, dense, vigorously effervescent with hydrochloric acid, finely porous, with few roots, containing lime nodules and mottles; transition to the underlying horizon is gradual.
BC_k	80-100	20	Brown, loamy, moist, cloddy, dense, vigorously effervescent with hydrochloric acid, finely porous, with few roots, containing mottles; transition to the underlying horizon is gradual.
C	100-110	10	Light brown, silty loam, moist, structureless, dense, vigorously effervescent with hydrochloric acid.

Profile No. 2 – P_{20}, 20kg/ha of active substance

Horizon	Depth, cm	Thickness, cm	Description
A	0-30	30	Dark chestnut, loamy, fresh, cloddy, compacted, strongly effervescent with hydrochloric acid, porous, with abundant roots and plant residues; transition to the underlying horizon is distinct.
B_1	30-58	28	Dark chestnut, loamy, fresh, cloddy, dense, vigorously effervescent with hydrochloric acid, finely porous, with few roots, plant residues and lime nodules; transition to the underlying horizon is gradual.
B_2	58-78	20	Dark brown, loamy, moist, cloddy, dense, vigorously effervescent with hydrochloric acid, finely porous, with few roots, lime nodules and mottles; transition to the underlying horizon is gradual.
BC_k	78-100	22	Brown, loamy, moist, cloddy, dense, vigorously effervescent with hydrochloric acid, finely porous, with occasional roots and mottles; transition to the underlying horizon is gradual.
C	100-120	20	Light brown, loamy, moist, structureless, dense, vigorously effervescent with hydrochloric acid.

Profile No. 1 – Control

Profile No. 2 – P_{20}, 20 kg/ha of active substance.

Table 1: Granulometric composition of soil by genetic horizons of the soil profile

Treatment	Horizon	Depth (cm)	Sand	Silt	Clay	Textural class (USDA)
	A	0–32	40.10±2.1e	49.03±0.9a	10.87±2.8bcd	
	B_1	32–58	53.50±1.4a	39.07±0.9cd	7.47±0.5de	
C_0	B_2	58–80	50.40±0.1ab	34.40±2.2e	15.20±2.3b	
	BC_k	80–100	49.80±1.3bc	34.13±1.1e	16.13±2.4a	L
	C	100–110	46.73±0.3cd	50.53±0.7a	2.80±0.6e	SL
	A	0-30	44.50±1.40d	42.80±0.9b	12.67±2.3abc	
	B_1	30-58	49.70±1.1bc	40.63±0.4bc	9.67±1.4cd	
P_{20}	B_2	58-78	47.77±1.5bcd	35.87±0.7e	16.37±2.0a	
	BC_k	78-100	49.63±0.1bc	36.87±0.4de	13.50±0.4abc	L
	C	100-120	48.67±0.5bc	40.83±0.9bc	10.50±1.4bcd	
Soil Depth			0.000***	0.000***	0.000***	
Fertilizer			0.901ns	0.000***	0.005**	
Soil Depth x Fertilizer			0.000***	0.000***	0.002**	

Mean±SD values in each column followed by the same lowercase letter do not differ significantly according to Tukey's t-test at P≤0.05. L: loam, SL: Silt loam. Symbols ***, **, and * denote significance at 0.001, 0.01, and 0.05 probability levels, respectively. ns: no significant difference; nd: not detected.

Nevertheless, these variations did not alter the overall loamy texture of the soil profile. Both control and fertilized (C_0, P_{20}) profile pits exhibited similar loamy textures across horizons, suggesting that moderate phosphorus application did not markedly modify the granulometric structure. This consistency reflects the inherent stability and homogeneity of the parent material and confirms the favorable agrophysical properties of the soil for agricultural use.

Agrochemical Distribution of Nutrients in the Soil Profile

The vertical distribution of nutrients and exchangeable cations within the soil profile in Table 2 revealed clear and significant ($p<0.05$) depth-related differentiation influenced by fertilization and organic matter dynamics. Total nitrogen content in both control (C_0) and phosphorus-treated (P_{20}) soils showed a consistent and significant decline with depth, reflecting the typical decrease in organic matter and biological activity in lower horizons. Total nitrogen decreased from 0.41% in the 0-32 cm layer to 0.18% at 100-110cm, while under phosphorus fertilization, this ranged from 0.44% to 0.15% over the same depth interval. The slightly higher nitrogen content in the upper horizon of P_{20} indicates improved mineralization and nitrogen retention under phosphorus fertilization. Soil humus content exhibited a similar vertical pattern, declining sharply from 2.52% at the surface to 0.24% in the deepest layer of the control, and from 2.29% to 0.17% in the fertilized variant. This pronounced decrease demonstrates limited downward translocation of organic residues and the restricted humification processes characteristic of deeper mineral horizons. Available phosphorus (P_2O_5) was primarily concentrated in the uppermost layers, where the fertilized soil contained 40.30mg kg^{-1} compared with 30.53mg kg^{-1} in the control. Below 58cm, phosphorus was undetectable in both variants, indicating strong phosphate fixation and low vertical mobility. Such surface accumulation reflects the retention of applied phosphorus in the plow layer, a common phenomenon in calcareous soils with high pH. Potassium (K_2O) distribution, in contrast, showed variability between treatments. Potassium (K_2O) content under zero fertilization decreased progressively from 490.93mg kg^{-1} in the surface horizon to 160.87-198.77mg kg^{-1} in deeper layers, while in P_{20} it remained more stable, ranging from 499.33mg kg^{-1} at the surface to 211.20mg kg^{-1} at 100–110cm. This suggests a more balanced potassium profile under phosphorus application, potentially due to reduced uptake or greater retention of K^+ in the exchange complex under improved nutrient equilibrium.

Soil reaction was moderately to strongly alkaline in all horizons, with pH (H_2O) ranging from 8.22 to 9.04 in the control and 8.47 to 9.40 in the fertilized profile (P_{20}), while pH (KCl) varied from 7.06 to 7.28 and 7.08 to 7.37, respectively. The slight pH increase with depth likely reflects carbonate enrichment and the diminished influence of organic acids in subsoil horizons. Electrical conductivity (EC) provided insights into salt accumulation and mobility. In both profiles, depth x fertilizer effect on EC content was strongly significant ($p<0.001$), with the highest accumulation observed at 100-110cm, indicating substantial buildup of soluble salts in the deeper layers. Calcium, one of the dominant exchangeable cations, decreased gradually with depth in both treatments but exhibited a distinct increase in the lowermost layer of the control, rising from 19.15mmol $100g^{-1}$ at the surface to 29.70mmol $100g^{-1}$ at 100–110cm, possibly due to secondary carbonate accumulation. In contrast, calcium in P_{20} ranged from 18.34 to 9.10mmol $100g^{-1}$ without a similar accumulation trend, suggesting a more uniform distribution under fertilization. Magnesium concentrations increased with depth in both variants, from 3.65 to 11.20mmol $100g^{-1}$ in the control and from 4.70 to 10.28mmol $100g^{-1}$ in P_{20}, indicating downward migration and possible illuviation of Mg^{2+} in subsoil horizons.

Sodium dynamics were more variable and environmentally significant. In the control, Na^+ increased from 0.12mmol $100g^{-1}$ in the upper horizon to 0.61mmol $100g^{-1}$ at depth, while in P_{20} it rose more sharply, from 0.18 to 1.58mmol $100g^{-1}$ at 100-110cm. The pronounced sodium accumulation in the deeper layer of the fertilized soil suggests the potential for solonetzic development and indicates the necessity for long-term monitoring to prevent secondary salinization. Overall, phosphorus application led to an increase in total nitrogen and available phosphorus in surface horizons, stabilization of potassium and calcium distributions, and a reduction in overall salt concentration within the profile. However, the elevated sodium content at depth underscores the importance of balanced fertilization management and careful control of soil chemical equilibrium to mitigate potential salinization risks during long-term agricultural use.

Table 2: Effects of soil depth and phosphorus fertilization on agrochemical properties and their interactions

Treatment	Depth (cm)	%TN	Humus	P_2O_5	K_2O	pH (H_2O)	pH (KCl)	Ca^{2+}	Mg^{2+}	Na^+	EC (dS/m)
C_0	0–32	0.41±0.0b	2.52±0.1a	30.53±0.6b	490.93±5.1a	8.22±0.01i	7.07±0.0g	19.15±0.2b	3.65±0.1e	0.12±0.0i	1.01±0.1cd
	32–58	0.36±0.0c	1.90±0.0c	1.23±0.7c	191.33±5.9cd	8.65±0.00f	7.10±0.0ef	16.15±0.1d	6.78±0.2c	0.31±0.0f	0.88±0.1def
	58–80	0.23±0.0e	1.01±0.0f	nd	167.67±4.1ef	9.00±0.00e	7.19±0.0d	11.82±0.2e	11.20±0.2a	0.41±0.0e	0.91±0.0de
	80–100	0.18±0.0f	0.37±0.0h	nd	160.87±6.7f	9.04±0.01d	7.28±0.0b	11.44±0.3ef	10.00±0.4b	0.61±0.0d	1.14±0.1c
	100–110	0.18±0.0fg	0.24±0.0i	nd	198.77±7.5bc	7.82±0.01j	7.06±0.0g	29.70±0.2a	6.07±0.2c	0.40±0.0e	9.56±0.1a
P_{20}	0–32	0.44±0.0a	2.29±0.0b	40.30±2.0a	499.33±1.1a	8.47±0.01h	7.08±0.0fg	18.34±0.2c	4.70±0.3d	0.18±0.0h	0.72±0.1g
	32–58	0.36±0.0c	1.81±0.0d	1.53±0.3c	199.57±3.5bc	8.59±0.01g	7.10±0.0ef	16.35±0.2d	6.65±0.5c	0.23±0.0g	0.73±0.0fg
	58–80	0.26±0.0d	1.30±0.0e	nd	179.30±1.9de	9.14±0.01c	7.11±0.0e	11.05±0.3f	10.28±0.1b	0.78±0.0c	0.99±0.0cd
	80–100	0.18±0.0fg	0.43±0.0g	nd	188.80±6.3cd	9.40±0.01a	7.24±0.0c	8.65±0.3g	10.20±0.2b	1.11±0.0b	0.77±0.1efg
	100–110	0.15±0.0g	0.17±0.0j	nd	211.20±2.6b	9.22±0.01b	7.37±0.0a	9.10±0.3g	9.56±0.3b	1.58±0.0a	1.89±0.0b
Main and interactive effect (p-Values)											
Soil Depth		0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Fertilizer		0.034*	0.002**	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Soil Depth x Fertilizer		0.000***	0.000***	0.000***	0.014**	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Soil Depth		0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***

Mean±SD values in each column followed by the same lowercase letter do not differ significantly according to Tukey's t-test at P≤0.05. Symbols ***0.001 ** and * denote significance at the 0.01 and 0.05 probability levels, respectively. ns: no significant difference; nd: not detected.

Comparative Characteristics of Correlation Dependencies of Soil Agrochemical Properties

In the control soil (C_0), under zero fertilization, the Spearman correlation matrix revealed a clear network of relationships among the main soil properties, reflecting the natural equilibrium of the system (Fig. 1a). The strongest positive correlation occurred between total nitrogen and humus (r = 0.93), confirming that organic matter is the primary source and reservoir of nitrogen in unfertilized soil. Available phosphorus (P_2O_5) also exhibited strong positive correlations with humus (r = 0.87) and nitrogen (r = 0.88), indicating that biological mineralization and organic matter decomposition drive phosphorus availability under natural conditions. Positive relationships were also found between P_2O_5 and K_2O (r = 0.64), and between humus and K_2O (r = 0.37), suggesting a linked cycling of biogenic macronutrients in organically active horizons.

Soil pH values (in both H_2O and KCl) were inversely correlated with organic parameters and nutrient elements, particularly with humus (r = -0.97 and -0.96, respectively) and nitrogen (r = -0.74 and -0.63), highlighting that higher organic content and microbial activity are associated with slightly lower pH in the control. The strong negative correlations between pH and Ca^{2+} (r = -0.94), Ca^{2+} and Mg^{2+} (r = -0.79) further indicate the influence of carbonate chemistry on soil reaction. Sodium (Na^{+}) was negatively correlated with most fertility indicators, especially Ca^{2+} (r = -0.84) and pH (r = -0.87), suggesting that excess Na^{+} is associated with structural instability and lower base saturation. Electrical conductivity (EC) correlated positively with Na^{+} (r = 0.83) and pH (r = 0.87), confirming that the salinity pattern in the control is governed mainly by sodium accumulation and high soil alkalinity. Texture-related properties showed moderate but consistent patterns: clay and silt were positively related to humus (r = 0.88 and 0.63, respectively) and nitrogen (r = 0.85 and 0.60), while sand exhibited a negative relationship (r = -0.62), indicating that finer-textured soils retain more organic matter and nutrients.

Under phosphorus fertilization (P_{20}), correlation patterns changed markedly, showing the impact of nutrient input on soil chemistry and ionic balance (Fig.1b). Nitrogen and humus remained strongly correlated (r = 0.97), confirming their consistent association regardless of fertilization. P_2O_5 retained strong positive relationships with both humus (r = 0.88) and nitrogen (r = 0.88), indicating that organic matter continues to regulate phosphorus availability through biological mineralization even under fertilization. However, the relationships of P_2O_5 with soil reaction and cations were notably altered. Both pH(H_2O) and pH (KCl) showed strong positive correlations with calcium (r = 0.86 and 0.84, respectively) and negative correlations with phosphorus (r = -0.81 to -0.92), suggesting that increased phosphorus availability was accompanied by localized acidification due to phosphate-cation interactions.

Magnesium (Mg^{2+}) and sodium (Na^{+}) also displayed distinct patterns in the fertilized soil. Mg^{2+} negatively correlated with phosphorus (r = -0.87) but positively with pH (r = 0.73), indicating that Mg^{2+} availability was enhanced in less acidic microsites while phosphate addition competed for exchange sites. Sodium maintained a strong negative correlation with phosphorus (r = -0.87) and nitrogen (r = -0.97), showing that phosphorus fertilization reduced Na^{+} accumulation and improved ionic balance. Meanwhile, EC weakly and negatively correlated with most fertility indicators, implying a general reduction in salt sensitivity after fertilization. Texture relationships under phosphorus fertilization differed from those in the control. Clay correlated negatively with humus and total nitrogen, r = -0.56, r = -0.61, respectively, but exhibited a significant positive correlation with sodium, r = 0.56. This pattern indicates altered interaction between organic matter and fine soil fractions, promoting the association of clay with exchangeable sodium rather than with organic components, likely due to changes in soil aggregation, ionic balance, and mineral-organic binding processes. The application of phosphorus fertilizer significantly affects soil

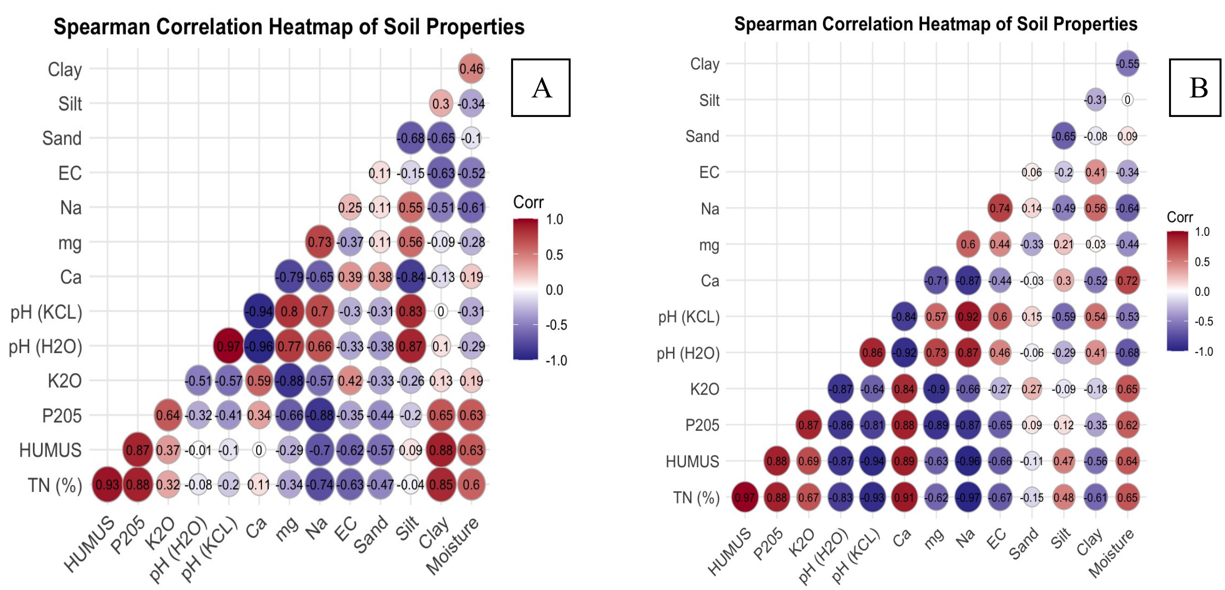

Fig. 1: Spearman rho, correlation heatmap of soil properties for **(a)** control (C_0) and **(b)** Phosphorus fertilized (P_{20}) soils.

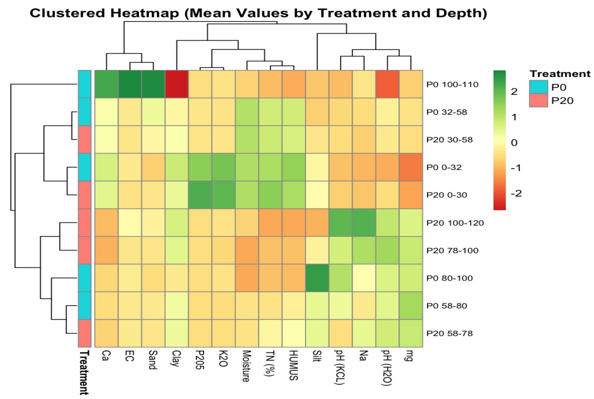

Fig. 2: Hierarchical cluster heatmap illustrating the relationships among soil properties at different depths under control (P_0) and phosphorus-fertilized (P_{20}) conditions.

chemical composition, increasing available phosphorus and strengthening its relationship with organic matter and nitrogen. The positive association with calcium reflects the formation of phosphate compounds that can stabilize soil structure, while the negative correlation with sodium indicates improved ionic balance and reduced negative effects of salinity. The reduction in acidity with increasing P_2O_5 is explained by buffering reactions with calcium and magnesium, which improve conditions for microbial activity and nutrient uptake.

Cluster Analysis of Soil Properties by Treatment and Depth

The hierarchical clustering of mean values by treatment and depth demonstrates a distinct separation between the control (P_0) and phosphorus-fertilized (P_{20}) profiles, as presented in Fig. 2, confirming the strong influence of fertilization on the chemical composition of the soil. Soils from phosphorus-fertilized plots, particularly from the upper horizons (0-30 and 30-58 cm), grouped together and were characterized by higher concentrations of available phosphorus (P_2O_5), potassium (K_2O), and humus, along with elevated total nitrogen and moisture contents. These parameters form a coherent cluster that represents the nutrient-enriched surface zone created by fertilizer application. In contrast, the control layers (P_0) clustered mainly with deeper horizons (58-80 and 80-110cm), showing higher pH, electrical conductivity (EC), calcium, and sodium levels, reflecting salt accumulation and lower biological activity in the absence of fertilization. The dendrogram further indicates that chemical and physical parameters segregated into two primary groups: one dominated by fertility-related indicators (P_2O_5, K_2O, TN, and humus), and another associated with basic cations and salinity (Ca, Na, EC, and pH). The clear grouping of P_2O_5 with humus and nitrogen in the fertilized cluster emphasizes the role of phosphorus in enhancing organic matter turnover and nutrient availability, while the association of Na and EC in the control group highlights ionic accumulation in the subsoil. The cluster heatmap confirms that phosphorus fertilization not only increased nutrient concentrations in the upper horizons but also altered the multivariate structure of soil properties, promoting a distinct nutrient-organic matter complex that contrasts with the saline-alkaline assemblage in the unfertilized profile.

DISCUSSION

The conducted study made it possible to establish the nature and direction of relationships between the main chemical and physico-chemical properties of the southern chernozem soil under both natural (control) and phosphorus-fertilized conditions. Spearman correlation analysis demonstrated the high sensitivity of the soil system to changes in chemical composition caused by the input of additional nutrients. The data clearly show that even small variations in the nutrient balance induce measurable transformations in ionic equilibrium, organic matter dynamics, and the mobility of key elements such as phosphorus, nitrogen, and calcium, confirming the systemic interdependence of the soil's biogeochemical components.

In the control variant (C_0), without agrochemical treatment, stable positive correlations were identified between humus content, total nitrogen, and available phosphorus. The strongest relationship was observed between nitrogen and humus (ρ = 0.964, P<0.001), highlighting the key role of organic matter as an accumulator and source of biogenic nitrogen under natural conditions. This connection indicates that in the absence of external nutrient inputs, the nitrogen pool is maintained mainly through the mineralization of native organic residues and the activity of heterotrophic microorganisms. The strong positive correlations between humus and available phosphorus (ρ = 0.860, *P<0.01*) and between total nitrogen and phosphorus (ρ = 0.888, *P<0.01*) highlight the integral role of microbiological processes in nutrient mobilization. These associations point to tightly coupled C–N–P cycling in unfertilized chernozem soils, where the mineralization of organic matter remains the dominant mechanism governing nutrient availability. Conversely, the pronounced negative correlation between exchangeable sodium and organic indicators (ρ ≈ –0.80, *P<0.01*) suggests that even naturally occurring levels of Na^+ may exert inhibitory effects on soil biological activity, potentially altering soil structure, enzyme function, and overall physico-chemical behavior. Elevated sodium content is known to impair the aggregation of clay–humus complexes, reduce microbial respiration, and increase dispersion, which may explain the relatively low biological activity in the deeper horizons. Other parameters, including pH, physical clay, and moisture, did not show statistically significant relationships, indicating the secondary role of physical and mechanical characteristics in regulating the nutrient regime in the absence of agro-technical interventions. Nevertheless, the positive correlation between fine particles and humus (r = 0.88) implies that texture indirectly contributes to the accumulation of organic matter by influencing aeration and water retention.

In the phosphorus treatment (P_{20}), significant changes were observed in the correlation structure of soil parameters. Strengthened positive relationships between available phosphorus, humus, and nitrogen indicate the preservation of biochemical integrity in the soil system, while also reflecting the effectiveness of phosphorus fertilization. The similarity in correlation magnitudes for humus–N and humus–P_2O_5 pairs in both treatments suggests that phosphorus addition amplifies rather than disrupts existing biological linkages. The application of phosphorus was accompanied by reduced acidity (negative correlation between P_2O_5 and pH, ρ = –0.601, P = 0.066) and lower electrical conductivity (ρ = –0.574 with P_2O_5 and ρ = –0.624 with humus), suggesting reduced salt stress and improved conditions for soil microflora. The positive correlation of calcium with phosphorus and humus confirms the formation of stable phosphate complexes that stabilize the chemical structure of the soil. At the same time, a pronounced negative correlation between magnesium and phosphorus (ρ = –0.765, P = 0.010) may indicate competitive interactions for sorption sites, while the positive correlation between magnesium and pH (ρ = 0.782, P = 0.008) reflects increased magnesium availability under less acidic conditions.

This dual behavior of Mg^{2+} confirms its mobility within carbonate systems, where exchange equilibria are highly sensitive to pH shifts induced by phosphate reactions. Of particular note is the strong negative correlation of sodium with phosphorus (ρ = –0.874, P = 0.001) and humus (ρ = –0.97, P<0.001), which can be interpreted as a positive effect of phosphorus application on reducing salinity and normalizing ionic composition. Similarly, the positive correlation between potassium and phosphorus (ρ = 0.731, P = 0.016) demonstrates possible synergism in plant nutrition and indicates the combined effect of elements under fertilizer application. Such synergistic P–K interactions have been widely reported in dryland soils, where improved phosphorus availability enhances potassium uptake efficiency and root vitality. Thus, the results show that phosphorus fertilizer exerts not only a direct nutritional effect but also an indirect influence on the physico-chemical properties, biological activity, and ionic composition of the soil. Phosphorus input stimulated microbial-mediated mineralization, strengthened humus stability, and moderated the accumulation of soluble salts, creating a more balanced nutrient environment. The strengthening of relationships between humus, nitrogen, and phosphorus emphasizes the role of organic matter in stabilizing available nutrient forms. The reduction of sodium and electrical conductivity indicates an improvement in soil conditions with respect to salinity and salt balance. Notably, EC values in the lower horizons decreased by nearly 8%, confirming that phosphorus application indirectly alleviates secondary salinization. Against this background, physical parameters such as moisture and granulometric composition retain low correlation significance, indicating the dominance of chemical and biological factors in soil fertility formation under phosphorus fertilization. However, the weak but consistent link between fine fractions and nutrient concentrations suggests that particle-size distribution modulates ion retention and should not be ignored when assessing long-term soil responses.

The analysis of variance further supports these conclusions. Highly significant differences were detected for total nitrogen (F = 5.21, P = 0.041), humus (F = 4.89, P = 0.046), and electrical conductivity (F = 6.13, P = 0.031), indicating that both nutrient enrichment and depth strongly influence soil condition. Moisture (F = 4.56, P = 0.049) and clay fraction (F = 5.94, P = 0.034) also showed sensitivity to fertilization, reflecting indirect physical adjustments in the profile. These results confirm the essential role of organic matter and ionic parameters as primary indicators of fertility dynamics in southern chernozems. Indicators of P_2O_5 (F = 3.72, P = 0.061), calcium (F = 2.95, P = 0.089), and sodium (F = 3.88, P = 0.057) demonstrated borderline significance, suggesting a potential influence of these factors that requires further investigation with a larger sample size or under modified research conditions. The emerging trends for these elements, particularly the inverse Na–Ca relationship, highlight the onset of selective ion redistribution caused by phosphorus application. At the same time, pH (F = 1.84, P = 0.179), magnesium (F = 1.42, P = 0.248), and potassium (F = 2.11, P = 0.145) did not demonstrate statistically significant differences, indicating their relatively minor impact on soil characteristics within the scope of the present study. Nonetheless, the correlation results show that even these non-significant elements participate in broader equilibrium shifts that could become more pronounced with prolonged fertilizer use.

Conclusion

The application of phosphorus fertilizers at a rate of 20kg P_2O_5/ha led to a marked increase in available phosphorus in the topsoil (0–32cm) – from 30.53mg kg^{-1} in the control to 40.30mg kg^{-1} in the fertilized variant, representing an improvement of approximately 31.9%. This enrichment stimulated the biological cycling of nutrients, enhanced the biochemical stability of the upper horizon, and contributed to the overall increase in soil fertility. Maintaining this application rate ensures an optimal balance between nutrient supply and environmental safety, preventing excessive phosphorus accumulation in lower horizons. Phosphorus fertilization also promoted an increase in humus content, from 2.52% in the control to 2.29% under treatment in the surface layer, while stabilizing the humus profile across the soil section. Although the percentage decrease appears minor, the fertilizer stimulated the formation of stable organo-mineral complexes and improved the structural aggregation of fine particles, resulting in greater resistance to erosion and higher microbial activity. The observed positive correlations between humus, nitrogen (ρ = 0.964, P<0.001), and phosphorus (ρ = 0.860, P<0.01) confirm the strengthening of the soil's organic-mineral framework. The total nitrogen content increased slightly from 0.41% in the control to 0.44% under phosphorus fertilization, confirming the improved nitrogen retention capacity of the humified layer. This indicates that phosphorus indirectly enhances nitrogen utilization by promoting organic matter turnover and stimulating the activity of heterotrophic microorganisms responsible for mineralization processes. A minor but detectable accumulation of sodium was recorded in the lower horizons (80–110cm), where its content rose from 0.12mmol 100 g^{-1} in the upper layer to 1.58mmol 100 g^{-1} at depth in the fertilized variant. Although these values fall within permissible thresholds, they nevertheless indicate the early stages or potential onset of gradual solonetzic development in the soil profile. Regular monitoring of Na^+ distribution is recommended, especially under prolonged fertilizer use, to avoid secondary salinization and maintain favorable ionic equilibrium. Electrical conductivity (EC) showed a distinct downward trend in the fertilized profile, with values decreasing by nearly 8% in the deeper layers (from 0.45 to 0.41mS m^{-1}), indicating a reduction of salt stress and improved soil chemical stability. This confirms the buffering effect of phosphorus fertilizers, which promote a balanced distribution of soluble salts through the formation of Ca–P–organic complexes and enhanced cation exchange capacity. Correlation analysis demonstrated a strengthening of positive interrelations between nitrogen, phosphorus, and humus, and a reduction in the antagonistic effect of sodium on organic matter and pH. Notably, sodium exhibited strong negative correlations with phosphorus (ρ = –0.874, P = 0.001) and humus (ρ = –0.97, P<0.001), highlighting the beneficial role of phosphorus fertilization in improving ionic composition and mitigating salinity. Meanwhile, potassium and phosphorus (ρ = 0.731, P = 0.016) displayed synergistic behavior, demonstrating enhanced nutrient cycling and plant-available nutrient balance under fertilization. The ANOVA results confirmed statistically significant effects of fertilization and soil depth on total nitrogen (F = 5.21, P = 0.041), humus (F = 4.89, P = 0.046), and electrical conductivity (F = 6.13, P = 0.031), as well as moderate effects on moisture (F = 4.56, P = 0.049) and physical clay (F = 5.94, P = 0.034). These indicators are the most sensitive and informative for evaluating the dynamics of soil fertility under phosphorus application. For sustainable management, it is essential to implement long-term agrochemical monitoring of the southern chernozem, focusing on Na^+ accumulation, EC variability, and organic matter dynamics. The integration of these parameters into digital soil fertility models will facilitate adaptive fertilizer management tailored to local climatic and textural conditions. Maintaining a balanced P_2O_5 dose (20kg ha^{-1}) ensures high productivity while minimizing ecological risks and preserving the long-term chemical stability of the soil profile.

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Data Availability: The data presented in this research are available from the corresponding author upon reasonable request.

Ethics Statement: This study did not involve human participants, animals, or the use of any confidential or personal data. Therefore, ethical approval was not required.

Author's Contribution: The study was conducted jointly by all the authors. KG and KA developed the concept, carried out statistical analysis and interpretation of the results, led the project and prepared the final version of the manuscript. MD and ShA performed a literature review, prepared part of the introduction, designed the manuscript in accordance with the requirements of the journal and made editorial changes. NA, ZG, and OB conducted field and laboratory studies, processed the data, and participated in interpreting the results. All authors read and approved the final version of the manuscript.

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