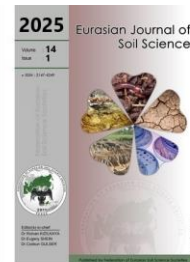




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Comparative agrochemical assessment of cultivated soils in East Kazakhstan: Implications for site-specific fertility management

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Abstract

Soil degradation driven by climate variability and unsustainable land use represents a growing challenge for agriculture in semi-arid and continental regions. This study presents a comparative agrochemical assessment of cultivated soils from two peasant farms—«Druzhba» (Ulansky District) and «Tamerlan & K» (Glubokovsky District)—in the East Kazakhstan Region. The objective was to evaluate site-specific fertility characteristics under contrasting climatic and landscape conditions and to provide practical recommendations for sustainable nutrient management. Composite soil samples were collected from three depth intervals (0–20, 20–40, and 40–60 cm) and analyzed for humus content, nitrate nitrogen, available phosphorus and potassium, sulfur, and pH using standardized GOST methodologies. The results revealed moderate fertility status in both farms, with humus levels ranging from 2.21% to 3.79%. Available nitrogen levels were relatively balanced; however, phosphorus availability was notably deficient in portions of the Tamerlan & K farm, posing potential constraints for phosphorus-demanding crops. Potassium and sulfur concentrations were generally adequate, while soil pH ranged from 7.00 to 7.47—slightly alkaline but within an acceptable range for most crops. Based on the agrochemical profiles and average nutrient uptake values, crop-specific fertilization strategies were developed. High-demand crops such as maize, sunflower, potato, and sugar beet require full NPK fertilization, while cereals like wheat and barley may be managed using NP fertilizers, supplemented with potassium every two to three years. The adoption of fertigation systems and the use of liquid organomineral fertilizers are recommended to enhance nutrient use efficiency and buffer heat and drought stress conditions. Furthermore, pH adjustment and organic matter restoration are critical to improve micronutrient availability and sustain long-term soil health. Overall, the study underscores the importance of adaptive, data-driven nutrient management approaches tailored to the agroecological diversity and evolving climate realities of East Kazakhstan.

Keywords: Agrochemical properties, Soil fertility, Nutrient management, Organomineral fertilizers, East Kazakhstan, Climate-resilient agriculture.

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Introduction

Soils serve as a cornerstone of terrestrial ecosystems, providing vital ecosystem services such as food production, nutrient cycling, carbon sequestration, and water regulation (Telo da Gama, 2023; Robb, 2024). Their functionality underpins both agricultural productivity and environmental resilience (Rudinskienė et al., 2022). However, global agroecosystems are increasingly threatened by the dual pressures of climate

change and unsustainable land management practices (Olowoyeye et al., 2024). Shifts in temperature regimes, irregular precipitation patterns, and an increased frequency of extreme weather events are already disrupting soil biogeochemical cycles, leading to declines in soil organic carbon (SOC), nutrient imbalances, and microbial dysbiosis (Nielsen and Ball, 2015; Yapiyev et al., 2018; Abdullaev et al., 2020).

These climatic stresses are further exacerbated by anthropogenic drivers such as intensive tillage, monoculture systems, and overgrazing, all of which accelerate processes of soil erosion, compaction, humus depletion, and nutrient leaching (Rodrigues et al., 2023). The combined effect is the progressive degradation of topsoil quality and structure, ultimately threatening long-term agricultural sustainability, particularly in vulnerable dryland and steppe ecosystems such as those found across Central Asia and Eastern Kazakhstan (Yapiyev et al., 2018; Rudinskienė et al., 2022). Recent research on organic matter dynamics in the chernozem soils of Northern Kazakhstan emphasizes that conservation tillage and diversified crop rotations are crucial in preventing SOM loss and maintaining fertility in such environments (Kalimov et al., 2024).

In Kazakhstan, the transition from Soviet-era land management systems to privatized agriculture introduced both opportunities and challenges for soil stewardship (Anarbayev et al., 2024). While productivity gains were sought through intensified cropping and mechanization, insufficient attention to nutrient recycling and organic matter restoration has led to widespread nutrient mining and soil fertility decline (Abdullaev et al., 2020). In many semi-arid regions, particularly those with continental climates and coarse-textured soils, this has resulted in increased sensitivity to climatic shocks such as drought, heat stress, and heavy rainfall (Bodner et al., 2015; Reinsch et al., 2024). The chronic phosphorus limitation reported in the chernozem soils of the Kostanay Region and low phosphorus use efficiency in alfalfa systems further demonstrate the pressing need for targeted fertilization strategies in Kazakhstan's agricultural zones (Massaliyev et al., 2024; Zharlygassov et al., 2025).

To address these emerging threats, agrochemical soil assessment has become an indispensable diagnostic tool for sustainable land-use planning (Futa et al., 2024). Site-specific soil surveys enable the identification of fertility limitations by quantifying key indicators such as humus content, available nitrogen, phosphorus, potassium, sulfur, pH, and trace elements. These data allow for the formulation of tailored nutrient management plans that maximize input efficiency, enhance crop productivity, and reduce the risk of environmental degradation (Yapiyev et al., 2018; Rudinskienė et al., 2022; İslamzade et al., 2024). Notably, Abitova et al. (2025) found that site-adapted foliar nutrient strategies—especially humic acid-enriched applications—can substantially improve nutrient uptake and crop performance in semi-arid cropping systems, reinforcing the benefits of localized diagnostics in fertilizer planning.

Moreover, there is growing consensus that integrated nutrient management (INM)—which combines mineral, organic, and organomineral fertilizers—is essential for rebuilding soil organic matter and improving soil structure (Yu et al., 2025). The application of liquid organomineral fertilizers, especially via fertigation systems, offers a promising avenue for increasing nutrient availability while simultaneously supporting soil biological health and climate resilience (Rudinskienė et al., 2022; Al-Shammary et al., 2024). In support of this, Zharlygassov et al. (2025) demonstrated that long-term cultivation without organic inputs severely reduces microbial biomass and nitrogen retention capacity in soils. Their findings underscore the necessity of using biologically supportive amendments to maintain nitrogen cycling and microbial functionality in intensively managed agricultural systems.

In this context, the East Kazakhstan Region presents a particularly relevant case study. Located in the eastern steppe zone, the region is characterized by significant agroecological heterogeneity, shaped by climatic gradients and varied land use histories. Peasant farms such as «Druzhba» (Ulansky District) and «Tamerlan & K» (Glubokovsky District) represent contrasting microclimates and management practices, offering a valuable opportunity to explore spatial patterns of soil fertility under real farming conditions.

Accordingly, the present study aims to: (i) assess the agrochemical characteristics of cultivated soils in these two representative farming systems; (ii) analyze the intra-site and inter-site variability of macronutrient levels; (iii) identify site-specific constraints and management opportunities; and (iv) provide a foundation for developing adaptive, resource-efficient, and climate-resilient fertility management strategies for the broader East Kazakhstan Region.

Material and Methods

Geographical and Environmental Setting

The East Kazakhstan Region is located in the eastern part of the Republic of Kazakhstan and is characterized by a diverse physical and climatic environment. The study was conducted in two administrative districts with contrasting natural conditions:

The Ulansky District, where the «Druzhba» farm is located, lies within the foothills of the Kalbinsky Mountains. The terrain is rugged, comprising mid- and low-mountain zones, which are commonly used as pastureland. The climate is moderately warm and semi-arid. The average temperature ranges from -14°C to -18°C in January, and 20°C to 21°C in July. Although the district spans three climatic subzones, it is generally classified within the dry steppe natural-economic zone.

The Glubokovsky District, home to the «Tamerlan & K» farm, is situated in the northeastern part of the region, and is dominated by mountainous taiga landscapes. The area includes the Ubinsky, Tigiretsky, and Ulbinsky ridges. The climate is sharply continental, with -18°C in January and around 20°C in July, and annual precipitation ranging from 600 to 700 mm. Snow cover can reach up to 90 cm by late winter. Soils include mountain chernozems, chestnut soils, and dark chestnut soils in the foothill zones.

These varying geographical and climatic features significantly influence soil formation processes, organic matter accumulation, and nutrient dynamics across the study sites.

Soil Sampling Procedure

Composite soil samples were collected during the 2024 growing season from cultivated plots on each farm. Sampling was performed at three depth intervals: 0–20 cm, 20–40 cm, and 40–60 cm, representing the plow layer and subsurface horizons. At each depth, multiple cores were taken and homogenized to form a composite sample representative of the site.

The total survey area was 1,576 hectares in the Druzhba farm and a comparable area in the Tamerlan & K farm. Sampling locations were georeferenced, and the approximate central coordinates of the study sites are $49^{\circ}57' \text{ N}$, $82^{\circ}37' \text{ E}$.

Laboratory Analysis

All soil samples collected from the field were first air-dried at room temperature to preserve their natural chemical integrity and then passed through a 2 mm sieve to remove coarse fragments and ensure sample homogeneity prior to laboratory analysis. The analytical procedures were conducted at the LLP "Republican Soil Center"—a nationally accredited laboratory certified under ISO/IEC 17025:2019 (Accreditation No. KZ.T.03.2359)—which specializes in agrochemical diagnostics across Kazakhstan. A suite of key soil fertility parameters was determined using standardized methods in accordance with national GOST regulations to guarantee methodological consistency and scientific rigor. Humus content, reflecting the organic matter status of the soils, was quantified using the [GOST 26213-91](#) protocol. Nitrate nitrogen ($\text{NO}_3^- \text{-N}$), a vital indicator of immediate nitrogen availability, was assessed via the CIAS method under [GOST 26488-85](#). Plant-available phosphorus (P_2O_5) and potassium (K_2O), crucial for early root development and yield formation, were measured following the Machigin method (modified CIAS variant) as per [GOST 26205-91](#). Additionally, available sulfur—a secondary macronutrient often overlooked in standard soil testing—was analyzed according to [GOST 26490-85](#). Soil reaction (pH) was determined in a salt extract solution (CIAS method) using [GOST 26483-85](#). Collectively, these measurements provide a comprehensive profile of the soil's agrochemical status and serve as the foundation for interpreting nutrient dynamics and informing region-specific fertilizer recommendations.

Results

Climatic Characteristics of the Study Year

The climatic conditions of the study area, situated in East Kazakhstan, are typified by a sharply continental climate with cold winters, hot summers, and marked intra-annual fluctuations in temperature and precipitation. Meteorological data for the year 2024, sourced from the regional branch of RSE "Kazhydromet", are summarized in Figure 1, presenting monthly averages of air temperature and precipitation for the two agroecological zones under study: AMP «Saratovka» (Ulansky District) and AMP «Sekisovka» (Glubokovsky District).

During 2024, the average annual air temperature at «Druzhba» farm (Ulansky) was 5.8°C , slightly higher than the 4.7°C recorded at «Tamerlan & K» farm (Glubokovsky). The highest temperatures were observed in July, peaking at 22.6°C and 20.9°C in Ulansky and Glubokovsky, respectively. The coldest month was February in both districts, with minimum values reaching -15.6°C and -16.1°C .

Total annual precipitation revealed substantial inter-site variation, with Ulansky receiving 548.6 mm and Glubokovsky 855.7 mm of rainfall. Notably, the highest precipitation was recorded in the summer months (June–August), accounting for 231.1 mm in Ulansky and 233.7 mm in Glubokovsky (Figure 1B). This

seasonal rainfall distribution coincides with the primary crop-growing period, thereby significantly influencing nutrient availability and uptake efficiency (Abdullaev et al., 2020).

The interplay between climatic drivers and soil processes has been emphasized in regional studies across Kazakhstan. For instance, Yapiyev et al. (2018) demonstrated that variations in annual precipitation and temperature substantially affect topsoil characteristics, particularly soil organic carbon (SOC), pH, and salinity gradients. Warmer temperatures in Ulansky may accelerate organic matter mineralization and microbial activity, while the higher moisture regime in Glubokovsky could enhance plant-available nutrient pools but simultaneously increase the risk of nutrient leaching and temporary waterlogging—especially during peak summer rainfall.

Overall, the agroclimatic contrast between the two sites reflects their differing soil formation conditions, biological activity, and fertility potential. These patterns warrant site-specific soil fertility management strategies tailored to thermal and hydrological regimes, in line with prior findings on moisture-temperature interactions in arid and semi-arid agroecosystems (Rudinskienė et al., 2022; Yapiyev et al., 2018).

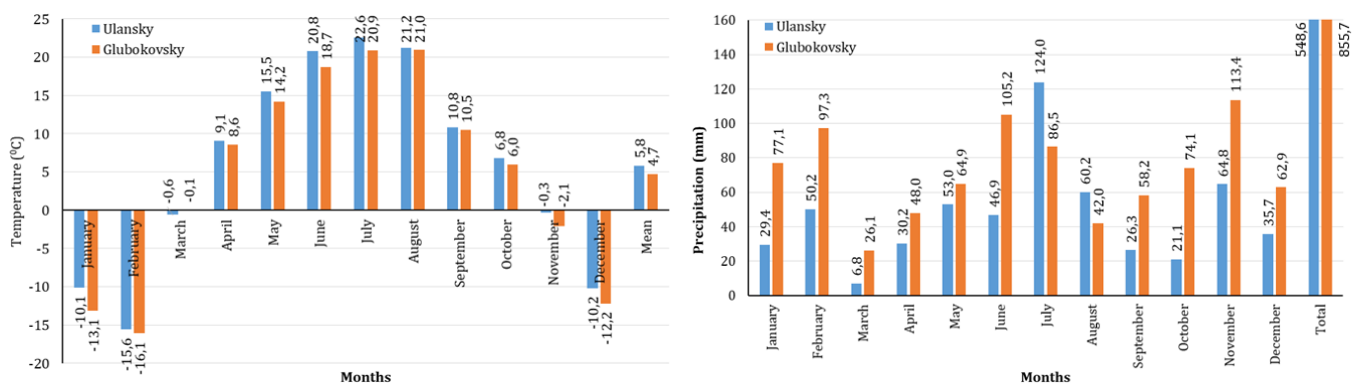


Figure 1. Monthly variation in climatic parameters during 2024 for AMP «Saratovka» (Ulansky) and AMP «Sekisovka» (Glubokovsky): (A) Average monthly air temperature; (B) Total monthly precipitation.

Agrochemical Properties of Cultivated Soils

The agrochemical analysis of cultivated soils from the Ulansky («Druzhba») and Glubokovsky («Tamerlan & K») farms indicates moderate fertility status with site-specific differences in nutrient profiles. The humus content ranged from 2.21% to 3.79%, with slightly higher values recorded at the «Tamerlan & K» farm (Table 1), suggesting relatively more favorable organic matter accumulation under local conditions.

Nitrogen content in both sites fell within the medium range (4.93–8.97 mg/kg), indicating an adequate but potentially limiting supply for crops with high nitrogen demand. While organic matter plays a key role in nitrogen retention and mineralization, the current levels imply that supplemental nitrogen fertilization may be required for optimal productivity (Abdullaev et al., 2020).

Phosphorus availability varied more substantially between sites. Soils from «Druzhba» exhibited higher phosphorus concentrations (up to 29.8 mg/kg), whereas several samples from «Tamerlan & K» recorded values near or below 15 mg/kg—levels that are often considered marginal for high-yielding crops (Rudinskienė et al., 2022). This heterogeneity likely reflects both historical fertilization regimes and the variable phosphorus-retention capacity of the soil matrix.

Potassium levels were generally high across both sites, ranging from 291 to 612 mg/kg. Topsoil samples tended to exhibit greater potassium availability, especially in fields with higher organic matter content. The importance of maintaining potassium balance is well-documented in Central Asian soils, as excessive irrigation or leaching can cause nutrient depletion over time (Yapiyev et al., 2018).

Sulfur concentrations, ranging from 7.9 to 11.8 mg/kg, fall within acceptable agronomic thresholds. Sulfur is increasingly recognized as a critical macronutrient for protein synthesis, especially in sulfur-sensitive crops such as brassicas and legumes.

Soil pH values were relatively consistent, ranging from 7.00 to 7.47 across all samples and depth intervals. This slightly alkaline reaction is typical of semiarid continental regions where carbonate accumulation and low leaching are common (Yapiyev et al., 2018). While such pH levels support microbial stability and organic matter persistence, they may reduce the availability of certain micronutrients such as iron (Fe) and zinc (Zn), particularly in the deeper horizons.

The observed vertical and spatial variability of nutrient concentrations across both sites emphasizes the importance of site-specific soil fertility management. A combination of organic matter enhancement and balanced nutrient supplementation, tailored to local agrochemical baselines, is essential for optimizing soil health and sustainable productivity.

Table 1. Agrochemical properties of cultivated soils at different depths (0–60 cm) from 'Druzhba' and 'Tamerlan & K' farms in East Kazakhstan.

Farm	Field No.	Dept (cm)	Humus (%)	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Sulfur (mg/kg)	pH
Druzhba	1	0–20	2.78	8.23	29.8	488	9.0	7.29
Druzhba	1	20–40	2.55	5.58	25.8	450	9.2	7.17
Druzhba	1	40–60	2.47	5.52	24.6	430	7.9	7.31
Druzhba	2	0–20	2.76	8.97	27.4	481	8.6	7.32
Druzhba	2	20–40	2.68	8.20	26.7	460	8.0	7.30
Druzhba	2	40–60	2.57	7.83	24.6	420	8.1	7.32
Druzhba	3	0–20	2.70	8.74	27.5	612	8.8	7.47
Druzhba	3	20–40	2.21	8.54	24.6	537	8.6	7.46
Druzhba	3	40–60	3.12	8.53	16.3	347	8.7	7.16
Tamerlan & K	1	0–20	2.83	8.25	15.2	310	8.6	7.16
Tamerlan & K	1	20–40	2.83	5.77	15.0	310	9.6	7.10
Tamerlan & K	1	40–60	2.96	5.47	15.4	362	9.2	7.25
Tamerlan & K	2	0–20	2.87	5.36	15.0	316	9.7	7.16
Tamerlan & K	2	20–40	2.86	4.93	14.9	302	9.4	7.14
Tamerlan & K	2	40–60	2.86	5.40	14.6	291	9.0	7.25
Tamerlan & K	3	0–20	3.79	6.65	25.7	601	11.0	7.30
Tamerlan & K	3	20–40	3.43	6.10	25.4	519	11.8	7.00
Tamerlan & K	3	40–60	2.96	5.19	24.0	515	11.4	7.10

Discussion

The findings of this study underscore the complex interplay between agroecological heterogeneity, historical land use, and climate variability in shaping soil fertility dynamics in East Kazakhstan. The comparative analysis of cultivated soils from the «Druzhba» and «Tamerlan & K» peasant farms revealed moderate overall fertility status but with marked spatial variability in key nutrient indicators, particularly phosphorus and humus content.

The higher humus levels observed in the «Tamerlan & K» farm (up to 3.79%) compared to «Druzhba» suggest a relative advantage in terms of soil organic matter reserves, potentially attributable to less intensive cultivation, longer fallow periods, or microclimatic conditions that reduce organic matter mineralization. According to Rudinskienė et al. (2022), such differences can significantly influence microbial activity, aggregate stability, and nutrient cycling capacity—factors critical for sustainable productivity in semi-arid systems. Similar trends were reported by Kalimov et al. (2024), who observed that long-term conservation practices, including minimum tillage and diverse crop rotations, contribute significantly to maintaining soil organic matter content in the chernozem soils of Northern Kazakhstan.

Conversely, the «Druzhba» farm exhibited relatively higher available phosphorus levels in the upper soil horizons, despite lower humus content. This pattern likely reflects a history of localized phosphorus fertilization or uneven nutrient redistribution due to erosion or tillage. However, the subsoil layers in both farms demonstrated nutrient depletion, especially with respect to phosphorus and potassium, highlighting the cumulative effect of years of unbalanced nutrient removal and inadequate replenishment. These observations align with the concerns raised by Abdullaev et al. (2020), who reported that post-Soviet agricultural systems in Kazakhstan frequently suffer from nutrient mining, particularly in the absence of organic amendments or integrated fertility strategies. Massaliyev et al. (2024) similarly emphasized the yield-limiting nature of phosphorus deficiency in light chestnut soils, recommending application rates above 100 kg/ha P₂O₅ for optimal alfalfa growth.

The neutral to slightly alkaline pH values (7.00–7.47) are generally favorable for crop growth but may reduce the availability of key micronutrients such as Fe and Zn. This is particularly relevant in calcareous soils common to continental steppe regions, where micronutrient deficiencies often emerge even under moderate pH conditions. Similar findings were discussed by Rudinskienė et al. (2022), emphasizing the need for foliar supplementation and pH-buffering strategies in such contexts. Abitova et al. (2025) also

demonstrated the positive impact of humic-acid-based foliar fertilization in improving nutrient uptake under semi-arid, alkaline soil conditions.

Importantly, this study reinforces the critical role of depth-specific nutrient monitoring. The substantial variation in nutrient levels between the 0–20 cm and 40–60 cm layers suggests that conventional surface-only sampling may overlook subsoil constraints that can limit root-zone nutrient access—especially in deep-rooted crops such as maize or sunflower. As [Zharlygassov et al. \(2025\)](#) highlighted, nutrient dynamics in deeper horizons are increasingly important under warming climate scenarios, where moisture availability and microbial activity are shifting downward due to surface droughts and extreme rainfall events.

The integration of liquid organomineral fertilizers and fertigation systems is especially timely under these conditions. Beyond improving nutrient use efficiency, these technologies support soil biological health, increase soil carbon inputs, and reduce nutrient leaching. The findings of [Zharlygassov et al. \(2025\)](#) further confirm that organomineral formulations enhance microbial nitrogen retention and enzyme-mediated nutrient release—functions that are vital in soils experiencing organic matter decline or abiotic stress. These conclusions are consistent with those of [Abitova et al. \(2025\)](#), who observed similar biological improvements in humus-depleted soils receiving foliar humic substances.

Additionally, our practical recommendations for crop-specific nutrient strategies—particularly the differentiation between high K-demanding crops (e.g., potato, sugar beet) and cereals—are consistent with nutrient budgeting models and agronomic efficiency principles highlighted in [Rudinskienė et al. \(2022\)](#) and [Yapiyev et al. \(2018\)](#). For instance, [Kaliyeva et al. \(2024\)](#) demonstrated that applying balanced NPK rates (130:130:130 kg/ha) significantly improved sugar beet productivity and quality in comparable agroecological settings. This further validates our crop-oriented fertilization guidelines.

In sum, this discussion demonstrates that soil fertility in East Kazakhstan is shaped by a mosaic of climatic, biological, and management factors. A shift toward integrated, diagnostics-based nutrient strategies—anchored in both mineral and organic sources—is essential to safeguard long-term productivity and resilience in the face of climatic and agronomic pressures.

Comparative Interpretation of Agrochemical Trends

A cross-site comparison between the two farms reveals notable distinctions in nutrient profiles that reflect underlying differences in land use intensity, organic matter turnover, and microclimatic influences.

Soils from the «Tamerlan & K» farm consistently exhibited slightly higher levels of humus (up to 3.79%) and sulfur (up to 11.8 mg/kg) across all depth layers. These findings may be attributed to less intensive cultivation, better vegetative cover, or enhanced organic matter stabilization under comparatively cooler and wetter conditions, as indicated in climatic data (Figure 1). Similar correlations between cooler microclimates and increased SOC/S content have been reported in East and Central Kazakhstan ([Yapiyev et al., 2018](#); [Abdullaev et al., 2020](#)). In line with these observations, [Kalimov et al. \(2024\)](#) emphasized that long-term conservation tillage practices and crop rotation in northern Kazakhstan support organic matter accumulation and sulfur retention by reducing oxidation processes and microbial turnover under milder conditions.

In contrast, the «Druzhba» farm demonstrated greater phosphorus availability, with surface P levels reaching up to 29.8 mg/kg. This may reflect historical application of phosphorus-based fertilizers or greater mineralization due to warmer temperatures in the Ulansky District. However, a consistent decline in phosphorus and potassium levels with depth suggests subsoil nutrient depletion, likely driven by intensive land use without proportionate nutrient replenishment—a scenario often reported in post-Soviet farming systems ([Rudinskienė et al., 2022](#)). [Massaliyev et al. \(2024\)](#) similarly reported that phosphorus depletion in light chestnut soils of southeastern Kazakhstan significantly limits productivity unless replenished through consistent and targeted fertilization strategies.

These spatial and vertical nutrient differences underscore the critical importance of site-specific nutrient management strategies. Fertilizer recommendations based solely on topsoil analysis may fail to address deeper nutrient deficiencies that affect long-term root development and nutrient acquisition, particularly in deep-rooting cereal and forage crops. As emphasized by contemporary agroecological research (e.g., [Rudinskienė et al., 2022](#)), incorporating vertical nutrient stratification into fertilization programs can significantly improve input efficiency and sustainability outcomes. [Zharlygassov et al. \(2025\)](#) further stress the importance of monitoring subsoil nutrient dynamics in steppe ecosystems, especially under climate change conditions that are shifting biological activity deeper into the soil profile due to surface drying.

Practical Implications for Soil Fertility and Crop Production Management

The current agrochemical profiles of the soils studied provide a critical baseline for developing crop-specific and site-adaptive fertilization strategies in the East Kazakhstan Region. Given the observed variability in macronutrient availability—especially phosphorus and potassium—tailored nutrient management is essential for optimizing yield potential and maintaining soil health.

Estimated nutrient uptake values per decare for key crops cultivated in the region are as follows:

- Wheat: 19 kg N, 8 kg P₂O₅, 25 kg K₂O
- Barley: 12 kg N, 5 kg P₂O₅, 22 kg K₂O
- Maize: 25 kg N, 13 kg P₂O₅, 28 kg K₂O
- Sunflower: 15 kg N, 9 kg P₂O₅, 40 kg K₂O
- Potato: 50 kg N, 20 kg P₂O₅, 60 kg K₂O
- Sugar beet: 27 kg N, 10 kg P₂O₅, 42 kg K₂O

These nutrient removal rates indicate that potassium-demanding crops (e.g., potato, sunflower, maize, sugar beet) should be cultivated with full NPK basal fertilization, ensuring continuous K₂O availability during critical growth stages. In contrast, cereals such as wheat and barley, which require less potassium, can benefit from a rotational fertilization schedule—typically NP fertilization annually, supplemented with full NPK application every 2–3 years, or as guided by periodic soil testing. This crop-oriented nutrient budgeting strategy aligns with the findings of [Kaliyeva et al. \(2024\)](#), who reported significant yield increases in sugar beet with balanced NPK (130:130:130) applications in similar steppe soils.

The implementation of fertigation technologies, particularly under drip or sprinkler irrigation systems, can significantly enhance nutrient use efficiency. Liquid organomineral fertilizers—rich in readily available nutrients and stabilized organic matter—are well suited for such systems. These inputs not only provide immediate nutrient availability but also contribute to long-term improvements in soil structure, microbial activity, and nutrient retention capacity ([Yapiyev et al., 2018](#); [Rudinskienė et al., 2022](#)). [Zharlygassov et al. \(2025\)](#) emphasized that organomineral fertigation contributes to enhanced microbial biomass and enzyme-mediated nutrient transformations, particularly under the abiotic stress conditions common to Eastern Kazakhstan.

Given the slightly alkaline pH (7.00–7.47) observed in both farms, micronutrient availability—particularly iron, zinc, and manganese—may be constrained. To address this, the following practices are recommended:

- Application of chelated foliar micronutrients during early vegetative stages,
- Elemental sulfur amendments to locally acidify the rhizosphere,
- Increased input of organic matter to buffer pH and enhance cation exchange capacity (CEC).

[Abitova et al. \(2025\)](#) demonstrated that foliar application of humic acid-enriched solutions improves micronutrient uptake and physiological performance under such alkaline semi-arid conditions.

In the context of climate change, characterized by increased temperature extremes and erratic precipitation, the role of organomineral fertilization becomes even more critical. These products can improve the water-holding capacity of soil, buffer against leaching losses, and maintain nutrient uptake efficiency under abiotic stress. Liquid organomineral formulations, especially when fertigated during peak heat and drought periods, help sustain crop vigor and productivity. This aligns with the conclusions drawn by [Budanov et al. \(2023\)](#), who advocated for organic-mineral fertilizer programs as an adaptive response to climatic uncertainty in steppe agriculture.

In conclusion, sustainable soil fertility management in East Kazakhstan demands a data-driven, crop-responsive, and climate-adaptive approach. Integrating routine soil diagnostics, balanced organomineral fertilization, and modern fertigation systems will be central to improving both short-term yields and long-term agroecosystem resilience.

Conclusion

The comparative agrochemical evaluation of cultivated soils from the «Druzhba» and «Tamerlan & K» peasant farms in East Kazakhstan revealed moderate but spatially heterogeneous fertility status. Humus levels were generally within the medium range (2.2–3.8%), while phosphorus availability displayed significant variability, with notably lower values in portions of the «Tamerlan & K» farm, potentially limiting the productivity of phosphorus-demanding crops. Potassium concentrations were largely sufficient, and soil pH remained within neutral to slightly alkaline range (7.1–7.4), with no signs of salinity or solonchik degradation.

Importantly, the observed decline in nutrient concentrations with increasing soil depth reflects the long-term effects of continuous cultivation without adequate nutrient replenishment. These patterns underscore the urgency for transitioning toward site-specific, diagnostic-based fertility management systems tailored to both crop needs and soil depth variability.

To support long-term soil productivity and agroecosystem sustainability in the region, the following integrated strategies are recommended:

- Crop-specific nutrient management, including full NPK applications for high-demand crops (maize, sunflower, potato, sugar beet) and rotational potassium fertilization for cereals (wheat, barley);
- Greater utilization of organic and organomineral fertilizers, aiming to rebuild humus content and stimulate microbial activity for improved nutrient cycling;
- Expansion of fertigation technologies for precise nutrient delivery, especially under water-stress and heatwave conditions;
- pH-buffering and micronutrient management, including foliar applications of chelated micronutrients and the use of elemental sulfur where necessary;
- Routine soil testing and adaptive fertilization, ensuring responsiveness to evolving agrochemical dynamics and climatic stressors.

In the context of climate change—marked by increased rainfall variability, elevated temperatures, and soil degradation risks—the integration of liquid organomineral fertilizers via fertigation represents a promising pathway to enhance nutrient uptake, improve soil resilience, and stabilize yields under fluctuating environmental conditions.

Overall, the findings provide a valuable scientific basis for designing adaptive, resource-efficient, and climate-resilient soil fertility strategies suited to the diverse agroecological zones of East Kazakhstan.

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