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# ORGANO-MINERAL FERTILIZATION STRATEGY FOR ENHANCING *MALUS DOMESTICA* GROWTH, YIELD, AND SHELF LIFE IN SOUTHEASTERN KAZAKHSTAN

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## SUMMARY

This study explored the benefits of organo-mineral fertilization to unlock the full potential of 'Golden Delicious' (*Malus domestica* L. Borkh.) apple cultivation in Southeastern Kazakhstan's irrigated chestnut soils. The research focused on assessing its effects on tree growth, fruit productivity, and the rhizosphere microbial activity. Field experiments conducted between 2021 and 2025 investigated the effects of various fertilization strategies on 3–4-year-old apple trees grafted on both MM106 and M9 rootstocks. The experimental design included an unfertilized control group, a mineral fertilization treatment ($N_{90}P_{90}K_{90}$), and several organo-mineral combinations incorporating Agroflorin, Al-Karal, BioSok Energy Plus, and vermicompost. Findings revealed organo-mineral fertilization significantly improved both the yield and quality of apple fruits, alongside enhanced storage performance. Specifically, the apple fruit yield saw a substantial increase of 39%–64% over the control group. Furthermore, soluble sugar and dry matter content rose by up to 1.9% and 1.5%, respectively. In light chestnut soils, a combination of vermicompost and BioSok Energy Plus fertilization delivered exceptional results for apple production. This treatment achieved the highest fruit yield, reaching 29.5 t per hectare, and remarkably extended shelf life to a full six months. Beyond these direct benefits, the fertilization also fostered a healthier soil environment by considerably increasing *Azotobacter* and *Pseudomonas* populations in the rhizosphere. This indicates a more robust nutrient cycle and heightened soil biological activity, confirming organo-mineral fertilization as a highly effective and sustainable strategy.

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**Keywords:** Apple (*M. domestica* L.), Golden Delicious, organo-mineral fertilization, apple productivity, rhizosphere microorganisms, soil-plant interaction, fruit quality

**Key findings:** This research demonstrated organo-mineral fertilization significantly enhances apple (*M. domestica* L.) fruit yield. Yields increased by an impressive 39%–64% compared with the unfertilized control. The optimal fertilization strategy for maximizing fruit productivity involved combining NPK with vermicompost and BioSok Energy Plus.

## INTRODUCTION

Apple (*Malus domestica* L. Borkh.) is one of the most economically important fruit crops cultivated in temperate and semi-arid regions worldwide. Orchard productivity, fruit quality, and post-harvest performance received considerable influences from soil fertility, water availability, and the physiological status of the tree. In irrigated orchard systems, sustainable nutrient management is crucial for maintaining tree growth and development, enhancing fruit yield, improving the biochemical composition of the fruit, and ensuring long-term soil productivity (Wang *et al*., 2016; Hoagland *et al*., 2019; Kapłan *et al*., 2023).

In Central Asia, apple orchards attain increasing exposure to various abiotic stresses, including elevated summer temperatures, intermittent water deficits, and low soil organic matter. These factors significantly impair nutrient uptake (Zhapayev *et al.,* 2023a, 2023b), hinder growth and development, and adversely impact fruit size, sugar accumulation, and shelf-life potential (Kunypiyaeva *et al.,* 2023a, 2023b). These challenges are particularly acute in the chestnut soils of Southeastern Kazakhstan (Budiman *et al*., 2017). The soils' characteristics include low organic carbon content (1.0%–1.5%), an alkaline reaction, weak aggregation, and limited biological buffering capacity, which collectively lead to reduced microbial activity and nutrient cycling efficiency (Gu *et al*., 2019; Holik *et al*., 2019).

Prolonged dependence on mineral fertilizers in intensive orchard management frequently leads to soil structural degradation and substantially reduces nutrient use efficiency. Biological soil fertility has reached a recognition as a key driver in enhancing crop productivity and maintaining ecosystem stability. Soil microorganisms play a pivotal role in regulating carbon and nitrogen cycling, solubilizing nutrients, and promoting root growth and stress resistance through various biochemical and hormonal mechanisms occurring in the root zone (Assefa and Tadesse, 2019; Shaji *et al*., 2021; Bamdad *et al*., 2022).

Organic and bio-based fertilizers significantly enhanced soil organic matter turnover, microbial diversity, and enzymatic activity, thereby improving nutrient availability and plant uptake (Zhang *et al*., 2019; Lin *et al*., 2019; Sun *et al*., 2023). In apple orchards, the rhizosphere microbiome is critical in nutrient acquisition, tree physiological performance, and fruit growth and development. Previous studies demonstrated that bio-organic and organo-mineral fertilization substantially improved apple fruit yield and quality by enhancing nitrogen fixation, phosphorus mobilization, and hormone-mediated root development (Aslantaş *et al*., 2007; Wang *et al*., 2016; Zhao *et al*., 2023; Yan *et al*., 2024).

Although the Golden Delicious apple cultivar is a prized and widely grown crop in Southeastern Kazakhstan owing to its high market value, it faces challenges related to soil fertility and rhizosphere microbial activity. Fortunately, integrated mineral and biological fertilization has shown promise in overcoming these limitations, leading to improved stress tolerance, enhanced carbohydrate accumulation, greater dry matter content, and a longer fruit shelf life (Kapłan *et al*., 2023; Ozherelieva *et al*., 2025).

As advances in fertilization practices are evident, a critical gap exists in our understanding of how organo-mineral fertilization specifically influences apple productivity and rhizosphere microbial communities in the irrigated chestnut soils found in Central Asia. This study therefore sought to investigate these combined effects, focusing on the growth, fruit yield and quality, storage capabilities, and rhizosphere microbial activity of 'Golden Delicious' apple trees cultivated on these particular soil types in Southeastern Kazakhstan.

## MATERIALS AND METHODS

### Study area and soil conditions

From 2021 to 2025, field experiments took place on apple trees (*M. domestica* L.) within a commercial orchard located in the Talgar District of the Almaty Region, Southeastern Kazakhstan (43°18′ N, 77°12′ E). The experimental site has a sharply continental climate, featuring hot, dry summers and cold winters. The mean annual air temperature is approximately 9.5 °C–10.5 °C, with summer highs frequently exceeding 30 °C and winter temperatures often dropping below −20 °C. Annual precipitation ranges from 400 to 500 mm, with the majority falling during spring and early summer. With insufficient rainfall throughout the growing season, drip irrigation has proven essential for maintaining stable soil moisture levels in apple orchards.

The soil at the experimental site has an irrigated chestnut loam classification, a soil type common in semi-arid regions. This soil is characteristically low in organic carbon, with weak aggregation and moderate biological activity. The collected composite soil samples (0–20 cm) underwent analysis to establish the baseline soil fertility status. The analysis revealed 1.3% humus, a slightly alkaline pH (7.6 in water), low available phosphorus, and medium exchangeable potassium. These soil conditions are representative of many apple-growing areas in Southeastern Kazakhstan. The inherent limitations in nutrient availability and biological buffering capacity make this site a valuable setting for assessing the efficacy of organo-mineral fertilization strategies.

### Plant material and orchard management

The study on apple (*M. domestica* L. cv. Golden Delicious) had the trees grafted onto clonal rootstocks MM106 and M9. These rootstocks are widely applicable in intensive orchard systems due to their moderate vigor and excellent compatibility with Golden Delicious.

The experiment commenced with apple trees aged 3–4 years, already in their early commercial bearing stage. The orchard, established at a spacing of 5 m × 2 m, supported a planting density of 1250 trees per hectare. In guaranteeing optimal conditions, employment of drip irrigation ran throughout the growing season, sustaining soil moisture levels at 70%–80% of field capacity. This practice effectively prevented water stress from hindering tree growth, fruit bearing, and overall development. Furthermore, all standard orchard management practices, including pruning, pest control, and weed management, entailed uniform application across the treatments. The visual representation of the orchard layout, tree canopy structure, and fruit load under this experimental management appears in Figure 1.

### Experimental design and fertilization treatments

The investigation of the effects of various fertilization strategies had a structure of the experiment in a randomized complete block design with three replications. Each experimental plot comprised a group of uniform trees, with border rows incorporated to minimize potential edge effects. Six fertilization treatments reached their evaluation: a) control (no fertilizers), b) mineral fertilization ($N_{90}P_{90}K_{90}$), c) NPK + Agroflorin, d) NPK + Al Karal, e) NPK + BioSok Energy Plus, and f) NPK + vermicompost. Mineral fertilizers' application was in two split doses—once in early spring before active vegetative growth and again after flowering during the period of intensive fruit set and shoot elongation. These

**Figure 1.** Organic apple orchard: tree canopy structure and fruit load enhanced under biologically enriched soil
(The pomological orchard of the Talgar Republican Branch of LLP ‘Kazakh Research Institute of Fruit and Vegetable Growing).

readily available forms of nitrogen, phosphorus, and potassium helped meet the nutritional requirements of the apple trees. Table 1 summarizes the fertilizer rates, application timing, and methods for all treatments.

Assessing different fertilization strategies had the application of Agroflorin, Al Karal, and BioSok Energy Plus following their manufacturers’ recommendations. These products succeeded in their utilization through both root and foliar applications during the growing season, with the specific aim of stimulating root development, enhancing microbial activity, and optimizing physiological processes within the apple trees. Additionally, vermicompost incorporation into the tree rows occurred. This organic amendment, as applied, had a rate equivalent to the nitrogen supplied by the mineral fertilization treatment, thereby providing a crucial source of organic nutrients and organic matter. The experimental design sought to facilitate a comprehensive comparison of purely mineral, purely organic, and integrated organo-mineral fertilization strategies, evaluating their respective impacts on apple tree performance and the biological properties of the soil.

**Yield and fruit quality assessment**

Annual apple yield recording transpired at harvest, with its expression as kilograms per tree and tons per hectare. Fruit composition and quality evaluation continued through standard laboratory determination of soluble sugar content (%) and dry matter (%). The assessment of postharvest performance comprised fruits from each treatment stored in controlled conditions maintained between +2 °C and +4 °C. Storage life quantification was the maximum duration for which fruits retained marketable quality. All collected data underwent the analysis of variance (ANOVA), with treatment means subsequently compared using the least significant difference ($LSD_{0.05}$) test.

**Soil microbiological analysis]**

Rhizosphere soil samples’ collection came from the 0–20 cm layer beneath Golden Delicious trees in each treatment. In ensuring comparability, sampling occurred at the same phenological stage annually. Afterward, composite samples reached preparation from multiple subsamples taken from the root zone of each apple tree.

**Table 1.** Fertilizer rates and application schemes in the apple orchard experiment.

| Treatment | Fertilizer / product | Rate | Time of application | Method of application |
|---|---|---|---|---|
| Control | – | – | – | – |
| NPK ($N_{90}P_{90}K_{90}$) | Nitrogen (urea/ammonium nitrate) | 90 kg N $ha^{-1}$ $yr^{-1}$ | 50% early spring; 50% after flowering | Soil application in tree rows |
| | Phosphorus ($P_2O_5$) | 90 kg $P_2O_5$ $ha^{-1}$ $yr^{-1}$ | Early spring | Soil application |
| | Potassium ($K_2O$) | 90 kg $K_2O$ $ha^{-1}$ $yr^{-1}$ | After flowering | Soil application |
| NPK + Agroflorin | Mineral NPK | As above | As above | Soil |
| | Agroflorin | 2.5 mL $L^{-1}$ (spray solution) | Root treatment before planting; foliar sprays at bud break and fruit set | Root dipping and foliar spraying |
| NPK + Al Karal | Mineral NPK | As above | As above | Soil |
| | Al Karal | 300 mL per 50 L water | Two foliar sprays: after flowering and during early fruit growth | Foliar spraying |
| NPK + BioSok Energy Plus | Mineral NPK | As above | As above | Soil |
| | BioSok Energy Plus | 300 mL per 5 L water | Root treatment before planting; two foliar sprays during vegetative growth | Root and foliar application |
| NPK + vermicompost | Mineral NPK | As above | As above | Soil |
| | Vermicompost | Equivalent to 90 kg N $ha^{-1}$ | Applied in spring before bud break | Incorporated into tree rows |

Mineral fertilizers were applied at a rate of $N_{90}P_{90}K_{90}$ kg $ha^{-1}$ per year, split between early spring and post-flowering stages, while biological products and vermicompost application were according to the schedule shown in Table 1.

Microbiological analyses proceeded utilizing established culture-based methodologies. Total microbial populations entailed quantification on meat-peptone agar. Specifically, nitrogen-fixing bacteria belonging to the genus *Azotobacter* gained enumeration on Ashby's nitrogen-free medium. *Pseudomonas* species received culturing and identification on King B medium. Amylolytic bacteria determination occurred on starch-ammonia agar, with microscopic fungi enumerated on Czapek–Dox medium. Post-incubation, all colonies sustained counting before expressing as colony-forming units (CFU) per gram of dry soil. These quantitative assessments enabled an evaluation of the response of critical functional groups, essential for nutrient cycling and soil fertility, under varying fertilization regimes.

## RESULTS AND DISCUSSION

The application of organo-mineral fertilizers demonstrated a robust positive effect on the productivity and quality of apple (*M. domestica* L.) fruits. Specifically, treatments that combined mineral and organic inputs led to a significant enhancement in apple fruit yield. Yield increased from 180 t $ha^{-1}$ in the unfertilized control group to an impressive 295 t $ha^{-1}$ when applying NPK + vermicompost together (Wang *et al*., 2016; Kapłan *et al*., 2023; Kunypiyaeva *et al*., 2023a, 2023b; Zhapayev *et al*., 2023d). The impact of different fertilization systems on apple fruit yield is available in Figure 2. Results indicate that organo-mineral fertilization regimes led to substantial improvements in fruit quality. Specifically, soluble sugar content rose by as

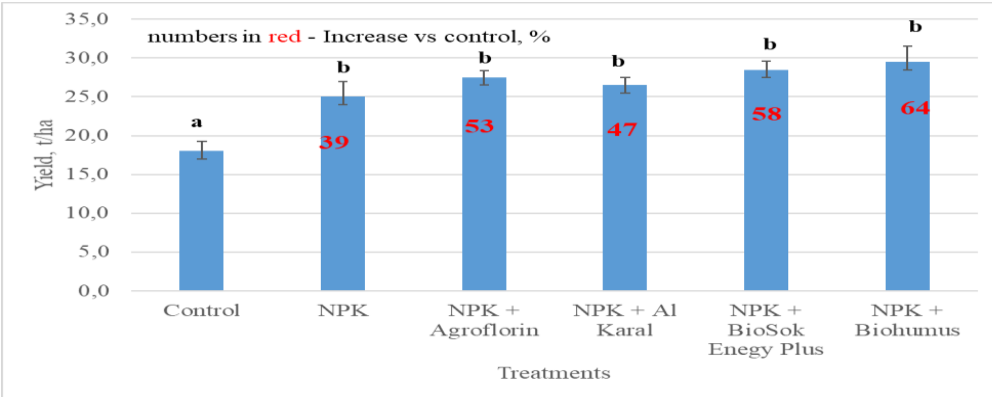


**Figure 2.** Effects of organo-mineral fertilization on the yield of *Malus domestica* cv. Golden Delicious. Bar chart showing apple yield (t $ha^{-1}$) under different fertilization systems. Error bars indicate standard error (n = 3).

**Table 2.** Effects of organo-mineral fertilization on yield and fruit quality of *Malus domestica* cv. Golden Delicious.

| Treatment | Yield (t $ha^{-1}$) | Total sugars (%) | Dry matter (%) | Storage life (months) |
|---|---|---|---|---|
| Control | 18.0 ±8 | 10.2 ±0.2 | 13.8 ±0.3 | 4.0 |
| NPK ($N_{90}P_{90}K_{90}$) | 25.0 ±10 | 11.0 ±0.2 | 14.3 ±0.2 | 5.0 |
| NPK + Agroflorin | 27.5 ±12 | 11.6 ±0.3 | 14.8 ±0.3 | 5.5 |
| NPK + Al Karal | 26.5 ±11 | 11.4 ±0.3 | 14.6 ±0.3 | 5.3 |
| NPK + BioSok Energy Plus | 28.5 ±13 | 11.9 ±0.3 | 15.0 ±0.3 | 5.8 |
| NPK + vermicompost | 29.5 ±14 | 12.1 ±0.4 | 15.3 ±0.3 | 6.0 |
| LSD ($P \leq 0.05$) | 4.3 | 1.1 | 1.1 | 1.0 |

Note: Values are means ± standard error (n = 3).

much as 1.9%, and dry matter increased by 1.5%. Crucially, these regimes also extended the storage life of the fruit from four to six months (Zhapparova *et al.*, 2023; Ozherelieva *et al.*, 2025; Myrzabaeva *et al.*, 2025). A detailed summary of these outcomes appears in Table 2.

The treatment with mineral fertilizers alone, specifically $N_{90}P_{90}K_{90}$, proved effective in increasing fruit yield to 250 t $ha^{-1}$. This outcome confirms that nitrogen, phosphorus, and potassium play a direct role in supporting vegetative growth and fruit formation. However, the integration of biological and organic components led to a significantly more pronounced response. Combining NPK fertilizer with Agroflorin, Al Karal, BioSok Energy Plus, and vermicompost further elevated fruit yield to a range of 265–295 t $ha^{-1}$. Notably, the highest yields emerged with the NPK + vermicompost treatment (295 t $ha^{-1}$) and the NPK + BioSok Energy Plus treatment (285 t $ha^{-1}$). These results are consistent with previous studies investigating the benefits of organo-mineral fertilization in apple plantations (Wang *et al*., 2016; Hoagland *et al*., 2019).

Improved tree physiological activities explain these apple fruit yield gains. Previous orchard studies have shown that bio-organic fertilization enhances leaf area development, chlorophyll content, and photosynthetic rate in apple trees. This leads to an increased assimilate production and a robust sink-source relationship (Aslantaş *et al*., 2007; Kapłan *et al*., 2023). In this latest experiment, an observed rise in shoot length and trunk

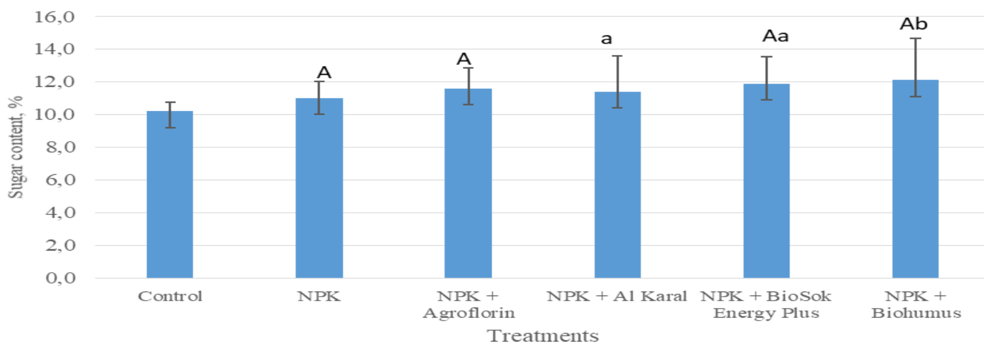


**Figure 3.** Effects of fertilization systems on total sugar content of apple fruits.
Total sugars (%) in fruits of *Malus domestica* cv. Golden Delicious under various mineral and organo-mineral treatments.

diameter with organo-mineral treatments indicated more vigorous vegetative growth and development and a larger photosynthetically active canopy.

The fruits' biochemical composition and overall quality showed a parallel response to improvements in physiological activities. Specifically, soluble sugar concentration increased from 10.2% in the control treatment to 12.1% when applying the NPK + vermicompost fertilizers. Concurrently, dry matter content rose from 13.8% to 15.3%, respectively. This enhanced sugar accumulation, illustrated in Figure 3, indicates a greater capacity for photosynthetic carbon assimilation and more efficient translocation of carbohydrates from the leaves to the fruits. Research in apple orchards has similarly linked augmentations in sugar and dry matter content under organic and bio-organic fertilization to enhanced nutrient uptake and heightened leaf metabolic activities (Wang *et al*., 2016; Kapłan *et al*., 2023).

Fruits treated with organo-mineral solutions demonstrated a remarkable increase in storage life, extending from four months in the control group to six months. This extended shelf life is a direct result of higher dry matter content and a more favorable mineral balance, particularly in potassium and calcium. These key minerals are crucial for fortifying cell walls and ensuring membrane stability, which, in turn, boosts fruit firmness and postharvest resilience against physiological disorders (Kapłan *et al*., 2023; Yan *et al*., 2024). Therefore, the observed improvement in storability is consistent with the enhanced physiological status of the apple trees and the ameliorated biochemical profile of the harvested fruits.

Supporting these physiological processes was the crucial activity of rhizosphere microorganisms. Table 3 illustrates that biological treatments and organo-mineral fertilization led to an approximate 2- to 2.5-fold increase in total bacterial populations. Among these, *Azotobacter* and *Pseudomonas* populations demonstrated particularly significant responses. The NPK + BioSok Energy Plus treatment yielded the highest *Pseudomonas* densities, reaching up to 4.0 × $10^6$ CFU $g^{-1}$ soil, with the NPK + vermicompost treatment showing the next highest. These beneficial bacteria are commonly playing vital roles, including phosphorus solubilization, phytohormone production, and substantial root growth stimulation. Consequently, they enhance nutrient uptake and improve the photosynthetic efficiency of apple trees (Wang *et al*., 2016; Zhao *et al*., 2023; Yan *et al*., 2024). The effects of different fertilization systems on rhizosphere microbial populations are available in Figure 4.

Boosting *Azotobacter* populations is the key to amplifying biological nitrogen fixation in the rhizosphere. This natural process effectively complements mineral nitrogen, driving sustained leaf growth, development,

**Table 3.** Rhizosphere microbial populations under various fertilization systems (CFU $g^{-1}$ dry soil).

| Treatment | Total bacteria ($\times 10^6$) | *Pseudomonas* ($\times 10^6$) | Amylolytic bacteria ($\times 10^5$) | *Azotobacter* ($\times 10^4$) | Microscopic fungi ($\times 10^4$) |
|---|---|---|---|---|---|
| Control | 1.03±0.10 | 1.2±0.01 | 1.1±0.03 | 0.9±0.02 | 1.4±0.03 |
| NPK | 1.45±0.12 | 1.6±0.02 | 1.5±0.04 | 1.2±0.03 | 1.6±0.04 |
| NPK + Agroflorin | 2.20±0.15 | 2.8±0.03 | 1.9±0.05 | 2.1±0.04 | 2.3±0.05 |
| NPK + Al Karal | 2.10±0.14 | 2.5±0.03 | 1.8±0.04 | 2.0±0.04 | 2.2±0.05 |
| NPK + BioSok Energy Plus | 2.40±0.10 | 4.0±0.01 | 2.0±0.05 | 2.3±0.03 | 2.6±0.04 |
| NPK + vermicompost | 2.30±0.12 | 3.6±0.02 | 1.9±0.04 | 2.2±0.03 | 2.5±0.04 |

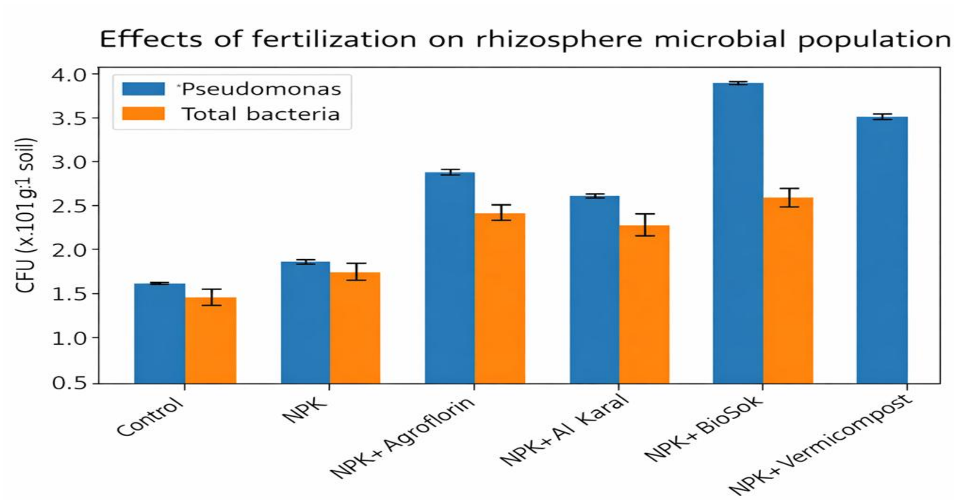


**Figure 4.** Effects of fertilization systems on rhizosphere microbial populations of *Malus domestica* cv. Golden Delicious. Bars show population densities of *Pseudomonas* spp. and total bacteria (CFU × $10^6$ $g^{-1}$ dry soil) under various fertilization treatments. Error bars indicate standard error (n = 3).

and chlorophyll synthesis. Moreover, a more vibrant and diverse microbial community accelerates organic matter decomposition and increases nutrient availability. This creates a powerful positive feedback loop, directly linking enhanced soil biological activity to superior plant physiological performance (Gu *et al*., 2019; Zhang *et al*., 2019).

The enhanced fruit yield, quality, and storage performance observed with organo-mineral fertilization can be ascribable to a synergistic interplay of factors. These include heightened soil biological activity, improved nutrient cycling, and more robust physiological functioning of apple trees. Ultimately, this integrated soil-plant-microbe interaction is the foundation for the boost in productivity and resilience characteristic of apple orchards managed with bio-based fertilization systems (Ye *et al*., 2020; Sivojiene *et al*., 2021; Wang *et al*., 2022).

This study demonstrates that organo-mineral fertilization substantially enhances apple productivity, fruit quality, and rhizosphere biological activity in light chestnut soils. These improvements likely stem from the synergistic interaction of mineral nutrients, organic matter, and biologically active microbial communities, fostering a more efficient and resilient soil-plant system. By directly addressing nutrient limitations, particularly nitrogen, phosphorus, and potassium, mineral fertilizers alone enhanced apple yield. These nutrients are fundamental for optimal leaf development, photosynthesis, and fruit formation. Nevertheless, the more pronounced yield increases observed in organo-mineral treatments highlighted a critical deficiency in relying solely on mineral nutrition for soils with low organic matter and weak biological buffering capacity. The integration of biological products and vermicompost proved more effective because it supplied additional nutrients as well as stimulated the soil's natural biological processes, which are vital for transforming, retaining, and making nutrients available to plants (Sarkar *et al*., 2021; Saljnikov *et al*., 2025).

A key mechanism behind the superior performance of organo-mineral systems lies in their ability to stimulate rhizosphere microbiota. This stimulation fosters a considerable increase in populations of beneficial bacteria like *Azotobacter* and *Pseudomonas*. These enhanced microbial communities are responsible for improved biological nitrogen fixation and phosphorus solubilization, as well as the production of crucial plant growth-promoting substances. Ultimately, these microbial activities lead to better root development and elevated nutrient uptake, thereby expanding the functional root surface area and reinforcing the physiological health of apple trees. Evidence from orchard soils amended with bioorganic fertilizers supports these findings, displaying a direct link between shifts in microbial community structure and both higher apple yields and more efficient nutrient utilization (Wang *et al*., 2016; Zhao *et al*., 2023; Yan *et al*., 2024).

The enhanced biochemical quality of fruits resulting from organo-mineral fertilization can be because of a direct link to improved tree physiological functions. Specifically, higher sugar and dry matter content in the fruits are indicative of heightened photosynthetic carbon assimilation and a more effective translocation of photosynthates from leaves to developing fruits. Supporting this, research by Aslantaş *et al*. (2007) and Kapłan *et al*. (2023) demonstrated that bio-organic amendments increase leaf chlorophyll concentration, boost photosynthetic rates, and promote carbohydrate accumulation in apple fruits. Consequently, the raised dry matter accumulation considerably contributes to improved fruit firmness and its postharvest storability, a benefit clearly reflected in the extended shelf life observed in our study.

Organo-mineral fertilization elevates apple fruit yield and quality as well as fortifies orchards against environmental stresses. This is particularly important for light chestnut soils, which naturally struggle with rapid organic matter depletion and poor soil aggregation, making them prone to drought and nutrient loss. By incorporating organic amendments and stimulating microbial activity, this fertilization approach effectively reconstructs soil structure, increases water-holding capacity, and improves nutrient retention. This biologically mediated stabilization of the soil environment acts as a crucial buffer, protecting apple trees from the adverse effects of climatic fluctuations and establishing itself as a cornerstone of sustainable orchard management in semi-arid regions (Gu *et al*., 2019; Zhang *et al*., 2019; Wang *et al*., 2022).

These results are highly consistent with the global trends toward biologically based orchard management systems. Such approaches endeavor to minimize dependence on purely mineral fertilization, thereby maintaining high productivity and improving fruit quality. By synergistically combining mineral nutrients with organic and microbial inputs, organo-mineral strategies deliver immediate nutrient availability alongside lasting improvements in soil biology. This powerful combination leads to stable, high-quality fruit yields and fosters truly sustainable soil resource management.

The results of this investigation suggest that organo-mineral fertilization constitutes a more sophisticated management strategy for apple orchards rather than simply an alternative to conventional mineral fertilization. This approach is demonstrably advantageous in ecologically sensitive soils, exemplified by the light chestnut soils of Southeastern Kazakhstan. Through the augmentation of soil-plant-microbe interactions, these integrated systems provide a framework for achieving increased productivity, enhanced fruit marketability, and the sustained ecological integrity of orchard environments.

## CONCLUSIONS

For apples (*M. domestica* L.), particularly the cultivar Golden Delicious cultivated on chestnut soils, integrated organo-mineral fertilization has proven to be a powerful tool for improving fruit productivity, quality, and postharvest resilience. Yields saw a remarkable increase of 39%–64% compared with unfertilized controls. Beyond increased production, the fertilization significantly enhanced key quality attributes, including fruit sugar content, dry matter accumulation, and storage longevity. Among the tested treatments, vermicompost and BioSok Energy Plus demonstrated the greatest efficacy. Importantly, organo-mineral fertilization also fostered a healthier soil ecosystem by stimulating the growth of *Azotobacter* and *Pseudomonas*, which, in turn, boosted nutrient cycling and soil biological activity. This integrated approach offers a sustainable and highly efficient solution for apple cultivation in the challenging semi-arid conditions of Central Asia.

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