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Humus status of light chestnut soil in Southeastern Kazakhstan under long-term fertilizer application

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Abstract

Humus is a central and relatively stable component of soil organic matter that regulates key fertility functions; therefore, robust evaluation of humus dynamics requires long-term stationary experiments. This study synthesizes results from long-term irrigated experiments on light chestnut soil in southeastern Kazakhstan (single-factor experiment, 1961–2005; multifactor experiment, 1991–2016) together with renewed environmental monitoring (2020–2023) to quantify the effects of mineral fertilization and cattle manure on humus status, plant-available nutrients, crop productivity, and environmental safety. Under continuous cropping without fertilizer input, humus in the 0–20 cm layer declined by 0.37 percentage points relative to the initial level. Mineral fertilization alone moderated humus loss but did not ensure a non-deficit humus balance, whereas combined organic–mineral fertilization (NPK + manure 60 t ha^{-1} once per rotation) increased humus by 0.20 percentage points, reaching 2.80% by the end of the fifth rotation. Fertilization substantially improved nutrient status: under mineral fertilization, available P_2O_5 and exchangeable K_2O reached 39.5 mg kg^{-1} and 601 mg kg^{-1}, respectively, while under the combined system they reached 52.3 mg kg^{-1} and 765 mg kg^{-1}. Regression models from the multifactor experiment quantified dose–response relationships between fertilizer/manure inputs and soil indicators. In the fifth rotation, yields of winter wheat, maize, and alfalfa increased by 1.4–2.0 times relative to the unfertilized control, while sugar beet yield increased more than threefold. Soil heavy metal concentrations remained below sanitary–hygienic thresholds across treatments; however, lead (Pb) in maize grain exceeded the maximum permissible concentration across all fertilization systems, indicating the need for continued product monitoring and source/pathway evaluation.

Keywords: Humus, soil organic matter, available phosphorus, exchangeable potassium, long-term experiment, heavy metals, crop yield, irrigated steppe.

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Introduction

Foothill light chestnut soils of Southeastern Kazakhstan are a strategic resource for irrigated crop production, yet they are inherently vulnerable to long-term fertility decline under intensive cultivation because organic carbon inputs are often insufficient to offset mineralization losses and high nutrient removal (Rau et al., 2023). Humus (soil organic matter; SOM) is the most stable and functionally important component of soil fertility, regulating aggregation, buffering, nutrient retention, and crop resilience; therefore, humus dynamics provide an integrative indicator of sustainability in irrigated steppe agroecosystems (Menšík et al., 2018).

Long-term experiments on Chernozems and related steppe soils consistently show that intensive mineral fertilization without adequate organic matter return can accelerate humus mineralization and contribute to qualitative deterioration of humus pools, whereas balanced nutrient regimes and the systematic return of organic substrates improve humus status and carbon stabilization. (Zhuravlev et al., 2024; Sedlář et al., 2023). Balayev et al. (2020) reported that biologization strategies based on crop-residue return and green manures

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support humus restoration and improve physicochemical properties of Chernozem soils under reduced-tillage systems, while Ivanina and Tabachuk (2023) showed that organo-mineral fertilization systems and crop-rotation structure significantly influence the humus condition of leached Chernozem, supporting improved humus status relative to mineral-only strategies. Lifanenkova et al. (2019) demonstrated that long-term organo-mineral fertilizer systems can restore humus to the initial level and maintain a positive humus balance in ordinary carbonate Chernozem under crop rotation.

Beyond carbon dynamics, long-term sustainability in irrigated steppe systems depends on maintaining a balanced supply of plant-available phosphorus and potassium, because high-yield rotations increase nutrient offtake and can shift soils from initially sufficient status to hidden deficits or, conversely, create surpluses when inputs exceed removal (Khramtsov & Boyko, 2021; Medinski et al., 2018). Maxotova et al. (2021) demonstrated that crop productivity on chestnut soils in southeastern Kazakhstan can remain highly responsive to increasing mineral nutrient supply: tomato yield and key yield components increased with rising NPK rates, and the highest performance tended to occur under the maximum dose (N210P180K150), leading the authors to conclude that typical regional NPK practice may be insufficient and that fertilizer rates should be calibrated for local chestnut soil conditions. Long-term field evidence from Kazakhstan chestnut soils further indicates that phosphorus can be a primary yield-limiting nutrient for sugar beet and that sustained P inputs markedly increase both total and available P stocks; in a 56-year stationary experiment, the N1P2K1 treatment (200% of P at recommended NK) produced maximum sugar beet yield and sugar content, while long-term P fertilization increased total/available P and shifted inorganic P towards Ca-bound fractions (Zhaksybayeva et al., 2022). Short- to medium-term studies also support the need for balanced nutrient management: varying NPK rates significantly increased barley grain yield and elevated soil nutrient availability, whereas nutrient contents declined as plants progressed through growth stages, reflecting dynamic exchange between plant uptake and soil supply (İslamzade et al., 2023). In management trials on light chestnut soils, Ospanbayev et al. (2023) showed that one season of cover-crop growth was insufficient to generate detectable changes in total soil organic matter or overall available nutrient status, while conventional tillage increased the most labile organic carbon fraction even within a three-month period, implying rapid organic matter turnover under intensive soil disturbance. Consistent with these patterns, phosphorus fertilization increased alfalfa yield and improved forage quality across varieties in irrigated light chestnut soils, with highest responses at 120 kg ha^{-1} P (Massaliyev et al., 2024), and balanced mineral fertilization (N130P130K130) increased soil available N, P and K and delivered the highest sugar beet yields for Aksu and Yampol cultivars in foothill light chestnut soils of the Almaty region (Kaliyeva et al., 2024). Finally, in northern Kazakhstan steppe conditions, Kalimov et al. (2024) reported that diversified crop rotations—especially an eight-field rotation—were most effective in preserving SOM, while tillage choice (conventional vs. no-till) had only limited influence on SOM levels under the region's arid climate.

At broader steppe and Chernozem scales, long-term experiments show that multi-decadal phosphorus fertilization can substantially increase both total P and plant-available P stocks, with enrichment detectable down to 60 cm depth, and that sustained surpluses can accumulate as legacy P if inputs are not balanced with crop removal (Medinski et al., 2018). In parallel, long-term findings suggest that organo-mineral management can optimize the distribution of P and K fractions and support the strongest yield responses: Barłóg et al. (2025) reported that slurry combined with mineral NPK improved soil P and K fractions and delivered the greatest yield response, whereas very high N rates without proportional PK adjustment reduced bioavailable P and K and diminished agronomic efficiency. Milić et al. (2019) similarly showed that manure combined with mineral fertilization improves readily available P and the distribution of soil P fractions in calcareous Chernozem, while Tyutyunov et al. (2024) reported that organo-mineral systems produced the highest levels of mobile P and improved mobile K status in long-term typical Chernozem compared with mineral-only and unfertilized treatments. Together, these findings indicate that sustained yield gains in irrigated steppe systems require nutrient stewardship that is both agronomically effective and balanced over time; however, long-term fertilization strategies must also be evaluated through an environmental-safety lens, particularly with respect to trace metal inputs and potential transfer to edible plant products.

In parallel, the environmental dimension of long-term fertilization has gained importance because repeated organic amendments may introduce trace metals (e.g., Cd, Cu, Zn, Pb) and can shift Cd and Zn toward more mobile exchangeable forms depending on soil chemistry and amendment composition. (Wu et al., 2025; Sun et al., 2023). Zhao et al. (2018) demonstrated that manure plus mineral fertilization can increase soil Cd, Cu, and Zn relative to mineral-only systems, while grain concentrations may increase slightly but often remain below national limits in well-managed long-term trials; evidence from Zhang et al. (2025) indicates that long-term application of different organic fertilizers can increase soil metal(loid)s, yet wheat grain concentrations

generally remain below regulatory limits and do not indicate elevated human health risk over decades in well-managed systems. Consequently, long-term stationary experiments are essential for simultaneously evaluating: (i) humus quantity and quality, (ii) plant-available P–K balance under contrasting fertilizer systems, (iii) crop productivity and product quality, and (iv) soil–grain environmental safety indicators, and the objectives of this study were to quantify long-term changes in humus under unfertilized, mineral NPK, and organo-mineral (NPK + manure) systems; evaluate trajectories of available phosphorus and exchangeable potassium under these systems and dose–response relationships in a multifactor experiment; assess crop yield and product quality responses in the sugar beet rotation; and evaluate heavy metal concentrations in soil and maize grain under contemporary monitoring (2020–2023).

Material and Methods

Study area

The research was conducted under irrigated conditions at long-term experimental stations of the Kazakh Research Institute of Agriculture and Plant Growing (KazNIIZiR) in the Karasai District, Almaty Region, Kazakhstan. The single-factor experiment site is located at 43°13′57″ N, 76°42′09″ E, and the multifactorial experiment site at 43°14′08″ N, 76°41′15″ E. The sites are situated in the foothill desert–steppe zone at approximately 750–850 m above sea level (±50 m).

The climate is sharply continental. Long-term climatic normals (1961–2020) indicate mean annual air temperature of approximately +9.0 to +10.0 °C, with mean January temperatures of −5 to −7 °C and mean July temperatures of +23 to +25 °C. Annual precipitation is approximately 600–700 mm, with a maximum in April–June. A warming trend has been observed over the past ~50 years. Crops were irrigated using furrow irrigation; seasonal irrigation rates were 0.6–1.6 thousand m^3 ha^{-1} for winter wheat, 2.5–4.5 thousand m^3 ha^{-1} for grain maize, ~2.5–3.5 thousand m^3 ha^{-1} for soybean, and 5.0–6.5 thousand m^3 ha^{-1} for sugar beet.

Experimental history and design

This paper integrates results from three experimental phases: (i) a long-term single-factor stationary experiment (1961–2005), (ii) a long-term multifactorial stationary experiment (1991–2016), and (iii) a renewed monitoring phase (2020–2023) focused on soil and crop responses and environmental safety.

In the single-factor experiment established in 1961, mineral fertilizers (complete NPK) and semi-decomposed cattle manure were compared with an unfertilized control. A systematic plot layout with four replications was used. The plot area was 215 m^2 (7.2 m × 30.0 m), with 2-m buffer strips separating replications to limit lateral movement of irrigation water and nutrients.

In the multifactorial experiment established in 1991, the effects and interactions of N, P, K, and manure were studied in a crop-rotation system. The design was an incomplete factorial scheme 1/8 (4×4×4×4) comprising 32 treatments with two replications, arranged as an 8 × 8 quasi-Latin square. The plot area was 122.4 m^2 (7.2 m × 17.0 m) with 2-m buffer strips between replications. For synthesis and interpretation, contrasting treatments are emphasized (control, N180P180K180, and N180P180K180 + 60 t ha^{-1} manure).

Soil characteristics at initiation

The soil is classified as light chestnut soil (medium loamy). Initial soil properties are summarized in Table 1.

Table 1. Initial characteristics of the light chestnut soil of the experimental stations.

Indicator	0–20 cm*	20–40 cm*	0–30 cm**	Method
Humus, %	2.60	2.47	2.49	GOST 26213-91
Total nitrogen, %	0.15	0.13	0.11	GOST 26107-84
Total phosphorus, %	0.21	0.21	0.18	GOST 26207-91
Total potassium, %	1.67	1.63	1.78	GOST 26208-91
Sand (2–0.05 mm) , %	33.00	33.00	33.00	GOST 12536-79
Silt (0.05–0.002 mm) , %	47.00	47.00	47.00	GOST 12536-79
Clay (<0.002 mm) , %	20.00	20.00	20.00	GOST 12536-79
pH_KCl (1 M KCl; 1:2.5)	7.70	7.70	7.80	GOST 26483-85
pH (water extract, 1:5)	7.20	7.20	7.40	GOST 26423-85
$CaCO_3$, %	2.00	2.10	2.50	GOST 26424-85
Bulk density (ρb), g cm^{-3}	1.30	1.33	1.35	GOST 5180-2015
Available phosphorus, mg kg^{-1}	24.0	19.5	17.0	GOST 26205-91
Exchangeable potassium, mg kg^{-1}	525.00	470.00	420.00	GOST 26205-91

* Long-term single-factor experiment. ** Long-term multifactor experiment.

Cropping system

The main system was an eight-field sugar beet crop rotation typical of irrigated lands in southeastern Kazakhstan: (1) winter wheat with undersown alfalfa; (2) second-year alfalfa; (3) third-year alfalfa; (4) sugar beet; (5) winter wheat; (6) sugar beet; (7) grain maize; and (8) sugar beet. A continuous sugar beet monoculture was maintained in parallel.

Fertilizer and manure treatments

Mineral fertilizers included ammonium nitrate and urea (N sources), single and double superphosphate and ammophos (P sources), and potassium chloride and potassium sulfate (K sources). Fertilizer rates are expressed in oxide form (P_2O_5 and K_2O). Phosphorus and potassium fertilizers and manure were incorporated during primary soil tillage, while nitrogen fertilizers were applied as top dressing at the tillering stage of winter wheat, at the 3–4 true-leaf stage of sugar beet, and at the 5–6 true-leaf stage of maize. Nitrogen fertilizers were not applied to soybean and alfalfa due to biological N fixation.

The average physicochemical composition of semi-decomposed cattle manure used throughout the experiments is shown in Table 2.

Table 2. Mean physicochemical composition of semi-decomposed cattle manure (n=5).

Indicator	Mean ± SD	Method
Moisture, %	57.40 ± 3.90	Oven drying at 105 °C
Dry matter, %	42.60 ± 3.90	Calculated by difference
pH (water extract)	7.20 ± 0.20	Potentiometric method
Organic matter, %	20.10 ± 1.80	GOST 26213-91
Ash content, %	79.90 ± 1.80	GOST 26213-91
Total nitrogen (N) , %	0.25 ± 0.06	GOST 26107-84
Ammonium nitrogen ($N–NH_4^+$), %	0.06 ± 0.02	Distillation–photometric
Total phosphorus (P_2O_5), %	0.43 ± 0.03	GOST 26951-86
Total potassium (K_2O) , %	0.86 ± 0.07	GOST 26951-86
Sulfur (S) , %	0.09 ± 0.02	Turbidimetric
Calcium (Ca) , %	0.42 ± 0.07	Complexometric
Magnesium (Mg) , %	0.18 ± 0.04	Complexometric

Soil and plant sampling, laboratory analyses, and regulations

Soil samples were collected from three sampling points within each treatment and combined into one composite sample. Sampling was performed after completion of each crop rotation cycle. Soil analyses were conducted in an accredited laboratory according to GOST standards: soil sampling and preparation (GOST 28168–89), humus (GOST 26213–91), available N, available P, exchangeable K (GOST 26205–91), and trace elements and heavy metals in soil (GOST ISO 22036–2014). Heavy metals in plant material were determined according to GOST ISO 27085–2012. For the long-term (1961–2005) series, soil indicators shown in Figures 1–3 and Tables 3a–3c were compiled for the initial state and after the 3rd and 5th crop rotations for 0–20 and 20–40 cm layers.

Regulatory documents for maximum permissible concentrations (MPCs) in soil were GN 2.1.7.2041-06 and GN 2.1.7.2511-09, and for grain TR TS 021/2011 and SanPiN 2.3.2.1078-01.

Yield and quality assessment

Yield accounting for winter wheat, alfalfa, and soybean was carried out by direct combine harvesting from an accounting area of 90 m^2 (four replications) in the long-term experiment and from 51 m^2 in the multifactor experiment. Yields of sugar beet roots and maize grain were determined manually from the same accounting areas. Sugar content in beet roots was determined by the polarimetric method (GOST 17421-82) using composite root samples (3–5 kg) corresponding to field replications.

Statistical analysis

The experimental plot was the statistical unit. Treatment effects in the long-term experiment were evaluated using analysis of variance (ANOVA). For the multifactor experiment, regression models were developed to quantify relationships between fertilizer/manure rates and soil indicators (humus, available P_2O_5, exchangeable K_2O) and crop yields. Model performance was evaluated using the correlation coefficient (r), and, where applicable, R^2 and RMSE. The number of observations used to build the regression models was 64 (corresponding to the number of experimental treatments). Agrochemical determinations were performed with three analytical replicates.

Results

Long-term humus dynamics

In the long-term (1961–2005) experiment, continuous cultivation without fertilizer inputs reduced humus in the 0–20 cm layer from 2.60% at initiation to 2.27% after the 3rd crop rotation and to 2.23% after the 5th rotation (−0.37 percentage points). (Figure 1; Table 3). With systematic mineral fertilization (NPK), humus declined only slightly, decreasing from 2.60% at initiation to 2.53% after the 3rd rotation and to 2.50% after the 5th rotation, indicating partial mitigation of organic matter losses. (Figure 1; Table 3). In contrast, the organo-mineral system (NPK + manure 60 t ha^{-1} applied once per rotation) increased humus to 2.83% after the 3rd rotation and maintained 2.80% after the 5th rotation (+0.20 percentage points relative to the initial state). (Figure 1; Table 3).

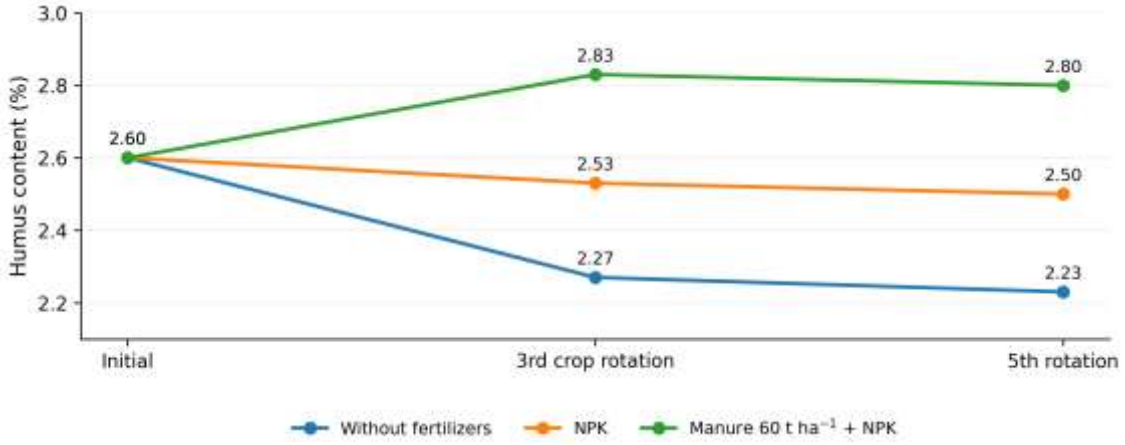


Figure 1. Changes in humus content (%) in irrigated light chestnut soil under long-term systematic fertilization (1961–2005).

Table 3. Humus content (%) at initiation, after the 3rd crop rotation, and after the 5th rotation under contrasting fertilization systems (0–20 cm).

Rotation stage	Without fertilizers	NPK	Manure 60 t ha^{-1} + NPK
Initial	2.60	2.60	2.60
3rd crop rotation	2.27	2.53	2.83
5th rotation	2.23	2.50	2.80

Changes in available phosphorus and exchangeable potassium

The initial content of available phosphorus was 24.0 mg kg^{-1} in the 0–20 cm layer and 19.5 mg kg^{-1} in the 20–40 cm layer. Across five rotations, cultivation without fertilizers depleted available P to 16.9 mg kg^{-1} (0–20 cm) and 14.0 mg kg^{-1} (20–40 cm), corresponding to losses of 7.1 and 5.5 mg kg^{-1}, respectively. (Figure 2; Table 4).

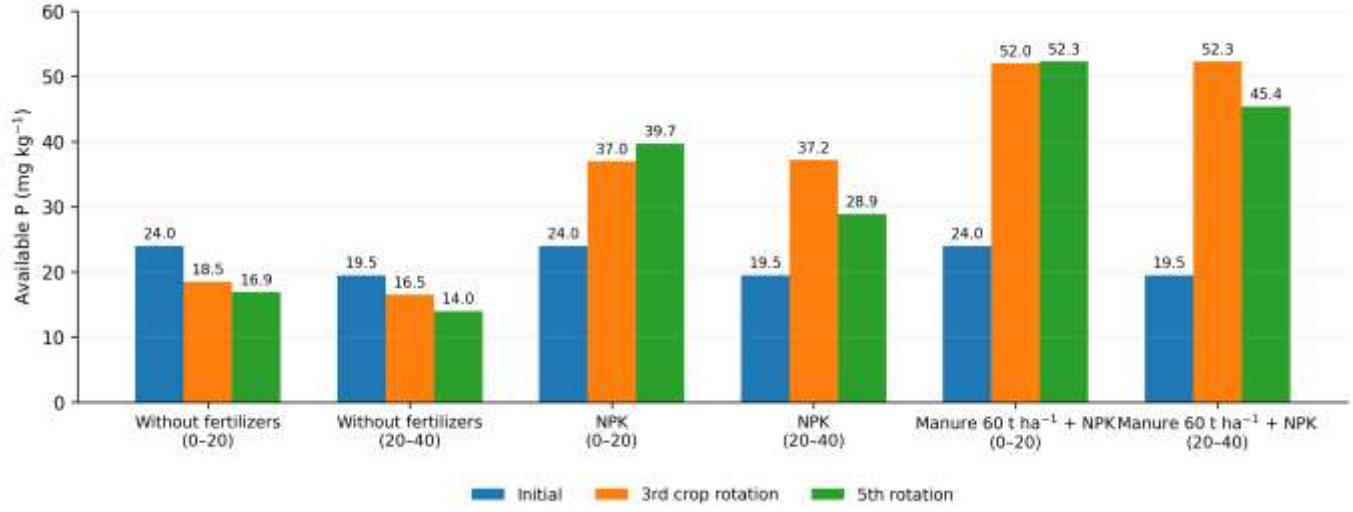


Figure 2. Changes in available phosphorus (mg kg^{-1}) in irrigated light chestnut soil under long-term systematic fertilization by depth and rotation stage (1961–2005).

In contrast, systematic NPK increased available P to an agronomically optimal range in the surface layer (39.7 mg kg^{-1} at 0–20 cm at the 5th rotation) and also increased P in the 20–40 cm layer (28.9 mg kg^{-1}), while NPK + manure produced the highest P levels (52.3 mg kg^{-1} at 0–20 cm; 45.4 mg kg^{-1} at 20–40 cm at the 5th rotation), indicating substantial enrichment of both layers under organo-mineral fertilization. (Figure 2; Table 4).

Table 4. Available phosphorus (mg kg^{-1}) at initiation, after the 3rd crop rotation, and after the 5th rotation by depth and fertilization system (1961–2005).

System	Depth (cm)	Initial	3rd rotation	5th rotation	Δ (5th–Initial)	Interpretation
Without fertilizers	0–20	24.0	18.5	16.9	-7.1	Depletion
Without fertilizers	20–40	19.5	16.5	14.0	-5.5	Depletion
NPK	0–20	24.0	37.0	39.7	+15.7	Optimal–high
NPK	20–40	19.5	37.2	28.9	+9.4	Increase
Manure 60 t ha^{-1} + NPK	0–20	24.0	52.0	52.3	+28.3	High
Manure 60 t ha^{-1} + NPK	20–40	19.5	52.3	45.4	+25.9	High

The soil was initially well supplied with exchangeable potassium (K_2O), with 525 mg kg^{-1} in the 0–20 cm layer and 470 mg kg^{-1} in the 20–40 cm layer. Without fertilizers, exchangeable K decreased to 490 mg kg^{-1} (0–20 cm) and 418 mg kg^{-1} (20–40 cm) by the 5th rotation. Under mineral NPK, exchangeable K increased to 601 mg kg^{-1} (0–20 cm) and 524 mg kg^{-1} (20–40 cm), while NPK + manure produced the largest gains (765 mg kg^{-1} at 0–20 cm; 717 mg kg^{-1} at 20–40 cm at the 5th rotation). (Figure 3; Table 5).

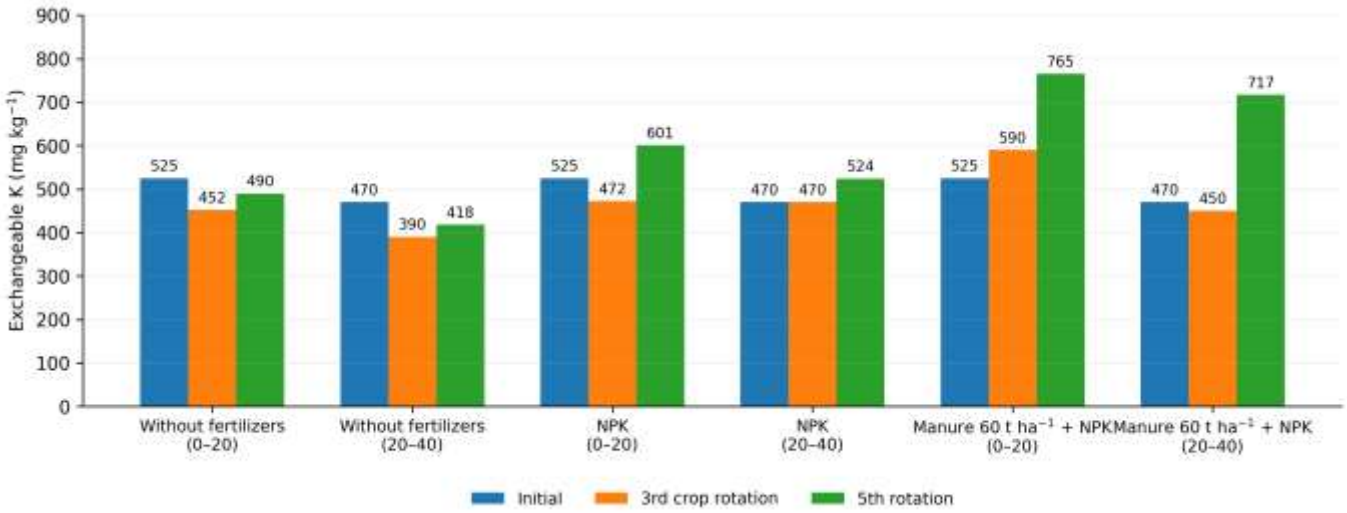


Figure 3. Changes in exchangeable potassium (mg kg^{-1}) in irrigated light chestnut soil under long-term systematic fertilization by depth and rotation stage (1961–2005).

Overall, the long-term series demonstrates a consistent ranking of nutrient status (control < NPK < NPK + manure) for both available P and exchangeable K and shows that organo-mineral fertilization most strongly enriched subsoil layers (20–40 cm) as well as the plough layer. (Tables 4 and 5).

Table 5. Exchangeable potassium (mg kg^{-1}) at initiation, after the 3rd crop rotation, and after the 5th rotation by depth and fertilization system (1961–2005).

System	Depth (cm)	Initial	3rd rotation	5th rotation	Δ (5th–Initial)
Without fertilizers	0–20	525	452	490	-35
Without fertilizers	20–40	470	390	418	-52
NPK	0–20	525	472	601	+76
NPK	20–40	470	470	524	+54
Manure 60 t ha^{-1} + NPK	0–20	525	590	765	+240
Manure 60 t ha^{-1} + NPK	20–40	470	450	717	+247

Dose–response relationships in the multifactor experiment

Regression analysis of the multifactor experiment (1991–2016; n = 64 observations) quantified dose–response relationships between long-term fertilizer/manure inputs and key soil indicators. Humus (%) was explained primarily by manure input, available P_2O_5 (mg kg^{-1}) responded strongly to phosphorus rate and its interaction with manure, and exchangeable K_2O (mg kg^{-1}) increased with potassium rate and manure (Table 6).

Table 6. Regression equations characterizing effects and interactions of mineral fertilizers and manure on soil indicators (1991–2016).

Indicator	Regression equation	r
Humus (%)	Y = 2.47 + 0.06 H	0.594
P_2O_5 (mg kg^{-1})	Y = 24.7 + 9.1 P + 15.7 $(P{\cdot}H)^{0.5}$	0.927
K_2O (mg kg^{-1})	Y = 343 + 29.9 K + 29.8 H	0.808

Note: H denotes manure rate; P and K denote rates of the corresponding fertilizers; exponent 0.5 indicates a diminishing effect with increasing rates.

In the manure dose series, the model implies incremental humus increases of approximately 0.06, 0.12, and 0.18 percentage points at 20, 40, and 60 t ha^{-1} manure, respectively, supporting the conclusion that long-term humus build-up in this system is driven mainly by organic inputs rather than mineral nutrients alone. (Table 6).

Crop yield response

Improved nutrient supply under fertilization increased crop productivity markedly in the sugar beet crop rotation during the 5th rotation (Figure 4). Relative to the unfertilized control, sugar beet yield increased from 15.20 to 45.90 t ha^{-1} under NPK and to 43.10 t ha^{-1} under NPK + manure; winter wheat grain yield increased from 2.40 to 4.90–4.80 t ha^{-1}; maize grain yield increased from 7.00 to 9.90–10.20 t ha^{-1}; and alfalfa hay yield increased from 11.00 to 15.30–15.80 t ha^{-1} under fertilization (Figure 4). Overall, fertilization resulted in a >3-fold yield increase for sugar beet, approximately a twofold increase for winter wheat, and ~1.4-fold increases for maize and alfalfa compared with the unfertilized control, with broadly similar yields under mineral and organo-mineral systems in this rotation stage (Figure 4).

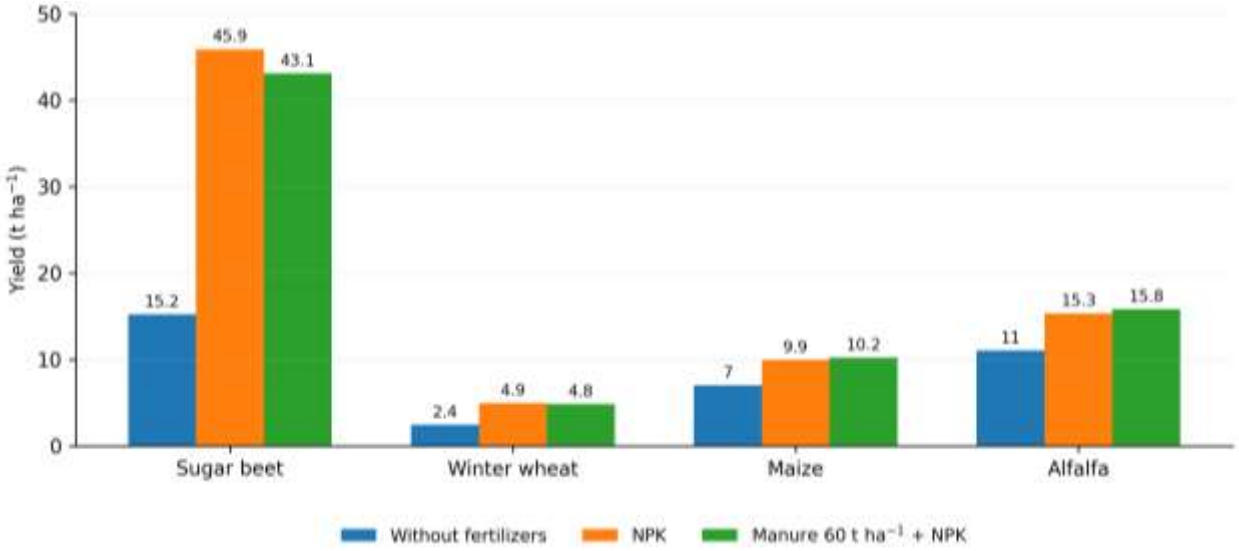


Figure 4. Yield response of major crops in the sugar beet crop rotation during the 5th rotation under contrasting fertilization systems.

These responses correspond to >3-fold yield gain for sugar beet, approximately 2-fold for winter wheat, ~1.4-fold for maize, and ~1.4-fold for alfalfa under fertilization, with broadly similar yields under mineral and organo-mineral systems in this rotation stage (Figure 4).

Environmental safety: heavy metals

Across treatments in the multifactor experiment (2020–2023), heavy metal concentrations in the plough layer remained far below soil MPC/TPC values. Observed ranges (mg kg^{-1}) were Cd 0.17–0.25, Cu 0.26–0.47, Zn 0.98–2.28, Ni 0.85–2.59, Pb 1.67–2.48, Co 0.67–1.14, and Cr 8.71–16.30. (Tables 7 and 8).

Table 7. Heavy metals in light chestnut soil under fertilizer treatments (2020–2023), mg kg^{-1}.

Variant	Cd	Cu	Zn	Ni	Pb	Co	Fe	Cr
No fertilizer	0.23	0.40	1.20	2.59	2.07	0.67	7.02	15.60
NPK	0.25	0.47	2.28	1.50	2.48	1.07	5.53	16.30
NPK+Manure	0.22	0.37	1.84	1.54	2.02	0.71	3.80	8.71
N0P0K0H0	0.17	0.32	0.98	1.77	1.67	0.76	4.56	12.10
N60P60K60H30	0.18	0.26	1.02	1.81	1.86	0.87	4.61	12.50
N120P120K120H60	0.17	0.30	1.14	0.85	2.12	1.14	3.94	14.69
N180P180K180H90	0.18	0.28	1.30	1.06	1.71	1.03	4.45	16.00

The maximum proportion of the soil MPC/TPC was recorded for Cd (up to 50% of MPC), whereas other metals were substantially lower (≤ 16.3% of MPC/TPC at their maxima), indicating no evidence of soil contamination attributable to the tested fertilizer/manure systems within the monitored period (Table 8).

Table 8. Maximum permissible and tentative permissible concentrations for soils (GN 2.1.7.2041-06; GN 2.1.7.2511-09).

Element	Actual (min–max), mg kg^{-1}	MPC/TPC, mg kg^{-1}	% of limit (max)
Cd	0.17–0.25	0.50	50.0%
Cu	0.26–0.47	55	0.9%
Zn	0.98–2.28	100	2.3%
Ni	0.85–2.59	40	6.5%
Pb	1.67–2.48	32	7.8%
Co	0.67–1.14	50*/60*	2.3%
Cr	8.71–16.30	100	16.3%
Fe	3.80–7.02	Not regulated	–

In maize grain, Cd (0.01–0.02 mg kg^{-1}), Cu (1.06–1.57 mg kg^{-1}), and Zn (14.8–18.7 mg kg^{-1}) remained below the respective MPC values, reaching at most 20%, 16%, and 37% of the permitted limits. Pb, however, ranged from 1.10 to 1.20 mg kg^{-1} and exceeded the stated MPC of 0.50 mg kg^{-1} by 2.2–2.4 times across all fertilization systems, showing no clear treatment dependency (Tables 9 and 10).

Table 9. Heavy metals in maize grain (2020–2023), mg kg^{-1}.

Variant	Cd	Cu	Zn	Ni	Pb	Co	Fe	Cr
Without fertilizers	0.01	1.06	14.8	1.62	1.20	0.10	12.30	6.90
NPK	0.02	1.57	18.7	2.64	1.12	0.18	16.40	5.10
NPK + manure	0.02	1.57	18.3	2.00	1.10	0.02	19.60	5.00

Accordingly, while soil heavy metal status indicates environmental safety of the tested fertilization systems, the grain Pb exceedance represents a food-safety-relevant finding that requires verification and pathway/source evaluation (Tables 9 and 10).

Table 10. MPC values for grain (TR TS 021/2011; SanPiN 2.3.2.1078-01) and exceedance (based on maximum observed value).

Element	Actual (min–max), mg kg^{-1}	MPC, mg kg^{-1}	Multiple of MPC (max)
Cd	0.01–0.02	0.10	0.20
Pb	1.10–1.20	0.50	2.40
Cu	1.06–1.57	10.0	0.16
Zn	14.8–18.7	50.0	0.37
Ni	1.62–2.64	Not regulated	–
Co	0.02–0.18	Not regulated	–
Cr	5.00–6.90	Not regulated	–
Fe	12.30–19.60	Not regulated	–

Discussion

Humus (Soil Organic Matter) dynamics

In this paper, the term humus is used as the humified and relatively stable fraction of soil organic matter (SOM) that governs long-term fertility functions such as aggregation, buffering, and nutrient retention. The long-term results demonstrate a consistent hierarchy in humus status across fertilization systems, with the lowest values under the unfertilized control, intermediate values under mineral NPK, and the highest values under the organo-mineral system (Figure 1; Table 3). In the control, humus in the 0–20 cm layer declined from 2.60% at initiation to 2.27% after the 3rd rotation and to 2.23% after the 5th rotation, indicating progressive depletion of SOM under continuous cropping without nutrient and carbon inputs (Figure 1; Table 3). Under systematic mineral fertilization, humus decreased only slightly from 2.60% to 2.53% and 2.50% after the 3rd and 5th rotations, respectively, suggesting that mineral fertilization mitigated, but did not eliminate, net SOM losses (Figure 1; Table 3). In contrast, the organo-mineral system (NPK + manure 60 t ha^{-1} once per rotation) increased humus to 2.83% after the 3rd rotation and maintained 2.80% after the 5th rotation, demonstrating that periodic organic carbon return was sufficient to offset mineralization and support net humus build-up in the plough layer under irrigated steppe conditions (Figure 1; Table 3).

This response is consistent with long-term evidence that humus balance under mineral-only regimes is sensitive to fertilization intensity and to the mismatch between carbon inputs and mineralization losses. Zhuravlev et al. (2024) reported that prolonged mineral fertilization in steppe Chernozems produced the

largest humus decreases under medium and high N–P doses, whereas minimal NP slowed humus losses and could support improved humic substance dynamics in later rotations, emphasizing that nutrient intensification without adequate organic matter return may accelerate net humus mineralization. Across long-term experiments, organic inputs typically increase SOM quantity and improve SOM quality indicators linked to stabilization in humified pools (Menšík et al., 2018; Sedlář et al., 2023). Balayev et al. (2020) showed that residue return and green manures contribute to deficit-free humus balance and long-term fertility restoration, reinforcing the central role of sustained carbon inputs. Ivanina and Tabachuk (2023) further reported that humus condition is strongly influenced by both fertilization system and crop-rotation structure, with organo-mineral strategies consistently supporting improved humus status relative to mineral-only management. Lifanenkova et al. (2019) showed that long-term organo-mineral fertilization can restore humus to the initial level and maintain a positive humus balance under crop rotation, highlighting the restorative potential of systematic organic inputs at the decadal scale. Sheudzhen et al. (2024) reported that combining organic amendments with mineral fertilizers can sustain a deficit-free humus balance and reduce humus losses even under intensive irrigated production systems, underscoring the stabilizing role of organo-mineral management in high-yield agroecosystems.

Regional agronomic context also supports the interpretation that management structure can shape SOM trajectories under continental steppe climates. Kalimov et al. (2024) reported that diversified crop rotations, particularly eight-field rotations, were most favorable for SOM preservation, whereas tillage system effects were comparatively limited under arid continental conditions. Ospanbayev et al. (2023) showed that conventional tillage can increase the labile organic carbon fraction within a single season in light chestnut soil—consistent with accelerated organic matter turnover under intensive disturbance—and emphasized that detectable improvements in total SOM generally require multiple years of sustained carbon inputs such as cover crops. Together, these findings provide a mechanistic explanation for the hierarchy observed in our long-term trial: mineral fertilization alone can reduce the rate of humus decline by supporting crop production and residue inputs, but sustained humus maintenance and net build-up in irrigated light chestnut soils requires systematic organic matter return through organo-mineral management (Figure 1; Table 3).

Available phosphorus–potassium balance

The long-term fertilization systems produced clear and differentiated trajectories for plant-available phosphorus and exchangeable potassium (Figures 2–3; Tables 4–5). In the unfertilized control, available P declined from 24.0 to 16.9 mg kg^{-1} in the 0–20 cm layer and from 19.5 to 14.0 mg kg^{-1} in the 20–40 cm layer by the 5th rotation, indicating progressive depletion under continuous nutrient offtake (Table 4). In contrast, systematic mineral fertilization increased available P to 39.7 mg kg^{-1} in the topsoil and 28.9 mg kg^{-1} in the subsoil, while the combined organo-mineral system increased available P to 52.3 mg kg^{-1} (0–20 cm) and 45.4 mg kg^{-1} (20–40 cm), demonstrating substantial enrichment across the profile under NPK + manure (Figure 2; Table 4). Exchangeable K followed the same ranking: by the 5th rotation, K_2O reached 601 mg kg^{-1} (0–20 cm) under mineral NPK and 765 mg kg^{-1} under NPK + manure, whereas the unfertilized control declined to 490 mg kg^{-1} in the topsoil and 418 mg kg^{-1} in the subsoil (Figure 3; Table 5).

These patterns align with long-term evidence that multi-decadal P fertilization can build both total and plant-available P stocks and that enrichment can extend well below the plough layer when inputs persist over rotations. Medinski et al. (2018) showed that long-term phosphorus application in Chernozem substantially increased plant-available and total P stocks down to 60 cm, and that persistent surpluses can accumulate as "legacy P" if inputs are not balanced with crop removal. In chestnut soils, the agronomic meaning of long-term P buildup should also be interpreted in the context of transformations among inorganic P pools. Zhaksybayeva et al. (2022) reported that long-term P fertilization increased total and available P and shifted inorganic P toward Ca-bound fractions, indicating that high soil P under carbonate buffering may increasingly be stored in less labile forms over time. At the same time, repeated high P inputs—particularly when organic sources contribute additional P—can increase environmental P saturation indices, emphasizing the need for periodic input–offtake accounting rather than relying on concentration targets alone (Asrade et al., 2024). The higher mobile P and improved K status commonly reported under organo-mineral systems in long-term trials (Tyutyunov et al., 2024) and the improved distribution of soil P fractions under manure plus mineral fertilization (Milić et al., 2019) provide a mechanistic context for the stronger P and K enrichment observed here under NPK + manure (Tables 4–5).

Potassium dynamics further reinforce the importance of explicitly managing nutrient balance in high-yield irrigated rotations. Khramtsov and Boyko (2021) showed that long-term intensive irrigated use can reduce mobile K fractions and lower exchangeable K over decades when K return is not proportional to offtake,

implying that hidden depletion can occur even in soils initially well supplied with K. Barłóg et al. (2025) similarly reported that cyclic slurry combined with mineral NPK optimized P and K fractions and delivered the strongest yield response, whereas very high N rates without proportional PK adjustment reduced plant-available P and K fractions and did not provide additional yield gains. In addition to long-term balance considerations, within-season dynamics can also contribute to fluctuations in bioavailable pools. İslamzade et al. (2023) observed that soil nutrient contents declined as crops progressed through growth stages despite higher initial availability under NPK, highlighting that fertilizer timing and proportionality to crop demand remain relevant even when long-term mean levels appear adequate.

Overall, the long-term results indicate that combined organic–mineral fertilization provided the most robust integrated P–K status in irrigated light chestnut soil, including enrichment in the 20–40 cm layer, while the unfertilized system showed clear depletion trends (Figures 2–3; Tables 4–5). From a management perspective, the findings support two complementary priorities: maintaining adequate P and K supply to sustain high-yield rotations, and implementing periodic nutrient balance evaluation (inputs versus removal) to avoid long-term P surpluses and prevent progressive depletion of mobile K pools under intensive irrigated cropping.

Crop productivity response under long-term fertilization

The marked yield gains observed in the sugar beet rotation during the 5th rotation (Figure 4) indicate that sustained nutrient replenishment effectively alleviated productivity constraints under irrigated light chestnut soil conditions. In particular, the >3-fold increase in sugar beet yield and the consistent gains in winter wheat, maize, and alfalfa suggest that the rotation system is highly responsive to improved nutrient supply when fertilization is applied systematically and maintained over successive cycles (Figure 4).

Regional field evidence supports the interpretation that chestnut soils in southeastern Kazakhstan can exhibit substantial yield improvements as mineral nutrient supply increases and that commonly applied fertilization regimes may be suboptimal under local conditions. Maxotova et al. (2021) reported a strong positive yield response of field tomato to increasing NPK rates on chestnut soils, with the highest yield attained under the maximum NPK dose, leading the authors to highlight the need for site-specific calibration of fertilization practices. This aligns with our observation that both mineral and organo-mineral fertilization substantially increased yields relative to the unfertilized control, indicating that nutrient supply is a primary driver of crop productivity in this irrigated steppe setting (Figure 4).

Within Kazakhstan chestnut soils, evidence further indicates that phosphorus can act as a dominant yield-forming nutrient for sugar beet under long-term management. Zhaksybayeva et al. (2022) showed in a 56-year stationary experiment that the highest phosphorus treatment produced maximum sugar beet yield and sugar content and increased total/available P stocks, emphasizing that sustained P supply can be decisive for beet performance in chestnut soils. In our long-term series, available P increased to an optimal range under mineral fertilization and to a high range under combined NPK + manure, concurrently with strong yield gains in the rotation, which is consistent with the view that improved P status underpins yield formation in high-demand crops under irrigation (Figure 2; Table 4; Figure 4).

The yield response of forage and cereal components in the rotation can also be interpreted in the context of nutrient-driven quality outcomes reported in the region. Massaliyev et al. (2024) found that phosphorus fertilization increased alfalfa yield and improved forage quality traits across varieties in irrigated light chestnut soils, indicating that P management can influence both productivity and quality formation in forage systems. Complementary evidence from foothill light chestnut soils suggests that balanced mineral fertilization can enhance soil nutrient availability and increase sugar beet yields across cultivars, underscoring cultivar-responsive nutrient management under Kazakhstan chestnut soils (Kaliyeva et al., 2024). Taken together, these studies support the inference that the productivity gains observed in our rotation reflect not only improved nutrient supply per se, but also a broader requirement for balanced, locally calibrated fertilization strategies that sustain both soil nutrient status and crop performance under irrigated steppe conditions.

Heavy metal accumulation in soil–grain systems

Long-term fertilization strategies are increasingly evaluated not only for agronomic benefits but also for environmental safety, because both mineral fertilizers and organic amendments can introduce trace elements or modify their mobility through changes in soil chemistry and organic matter turnover. Wu et al. (2025) showed that continuous fertilization—particularly when organic inputs are involved—can increase soil heavy metal pools and alter microbial and chemical processes that control metal retention and bioavailability. Sun et al. (2023) similarly emphasized that long-term organic amendments may lead to measurable accumulation

of trace metals in soil profiles, with risk depending on amendment composition, application rate, and soil buffering capacity. In a long-term wheat system, Zhang et al. (2025) reported that repeated applications of different organic fertilizers increased several soil metal(loid) concentrations, although transfer to grain remained generally limited under well-managed conditions.

In the present study, however, the monitored heavy metal status of the plough layer (2020–2023) indicates that the studied fertilization systems did not cause soil contamination. Across all treatments, concentrations remained far below the applicable sanitary–hygienic thresholds (Tables 7–8). The observed ranges were Cd 0.17–0.25 mg kg^{-1}, Cu 0.26–0.47 mg kg^{-1}, Zn 0.98–2.28 mg kg^{-1}, Ni 0.85–2.59 mg kg^{-1}, Pb 1.67–2.48 mg kg^{-1}, Co 0.67–1.14 mg kg^{-1}, and Cr 8.71–16.30 mg kg^{-1} (Table 7), corresponding to at most 50% of the soil MPC for Cd and 16.3% for Cr, while the remaining metals represented only a small fraction of their limits (Table 8). These results contrast with long-term trials in which organic fertilizers increased soil Cd, Cu, Zn, and other trace elements relative to mineral-only systems, particularly under repeated or high-rate organic inputs (Zhao et al., 2018; Zhang et al., 2025). The absence of soil accumulation effects in the present experiment likely reflects the combined influence of the soil's carbonate buffering, neutral-to-alkaline reaction, and the applied fertilization regimes, which together can constrain metal solubility and reduce the probability of rapid buildup in the topsoil under monitored management conditions.

The grain results, however, reveal an important food-safety-relevant signal that warrants targeted follow-up. In maize grain, Cd (0.01–0.02 mg kg^{-1}), Cu (1.06–1.57 mg kg^{-1}), and Zn (14.8–18.7 mg kg^{-1}) were well below the maximum permissible concentrations (Tables 9–10). In contrast, Pb ranged from 1.10 to 1.20 mg kg^{-1}, exceeding the stated MPC (0.50 mg kg^{-1}) by 2.2–2.4 times across all fertilization systems (Tables 9–10). Because Pb exceedance was present even in the unfertilized treatment and did not increase systematically with mineral or organo-mineral fertilization, the pattern is more consistent with a background or pathway-specific source than with direct fertilizer/manure-driven accumulation. This differs from the dominant trend reported in many long-term systems, where grain heavy metal concentrations typically remain below regulatory limits under good agronomic management, even when soil metal pools increase modestly (Zhao et al., 2018; Zhang et al., 2025). Therefore, the most defensible interpretation is that Pb in maize grain should be verified through expanded sampling and traced through potential exposure pathways (e.g., irrigation water quality, atmospheric dust deposition, field-edge contamination sources, or post-harvest handling). Sun et al. (2023) also highlight that risk outcomes can be strongly pathway-dependent, and that soil thresholds alone may not fully predict crop product compliance in all contexts, reinforcing the need for integrated soil–water–crop monitoring when an exceedance is detected.

Conclusion

Long-term cultivation under irrigated steppe conditions led to a measurable decline in soil humus when no fertilizer inputs were applied. Over the 1961–2005 period, humus in the 0–20 cm layer decreased by 0.37 percentage points relative to the initial status, confirming progressive depletion of soil organic matter under continuous cropping without carbon and nutrient replenishment.

Mineral fertilization alone moderated, but did not eliminate, humus losses and therefore did not ensure a non-deficit humus balance. In contrast, the organo-mineral system—mineral NPK combined with manure at 60 t ha^{-1} applied once per rotation—supported humus maintenance and net build-up, increasing humus in the 0–20 cm layer by 0.20 percentage points and reaching 2.80% by the 5th rotation. These results demonstrate that sustained carbon return through organic amendments is essential for stabilizing humus in irrigated steppe crop rotations.

Fertilization substantially improved the nutrient regime of the soil. Available phosphorus and exchangeable potassium increased to agronomically optimal/high levels under fertilization, with the highest values consistently achieved under combined organic–mineral management, including enrichment in the 20–40 cm layer. This confirms that organo-mineral fertilization provides the most robust integrated P–K status under intensive irrigated production, while also implying that long-term nutrient stewardship should be managed as a balance between inputs and crop offtake.

Improved soil nutrient supply translated into strong productivity gains and enhanced product quality within the sugar beet rotation. Fertilization increased yields markedly across crops, including multi-fold increases in sugar beet and clear gains in winter wheat, maize, and alfalfa, accompanied by improvements in key quality attributes (e.g., sugar content in beet roots and crude protein in cereals). These agronomic benefits emphasize the effectiveness of systematic fertilization, particularly under organo-mineral strategies that simultaneously sustain soil fertility and crop performance.

From an environmental safety perspective, heavy metal concentrations in the plough layer remained well below soil regulatory thresholds across treatments, indicating no evidence of soil contamination attributable to the studied fertilization systems during the monitoring period. However, lead concentrations in maize grain exceeded the stated MPC across all treatments, suggesting a background or pathway-specific source independent of fertilization and highlighting the need for continued monitoring of edible products in addition to soil. Future work should prioritize verification of grain Pb, identification of potential sources (e.g., irrigation water, atmospheric dust, local inputs), and implementation of risk management measures to ensure food safety under long-term irrigated steppe farming.

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