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Sustainable nutrient management and agricultural productivity in chernozem soils of the Kostanay Region, Kazakhstan

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Abstract

Chernozem soils, known for their high organic matter and fertility, are crucial for agricultural productivity in northern Kazakhstan's Kostanay region. This study evaluated the physical, chemical, and biological properties of these soils to assess their suitability for crop production and propose sustainable management practices. Soil samples were collected from 0-20 cm depths across various locations to represent the region's main nutrient profile. Physical analyses included texture determination, while chemical analyses measured pH, electrical conductivity (EC), organic matter, and nutrient levels (N, P, K, Ca, Mg, Fe, Cu, Zn, and Mn) using standard methods. Biological assessments focused on microbial biomass carbon (C_{mic}), basal soil respiration (BSR), dehydrogenase and catalase activities, as well as Cmic: Corg and metabolic quotient (qCO_2) ratios. Results indicated high organic matter content (mean 4.49%), sufficient total nitrogen (>0.25%), and high levels of potassium and calcium. However, phosphorus levels were low (<8 mg kg^{-1}), marking it as a key limiting nutrient. Biological analysis revealed robust microbial activity, with high catalase activity supporting aerobic processes, but low C_{mic}: C_{org} and qCO_2 values suggested limited microbial biomass, potentially slowing organic matter decomposition. This trait, while preserving organic matter, may restrict nutrient mineralization, impacting crop nutrient availability. Based on these findings, we recommend prioritizing phosphorus and potassium fertilization integrated with organic matter management to balance nutrient levels and enhance crop productivity. The application of liquid or solid organic or organomineral fertilizers is suggested to maintain soil organic matter and promote sustainable practices. Additionally, foliar applications of manganese and iron, along with nitrogen supplementation, are recommended to address micronutrient deficiencies and support plant growth. Overall, sustainable management of Chernozem soils in Kostanay requires balanced nutrient management, organic matter preservation, and targeted micronutrient interventions to ensure long-term fertility and productivity.

Keywords: Chernozem Soils, Soil Fertility, Nutrient Management, Organic Matter, Sustainable Agriculture.

Introduction

Chernozem soils, characterized by their high organic matter and humus content, provide ideal conditions for productive agriculture. These unique soils are found in limited regions around the world, with significant

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concentrations in countries such as Russia, Ukraine, Kazakhstan, Canada, and the United States. The largest concentration of Chernozems is within the expansive steppe regions of Russia and Ukraine, known as the "Black Earth Belt," which accounts for approximately 60% of the world's total Chernozem areas (Yapiyev et al., 2018; Djalankuzov et al., 2004). Globally, Chernozem soils are estimated to cover over 230 million hectares, with about 25 million hectares located within Kazakhstan's borders. This distribution makes Kazakhstan a significant repository for these highly productive soils (Funakawa et al., 2004; Rolinski et al., 2021). Chernozem soils are not only vital for agricultural productivity but also play a crucial role in climate change mitigation due to their high organic carbon content and capacity for atmospheric carbon sequestration.

In Kazakhstan, Chernozem soils are primarily concentrated in the northern regions, playing a crucial role in the country's grain production. Kazakhstan has a total land area of 272 million hectares, with approximately 30 million hectares allocated for agricultural activities, of which 23 million hectares are active farmlands (Djalankuzov et al., 2004). The extensive Chernozem regions in northern Kazakhstan account for over 20% of the country's arable land, making them a key resource for grain production and a major contributor to food security (Kusherbayev et al., 2023). Additionally, Chernozem soils, with their rich organic carbon content, are effective in sequestering atmospheric carbon, thus holding significant potential in mitigating climate change impacts (Funakawa et al., 2004).

However, Kazakhstan's Chernozem soils have undergone various changes over time due to agricultural policies and intensive land use. Notably, during the Soviet era, the "Virgin Lands Campaign" opened millions of hectares to agriculture, disrupting the natural balance of these soils and leading to organic matter loss and declining soil quality (Yapiyev et al., 2018; Karbozova–Saljnikov et al., 2004). For example, while traditional Chernozem soils generally contain 5-6% organic carbon, the campaign resulted in losses of up to 11%, reducing organic carbon levels to 4.5-5%. In some areas of northern Kazakhstan, the continuous practice of fallow rotation and monoculture wheat cultivation has led to organic carbon reductions of 28-30% (Karbozova–Saljnikov et al., 2004; Funakawa et al., 2004; Kalimov et al., 2024). These losses have been exacerbated by fallow practices, which, while aimed at increasing the soil's water retention capacity, ultimately accelerate organic matter mineralization and carbon depletion over time.

Kazakhstan's Chernozem soils remain a crucial resource for the country's agricultural sustainability and food security. However, fertilizer applications on these lands are typically not based on soil analysis, leading to suboptimal management practices. In wheat cultivation, farmers often rely on limited nitrogen and phosphorus applications alongside seeding, resulting in a decline in the organic matter content and levels of essential nutrients in Chernozem soils. The objective of this study is to comprehensively analyze the physical, chemical, and biological properties of Chernozem soil samples from the Kostanay region of northern Kazakhstan to evaluate their suitability for sustainable agricultural production. Specifically, the study aims to identify nutrient limitations and other soil characteristics that may affect crop growth and productivity. By examining these properties, the research seeks to propose evidence-based fertilization strategies and soil management practices that balance nutrient levels, maintain soil organic matter, and support long-term agricultural sustainability. Through this evaluation, nutrient deficiencies and other limiting factors affecting agricultural productivity will be identified, guiding the development of effective practices to optimize soil fertility and enhance crop productivity. The main research questions addressed in this study include identifying nutrient deficiencies present in Chernozem soils, assessing whether the biological activities of these soils are sufficient to sustain long-term productivity, and determining the most effective fertilization and soil management strategies to enhance soil fertility and crop yield.

Material and Methods

Study Area and Soil Sampling

This study was conducted in the Kostanay region of northern Kazakhstan, an area characterized by Chernozem soils, known for their high fertility and significance for agricultural activities. The region has a continental climate, marked by cold winters and warm summers. Long-term and 2023 climate data, including precipitation and temperature for the sampling sites, are presented in Figure 1. In 2023, the annual total rainfall in Kostanay was 447.2 mm, significantly exceeding the long-term annual average of 340 mm. Monthly rainfall showed notable deviations from the average, with August experiencing an exceptionally high rainfall of 102.4 mm, compared to the long-term average of 35 mm. On the other hand, spring months (March to May) received lower-than-average rainfall, which may affect early crop development, whereas higher-than-average rainfall in summer and fall could potentially benefit mid-season crop growth but may also increase the risk of waterlogging in certain areas.

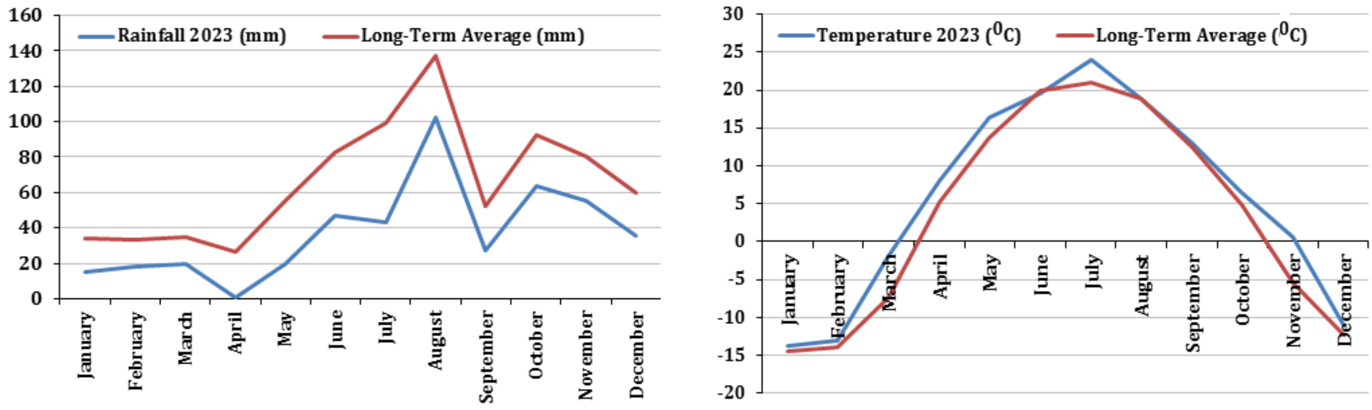

Figure 1. Monthly rainfall and temperature data for 2023 compared to long-term averages in Kostanay, Kazakhstan.

The region's temperature patterns also exhibit significant seasonal fluctuations. In 2023, the average annual temperature was 5.6°C, slightly higher than the long-term average of 3.6°C. Monthly temperatures in 2023 showed some deviations from historical averages, with warmer-than-average conditions in March (−1.9°C compared to −7.4°C long-term average) and November (0.6°C compared to −5.5°C). The summer months, particularly July, experienced above-average temperatures, reaching 24°C compared to the long-term average of 20.9°C. These temperature deviations may impact crop growth cycles and influence the region's agricultural productivity.

Sampling Procedure

The soil samples were collected from Chernozem areas, allowing for a broad examination of the soil's physical, chemical, and biological properties. Soil samples were collected from a depth of 0-20 cm according to Jones (2001), as this layer is critical for nutrient availability and root development in agricultural systems. At each sampling location, multiple sub-samples were collected and combined to form a composite sample, ensuring a representative sample for each site by accounting for spatial heterogeneity. A portion of the collected soil samples was stored at +4°C for biological analyses. The remaining soil samples were air-dried, sieved to 2 mm, and stored for further physical and chemical analysis.

Physical and Chemical Analyses

To determine the physical and chemical properties of the soil, various standard methods were employed. Soil texture was analyzed using the hydrometer method (Bouyoucous, 1951). For chemical analyses, soil pH was measured in a 1:1 soil-to-water suspension using a pH meter (Peech, 1965), and electrical conductivity (EC) was measured in a 1:1 soil-to-water extract (Rowell, 1996). Organic matter content was determined by the Walkley-Black method (Walkley and Black, 1934), while total carbonate content was analyzed using the Scheibler calcimeter (Loeppert and Suarez, 1996). Total nitrogen (N) was measured using the Kjeldahl method (Bremner, 1965a), and mineral nitrogen (NH_4 and NO_3) contents were extracted with 1N KCl and determined by the Kjeldahl distillation method (Bremner, 1965b). The C/N ratios of the soils were calculated based on the total organic C and N determined in the analyses (Rowell, 1996). Available phosphorus (P) was assessed using the Olsen method with a 0.5 M $NaHCO_3$ extraction, which is suitable for calcareous soils like Chernozems (Olsen and Dean, 1965). Exchangeable cations (K, Ca, Mg, and Na) were extracted with 1 N ammonium acetate; K and Na were determined by flame photometry, while Ca and Mg were measured by EDTA titration (Pratt, 1965; Heald, 1965). Available micronutrients, including Fe, Cu, Zn, and Mn, were determined by DTPA extraction followed by Atomic Absorption Spectrophotometry (Lindsay and Norvell, 1978).

Biological Analysis

Microbial biomass carbon (C_{mic}) was determined by the substrate-induced respiration method of Anderson and Domsch (1978), while basal soil respiration (BSR) was measured according Anderson (1982). Dehydrogenase activity (DHA) was analyzed following Pepper (1995), and catalase activity (CA) was measured using the Beck method (Beck, 1971). The C_{mic}/C_{org} ratios (The microbial biomass C to total organic C ratio) and metabolic quotient (qCO_2) calculated by dividing the CO_2-C released from the sample in 1 h by the biomass C content, were also obtained (ŠantruuČková and SiraŠicraba, 1991).

Data Analysis

The data from the physical, chemical, and biological analyses were compiled to assess the variability of soil properties across different sites. The suitability of Chernozem soils for specific crops, including wheat, barley, potatoes, corn, and soybeans, was evaluated by examining nutrient levels and other soil characteristics in each sample. Sustainable fertilization recommendations were developed by identifying nutrient limitations and proposing strategies to address deficiencies for optimal crop growth.

Results and Discussion

In this study, the fertility status of the Chernozem soils collected from the Kostanay region of Kazakhstan was determined by analyzing their physical, chemical, and biological properties, as shown in Table 2.

Table 2. Physical, Chemical, and Biological Properties of Chernozem Soils Collected from the Kostanay Region of Kazakhstan

Parameters (n=12)	Minimum	Maximum	Average
Clay, %	15,63	59,50	41,02
Silt, %	13,05	31,38	22,45
Sand, %	22,58	71,32	36,53
pH	6,01	7,50	6,79
Electrical Conductivity, µS cm^{-1}	151,40	628,70	304,30
Organic Matter, %	3,07	5,81	4,49
$CaCO_3$, %	0,14	1,45	0,40
C/N ratio	5,93	10,88	7,92
Nutrient Content of the Soils			
Total N, %	0,24	0,44	0,33
Available P, mg kg^{-1}	3,03	14,79	6,58
Available K, mg kg^{-1}	240,17	963,18	619,33
Available Ca, mg kg^{-1}	1668,60	8022,16	3775,42
Available Mg, mg kg^{-1}	678,61	3258,72	2453,98
Available Fe, mg kg^{-1}	0,70	11,47	4,29
Available Cu, mg kg^{-1}	0,20	0,47	0,34
Available Zn, mg kg^{-1}	0,98	16,68	7,13
Available Mn, mg kg^{-1}	0,27	1,18	0,62
Exchangeable Cations			
Exchangeable Ca, me $100g^{-1}$	8,34	40,11	18,88
Exchangeable Mg, me $100g^{-1}$	5,66	27,16	20,45
Exchangeable Na, me $100g^{-1}$	0,95	2,25	1,24
Exchangeable K, me $100g^{-1}$	0,62	2,47	1,59
Exchangeable Na Percentage (ESP), %	1,78	4,96	3,05
Ca/K ratio	6,62	37,26	13,57
Mg/K ratio	3,49	26,78	15,06
Biological Properties			
Basal soil respiration (BSR), mg CO_2 g^{-1} $24h^{-1}$	0,008	0,067	0,026
Microbial biomass carbon (C_{mic}), mg C g^{-1} $24h^{-1}$	11,566	24,207	16,310
C_{mic}:C_{org}	0,450	0,937	0,636
Metabolic coefficient (qCO_2)	0,001	0,005	0,002
Dehydrogenase activity (DHA), µgTPF g^{-1} $24h^{-1}$	26,140	56,692	43,792
Catalase activity (CA), ml O_2 g^{-1} $3min^{-1}$	127,792	267,080	202,391

Soil Physical Properties

- The Chernozem soils from the Kostanay region exhibited a range of textures, as shown in Table 2. Clay content ranged from 15.63% to 59.50% (average 41.02%), silt content from 13.05% to 31.38% (average 22.45%), and sand content from 22.58% to 71.32% (average 36.53%). These results indicate that the predominant soil texture is clay or sandy clay loam, which is beneficial for water retention and nutrient-holding capacity, essential for supporting crop growth (USDA, 2001).

Soil Chemical Properties

- **pH and Electrical Conductivity (EC):** The pH of the soil samples varied from 6.01 to 7.50 (average 6.79), indicating slightly acidic to neutral conditions. Electrical conductivity (EC) ranged from 151.40 to 628.70 µS cm^{-1} (average 304.30 µS cm^{-1}), confirming non-saline conditions (<980 µS cm^{-1}) suitable for crop production (USDA, 2001).

- **Organic Matter and $CaCO_3$ Content:** The organic matter content ranged from 3.07% to 5.81% (mean 4.49%), indicating sufficient levels (>3%) for maintaining soil fertility. The $CaCO_3$ content was low, ranging from 0.14% to 1.45% (mean 0.40%), classifying the soils as non-calcareous (<2%), which supports better nutrient availability (Hazelton and Murphy, 2007).

Nutrient Content Analysis

- **Total Nitrogen (N) and C/N Ratio:** The total nitrogen content ranged from 0.24% to 0.44% (mean 0.33%), which is sufficient (>0.25%) for supporting plant growth. The average C/N ratio was 7.92, reflecting balanced decomposition rates and nutrient availability (Hazelton and Murphy, 2007).
- **Phosphorus (P):** vailable phosphorus was consistently low, ranging from 3.03 to 14.79 mg kg^{-1} (mean 6.58 mg kg^{-1}), indicating a limitation for optimal crop production (<8 mg kg^{-1}). This deficiency could restrict root growth and reduce yield potential (Hazelton and Murphy, 2007).
- **Potassium (K), Calcium (Ca), and Magnesium (Mg):** Available potassium levels varied from 240.17 to 963.18 mg kg^{-1} (mean 619.33 mg kg^{-1}). Calcium ranged from 1668.60 to 8022.16 mg kg^{-1} (mean 3775.42 mg kg^{-1}), and magnesium from 678.61 to 3258.72 mg kg^{-1} (mean 2453.98 mg kg^{-1}). High levels of potassium, calcium, and magnesium (>250 mg kg^{-1}, >2860 mg kg^{-1}, and >115 mg kg^{-1}, respectively) support plant structure and stress resistance. However, imbalances in the Ca/K and Mg/K ratios could affect nutrient uptake efficiency. Although these levels are generally sufficient, the Ca/K and Mg/K ratios, averaging 13.57 and 15.06 respectively, highlight potential imbalances that may influence nutrient absorption. Ideal Ca/K and Mg/K ratios are typically lower (optimum Ca/K ratio is 12, and Mg/K ratio is 2), suggesting that these imbalances could impact plant growth and nutrient uptake (Hazelton and Murphy, 2007).
- **Micronutrients:** Available Fe levels ranged from 0.70 to 11.47 mg kg^{-1} (mean 4.29 mg kg^{-1}), and Mn levels ranged from 0.27 to 1.18 mg kg^{-1} (mean 0.62 mg kg^{-1}), both indicating potential deficiencies (<4.5 mg Fe kg^{-1} and <14 mg Mn kg^{-1}). Zn (mean 7.13 mg kg^{-1}) and Cu (mean 0.34 mg kg^{-1}) levels were sufficient (>0.7 mg Zn kg^{-1} and >0.2 mg Cu kg^{-1}) for plant health (Lindsay and Norvell, 1978).

Soil Biological Properties

- **Basal Soil Respiration (BSR)**: BSR ranged from 0.008 to 0.067 mg CO_2 g^{-1} $24h^{-1}$ (average 0.026 mg CO_2 g^{-1} $24h^{-1}$), reflecting energy utilization by soil microflora and indicating the efficiency of organic carbon breakdown, despite some debate over its interpretation (Wardle and Ghani, 1995).
- **Microbial Biomass Carbon (C_{mic})**: C_{mic} values ranged from 11.57 to 24.21 mg C g^{-1} (average 16.31 mg C g^{-1}). Microbial biomass carbon plays a vital role as a component of soil organic matter and is integral to the biogeochemical cycling of essential nutrients (C, N, P, S) and related energy flows (Smith and Paul, 1990; Meli et al., 2002; Kızılkaya et al., 2004).
- **C_{mic} : C_{org} Ratio and Metabolic Quotient (qCO_2)**: The C_{mic} : C_{org} ratio (average 0.636) and the metabolic quotient (qCO_2) (average 0.002) suggest that while the microbial community is present and functional, it operates with limited efficiency, potentially affecting nutrient mineralization (Hart et al., 1989; Anderson and Domsch, 1989; Insam et al., 1989). The qCO_2, which assesses specific microbial respiration, shows that lower values indicate higher efficiency per unit of microbial biomass. The average value of 0.002 aligns with studies indicating efficient carbon use but slower organic matter decomposition rates (Wardle and Ghani, 1995; Kızılkaya and Hepşen, 2007).
- **Dehydrogenase and Catalase Activity**: Dehydrogenase activity (DHA), which ranged from 26.14 to 56.69 µg TPF g^{-1} $24h^{-1}$ (average 43.79 µg TPF g^{-1} $24h^{-1}$), was high, suggesting active metabolic processes (Gong, 1997; Obbard, 2001; Kızılkaya, 2008). Catalase activity (CA) varied from 127.79 to 267.08 ml O_2 g^{-1} $3min^{-1}$ (average 202.39 ml O_2 g^{-1} $3min^{-1}$), further indicating strong aerobic microbial activity (Pascual et al., 1998; Durmuş and Kızılkaya, 2022; Toor et al., 2024).

In recent years, the results of soil fertility analyses conducted in the Kostanay region show similarities with the findings of this study. However, when compared to data from past decades, a declining trend in organic matter content has been observed. This can be attributed to several factors, including agricultural practices, climate conditions, and soil management strategies. Long-term monoculture cropping can lead to soil fatigue and reduced organic matter (Belete and Yadete, 2023). Continuous tillage and soil disturbance are significant contributors to organic matter loss. Furthermore, extensive and non-analysis-based use of chemical fertilizers can disrupt natural soil biological cycles, leading to a decline in organic matter levels. The sufficient inorganic nitrogen and a C/N ratio of approximately 7.9 in mature plant areas support this observation. This can hinder the regeneration of organic matter in the soil over time, leading to further declines. Additionally, the inadequate retention or removal of plant residues post-harvest may contribute to the reduction in organic matter levels.

In this study, which aimed to evaluate the biological properties of Chernozem soils in Kazakhstan's Kostanay region, it was determined that the soils had sufficient levels of biological activity. The high catalase activity indicated robust aerobic microbial processes. However, the C_{mic} : C_{org} ratio and the qCO_2 values were found to be relatively low, suggesting limited microbial biomass. This observation implies that, while the microbial population is present, it does not actively decompose organic material at a rapid rate. This can be advantageous, as it indicates that the existing organic matter is not rapidly depleted. However, in agricultural contexts, this limitation may pose a challenge for nutrient mineralization and availability, potentially impacting crop productivity.

Plant Nutrition Strategies

he development of targeted plant nutrition strategies is crucial for maximizing crop productivity and maintaining soil health, especially in regions like the Kostanay area where nutrient imbalances and environmental challenges can significantly impact agricultural outcomes. Considering the nutrient content of the Chernozem soils and their effects on plant growth, appropriate strategies are essential. In Kazakhstan's Kostanay region, the main crops grown in Chernozem soils are wheat, barley, potatoes, corn, and soybeans. Table 3 presents the amounts of nutrients removed by these crops and the levels of plant-available nutrients in the region's Chernozem soils.

Table 3. Nutrient removal by major crops and available nutrient content in Chernozem soils of the Kostanay region

Crops	**N, kg ha^{-1}**	**P_2O_5, kg ha^{-1}**	**K_2O, kg ha^{-1}**	**CaO, kg ha^{-1}**	**MgO, kg ha^{-1}**
Wheat	190	80	250	40	40
Barley	120	50	220	40	40
Potatoes	500	200	600	200	100
Corn	770	140	390	180	70
Soybeans	250	130	280	60	60
Chernozem Soils	418 (299 – 556)*	38 (17 – 85)*	1870 (724 – 2902)*	13214 (5840-28078)*	10225 (2827-13578)*

* Values in parentheses represent the minimum and maximum nutrient levels in the Chernozem soils of the region.

An analysis of the available nutrient content in Chernozem soils and the nutrient uptake by crops during a growing season (Table 3) reveals that phosphorus is insufficient for all crops, and nitrogen is inadequate for potatoes and corn. Potassium, calcium, and magnesium levels are adequate for all crops, but their balance is skewed. The ideal Ca/K ratio is 12, but in Chernozem soils, it averages 13.57. Similarly, the ideal Mg/K ratio is 2, but it averages 15.06 in these soils. This indicates that despite adequate potassium levels, crops—especially potatoes and corn—may respond positively to potassium fertilization. Therefore, phosphorus and potassium among the macronutrients, and manganese and iron among the micronutrients, are identified as critical nutrients for crop cultivation in the region.

The study emphasizes that maintaining soil organic matter, which has declined over the years, should be central to fertilization programs for Kostanay's Chernozem soils. Intensive nitrogen fertilization could narrow the C/N ratio, accelerating the mineralization of soil organic matter. Therefore, careful nitrogen management is required, and phosphorus and potassium fertilizers should be applied during seeding. Instead of chemical fertilizers, using liquid or solid organic or organomineral P and K fertilizers is recommended. This practice helps maintain soil organic matter and promotes environmentally sustainable agriculture.

The application of liquid organomineral PK fertilizers, which contain no carrier materials, could offer a more conservation-focused approach. Liquid organomineral fertilizers offer several advantages over granulated types (Paré et al., 2010; Šarauskis et al., 2021; de Melo Benites et al., 2022; Sobreira et al., 2024):

- **Enhanced Nutrient Availability:** Liquid fertilizers are already dissolved, allowing immediate nutrient uptake by plant roots. This promotes faster and more effective absorption, especially during critical early growth stages.
- **Reduced Dependence on Water:** Granulated fertilizers need soil moisture to dissolve, which can be challenging under water-limited conditions. Liquid fertilizers provide nutrients directly, reducing reliance on external water sources. This is particularly important given the increasing frequency of droughts and irregular rainfall patterns due to climate change.

- **Adaptation to Climate Challenges:** Global warming leads to prolonged dry periods and reduced water availability, hindering traditional fertilization methods. Liquid organomineral fertilizers ensure essential nutrients are accessible to crops even under suboptimal moisture conditions.
- **Ease of Application:** Liquid fertilizers can be applied through existing irrigation systems or sprayed directly on the soil surface, saving time and ensuring uniform nutrient distribution.

Given the limitations of granulated fertilizers—particularly their dependency on sufficient moisture for nutrient release—liquid organomineral fertilizers offer a resilient alternative suitable for the changing climate. They provide immediate nutrient availability, enhance nutrient use efficiency, and contribute to long-term soil health by adding organic matter. This reduces nutrient leaching and supports microbial activity, which is essential for sustained soil fertility. Additionally, the insufficient levels of manganese and iron are significant barriers to achieving desired yields in crop production. Therefore, foliar application of these micronutrients is necessary. Supplementing nitrogen through foliar feeding along with micronutrients can significantly boost plant production while helping preserve soil organic matter.

Conclusion

This study reveals the critical nutrient imbalances in the Chernozem soils of Kazakhstan's Kostanay region and highlights the need for targeted fertilization strategies to optimize crop productivity and promote long-term soil health. The findings underscore the widespread deficiency of phosphorus for all major crops, with additional nitrogen deficits observed specifically in potatoes and corn. While potassium, calcium, and magnesium levels are generally sufficient, the skewed Ca/K and Mg/K ratios suggest that crops, particularly high-demand species like potatoes and corn, may still respond positively to supplemental potassium.

Sustaining soil organic matter, which has shown a declining trend in recent years, must be a primary consideration in developing fertilization programs for this region. Excessive nitrogen applications risk narrowing the C/N ratio, accelerating organic matter decomposition. Therefore, careful nitrogen management, combined with phosphorus and potassium fertilization at seeding, is essential to balance crop needs with soil conservation. Implementing liquid or solid organic and organomineral P and K fertilizers offers a more sustainable alternative to traditional chemical fertilizers, helping to maintain soil structure and organic content over time.

The study also identifies the low levels of micronutrients, particularly manganese and iron, as significant barriers to achieving optimal yields. Foliar application of these nutrients, combined with nitrogen, is recommended to enhance plant growth and reduce reliance on soil-stored nutrients, further aiding in the preservation of organic matter.

These recommendations aim to improve short-term crop productivity while fostering sustainable soil management practices. Implementing this comprehensive approach—balancing nutrient inputs, conserving organic matter, and addressing micronutrient deficiencies—ensures the long-term sustainability and productivity of the Chernozem soils in Kostanay and similar regions facing climate and environmental challenges.

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