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Evaluation of foliar biostimulants and micronutrient complexes for improving tomato growth, yield, and fruit quality in Southeastern Kazakhstan

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Abstract

Tomato (*Lycopersicon esculentum* L.) is a vital horticultural crop in Kazakhstan, especially in the southern and southeastern regions, where yields often fall short of their biological potential. This study evaluated the effects of selected foliar-applied biostimulants and micronutrient formulations on vegetative growth, yield, fruit quality, and economic performance of tomato under the agroecological conditions of Southeastern Kazakhstan. The experimental design included seven treatments: six commercial products—Fitolaza, Nano Sulfur, Scudo, Calcium Humate, CompleMet-Tomato, and BioSok Energy—applied individually or in combination, alongside a non-treated control. All treatments improved vegetative parameters such as plant height, stem diameter, leaf number, and total biomass. The T3 treatment (Fitolaza + Nano Sulfur) consistently delivered superior performance across all growth stages and achieved the highest fruit yield (26.10 t/ha), representing a 31.49% increase over the control. T7 (CompleMet-Tomato) and T5 (Calcium Humate) also demonstrated notable yield improvements. Biochemical analyses revealed that these treatments enhanced dry matter, total sugar, and vitamin C content in fruits, while keeping nitrate levels below the permissible threshold. Economic evaluation identified T3 as the most profitable treatment (USD 1,932.99/ha), followed by T7 and T5, with profitability rates exceeding 140%. These results highlight the potential of foliar biostimulant strategies to enhance both productivity and profitability in tomato cultivation, offering a viable path toward more sustainable and resource-efficient horticultural practices.

Keywords: Tomato, biostimulant, foliar fertilizer, yield, fruit quality, economic efficiency, Southeastern Kazakhstan.

Introduction

Tomato (*Lycopersicon esculentum* L.) is one of the most widely cultivated and consumed vegetable crops worldwide, belonging to the Solanaceae family, which includes over 3,000 species (Raiola et al., 2014; Subramaniyan et al., 2023). Its global importance stems from its nutritional, economic, and functional roles (Tambe et al., 2024). Tomato fruits are rich in bioactive compounds such as ascorbic acid, lycopene, β-carotene, flavonoids, and anthocyanins, which are associated with antioxidant properties and multiple human health benefits (Quinet et al., 2019; Li et al., 2018; Ali et al., 2021).

Globally, tomatoes represent about one-seventh of all vegetable production and up to 60–70% of processed fruit and vegetable raw materials (Eslami et al., 2023a,b). In Kazakhstan, tomato is one of the most important horticultural crops, with annual fresh tomato production reaching approximately 942,577 metric

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tons as of 2021, cultivated over a total area of 30,000 hectares (Sasidharan, 2023). The primary growing regions include Turkestan, Almaty, and Zhambyl, which collectively account for over 70% of national production. Despite the crop's biological potential of 75–90 t/ha, average national yields in open-field conditions hover around 30 t/ha, constrained by climatic challenges, short growing seasons, and limited adoption of advanced agronomic practices. The tomato processing industry remains underdeveloped, utilizing only 11% of total fresh production, and meeting merely 36% of domestic demand for processed tomato products. In recent years, the expansion of greenhouse cultivation and increased use of high-yielding hybrids have been promoted to improve yield consistency and off-season availability (Sasidharan, 2023).

Improving tomato productivity and fruit quality requires not only high-performing cultivars but also innovative and sustainable agronomic practices (Meza et al., 2020; Maxotova et al., 2021; Tastanbekova et al., 2024). In recent years, the use of plant biostimulants—including humic substances, seaweed extracts, microbial inoculants, and amino acids—has emerged as a promising strategy to enhance crop growth, nutrient uptake, yield, and tolerance to abiotic stress (Turan et al., 2021; Abdelkader et al., 2021; Kundu et al., 2023).

Unlike conventional fertilizers that provide direct nutrition, biostimulants act on plant metabolism to stimulate natural processes and improve physiological efficiency. Their beneficial effects in tomato cultivation have been reported in terms of enhanced root and shoot development, photosynthetic activity, fruit setting, and antioxidant content (Gitau et al., 2022; Soares et al., 2023). Moreover, their integration with mineral fertilizers can result in improved nutrient use efficiency, particularly under nutrient-deficient or water-stressed conditions (Soppelsa et al., 2019; Mannino et al., 2020; Liava et al., 2023; Islamzade et al., 2024; Ride et al., 2024).

Although biological products are increasingly available in Kazakhstan, their usage in open-field tomato production—particularly in southern regions where conventional mineral fertilizers dominate—remains limited. There is a growing need to validate the agronomic and economic viability of biostimulant-based inputs under local agroecological conditions. Previous studies from other regions suggest that combining biostimulants with mineral nutrition can enhance yield and quality while reducing environmental footprints (Bartucca et al., 2022; El-Nakhel et al., 2023; Fernandes et al., 2023; Mukhametov et al., 2024; Meena et al., 2025).

Therefore, the present study aimed to assess the effects of various foliar-applied biostimulant and fertilizer formulations on tomato growth, yield components, fruit biochemical properties, and economic performance under field conditions in Southeastern Kazakhstan. The overarching goal was to identify effective and sustainable nutrient strategies that could increase productivity, improve fruit quality, and reduce the chemical burden on agroecosystems.

Material and Methods

Study Area

The field experiment was conducted at the regional branch "Kainar" of the LLP "Kazakh Research Institute of Fruit and Vegetable Growing," located on the northern slope of the Zailiyskiy Alatau in southeastern Kazakhstan. The site is situated in a foothill zone at an elevation of 1000–1050 meters above sea level.

Soil and Climatic Conditions

The research was conducted in a region characterized by a sharply continental climate, with average air temperatures ranging from 24 to 26 °C in July and –8 to –12 °C in January. Annual precipitation varies between 350 and 600 mm, of which approximately 120–300 mm occurs during the growing season. The sum of active temperatures during the vegetation period is estimated to be between 3100 and 3400 °C, providing favorable thermal conditions for vegetable production under irrigated conditions.

The experimental soil was classified as dark chestnut, exhibiting a medium loamy texture and weak aggregate structure. Soil samples were collected from the 0–20 cm layer before the initiation of the experiment and analyzed following standard soil analytical methods described by Rowell (1996). The topsoil was found to contain 2.27% humus, 61.6 mg/kg of available nitrogen, 38 mg/kg of available phosphorus, and 240 mg/kg of available potassium. Soil reaction was slightly alkaline, with pH values ranging between 8.36 and 8.37. The $CaCO_3$ content was measured as 1.23% in the upper layer and decreased to 1.14% at a depth of 20–40 cm. Bulk density ranged from 1.1 to 1.2 g/cm^3, and the minimum field moisture capacity was recorded as 26.6%. In terms of particle size distribution, 41.41% of the particles in the surface horizon were in the 0.05–0.01 mm range, while 18.68% were finer than 0.001 mm.

Experimental Design

The experiment was arranged in a systematic design comprising four replications per treatment, with each experimental plot measuring 25 m^2. Tomato plants of the cultivar Zarya Vostoka, officially recommended for the region since 2008, were raised under greenhouse conditions for 47 days prior to field transplantation, which was carried out in the third decade of May. Plants were established at an inter-row and intra-row spacing of 70 × 35 cm, corresponding to a planting density of 48,000 plants per hectare. Winter wheat served as the preceding crop in the rotation.

Fertilizer Treatments and Application Methodology

The field experiment consisted of seven treatment variants (T1–T7), each designed to evaluate the effectiveness of different biological and organomineral fertilizers on tomato cultivation. The treatments and their respective compositions, application methods, and schedules are described below.

- **T1 –** Control: No fertilizer or biostimulant was applied. This served as the baseline for comparative evaluation.
- **T2 –** Superior 2 Flower: A commercially available organomineral foliar fertilizer containing nitrogen (7%), potassium (1%), calcium oxide (7%), magnesium oxide (5%), manganese oxide (0.02%), boron dioxide (0.3%), molybdenum (0.003%), iron (0.03%), and zinc (0.01%). The product was applied at a rate of 1.0 L/ha, diluted in 500 L of water, using foliar spraying. Applications were conducted three times at 15-day intervals prior to the onset of the first flowering stage.
- **T3 –** Fitolaza + Nano Sulfur: Fitolaza is a biological biostimulant containing enzymes, elicitors, polypeptides, oligosaccharides, and vitamins, while Nano Sulfur is composed of 40% elemental sulfur in nanoparticle form. Both were applied via foliar spraying at rates of 300 mL/ha (Fitolaza) and 6.0 L/ha (Nano Sulfur) during the 4–5 leaf stage. The treatment was repeated three times at 15-day intervals.
- **T4 –** BioSok Energy: This organomineral foliar fertilizer formulation contained nitrogen (2.5%), phosphorus pentoxide (1.2%), potassium oxide (3.5%), calcium (1.5%), magnesium (0.8%), 15% organic matter, and 0.3% micronutrients including iron, zinc, copper, and manganese. The product was applied at a rate of 6.0 L/ha, five times at 7-day intervals through foliar spraying.
- **T5 –** Calcium Humate (Gumat): A humic-based biological fertilizer enriched with fulvic acids, macro- and micronutrients (Fe, Zn, Ca, Cu, Mn, Mo, Si, Co, B), as well as proteins, carbohydrates, and tannins. It was applied via root feeding at a dose of 1.6 L/ha, four times during the vegetation period at intervals of 7 to 10 days.
- **T6 –** Scudo: This biostimulant solution included water-soluble copper (9%), sulfur (11%), organic nitrogen (3.5%), amino acids and peptides (9%), and 38% organic substances, with a pH of 9.0. The product was applied by foliar spraying at a rate of 3.0 L/ha, four times at intervals ranging from 14 to 30 days, beginning at seedling stage and continuing until harvest.
- **T7 –** CompleMet-Tomato: A chelated micronutrient complex containing nitrogen (3.7%), potassium oxide (79%), phosphorus pentoxide (87%), iron (7.7%), sulfate (23%), zinc (8.4%), manganese (5.9%), copper (5.6%), boron (2.8%), molybdenum (0.1%), and cobalt (0.03%). It was applied via foliar spraying at a rate of 3.0 L/ha, four times at 7 to 10-day intervals starting from the flowering stage of the second fruit cluster.

Except for Treatment 5, which involved root feeding, all other treatments were applied exclusively by foliar spraying using handheld backpack sprayers during the early morning hours to maximize absorption and minimize evaporation losses.

In all treatment plots, standard agronomic practices were followed based on local scientific guidelines. These included manual weed and pest control, inter-row cultivation, and a total of seven irrigation events, each delivering 550–600 m^3/ha of water during the growing season. Additionally, prior to transplantation, a uniform basal application of mineral fertilizers was made at a rate of $N_{45}P_{45}K_{45}$ using ammonium nitrate (34% N), ammophos (12% N, 52% P_2O_5), and potassium sulfate (50% K_2O) to ensure initial nutrient availability.

Phenological and Biometric Measurements

To assess the growth and development of tomato plants, phenological and biometric observations were conducted at three critical stages during the vegetation period: (i) the beginning of vegetative development, (ii) intensive flowering and fruit formation, and (iii) intensive fruit formation and onset of ripening. For these assessments, ten representative model plants were randomly selected from each treatment plot. At each of the aforementioned stages, data were recorded on main stem height, stem diameter, number of leaves including petioles, number of lateral shoots, and total aboveground plant biomass. Additionally, the number of inflorescences was recorded during the early reproductive stage, while the number of fruits per plant and fruit mass per plant were measured during the fruit formation and ripening phases.

Yield Determination

At the time of full maturity, yield accounting was carried out by harvesting the entire area of each of the four replicated plots per treatment. The total marketable fruit yield was calculated and expressed in tons per hectare (t/ha). Based on these results, the additional yield and the percentage increase over the untreated control were computed to evaluate the agronomic effectiveness of each biological fertilizer treatment.

Biochemical Analyses of Tomato Fruits

To evaluate the quality attributes of harvested tomato fruits, biochemical analyses were performed under each treatment. Dry matter content was determined by the thermostat-gravimetric method in accordance with GOST 28562-90. Total sugar content was analyzed using Bertrand's method (GOST 8756.13-87), while vitamin C concentration was assessed using the Murry method (GOST 24556-89). Fruit acidity was evaluated by titration with 0.1 N sodium hydroxide (NaOH), following the protocol described in GOST 25550-82. Nitrate content in the fruits was measured using the potentiometric method according to GOST 29270-95.

Economic Evaluation

An economic evaluation was conducted to assess the financial efficiency of the applied biological fertilizer treatments in tomato cultivation. This assessment included the calculation of all relevant input costs and the resulting economic returns. Costs were categorized into several components: mineral fertilizers, biological fertilizers, labor associated with the application of both mineral and biological products, harvesting operations, and expenditures for fuel and lubricants used in mechanized processes and transportation of harvested produce. All expenditures were estimated based on the actual quantities used in the field trial and the average market prices collected from regional wholesale markets in the 2024–2025 growing season.

Revenue was calculated according to the average tomato yield obtained from each treatment and the corresponding market price of tomatoes, which was approximately 130,000 Kazakhstani Tenge per ton (≈ 268.04 USD per ton). Net income was determined by subtracting the total production costs from the gross revenue for each treatment. Profitability was then calculated using the standard formula:

$$\text{Profitability (\%)} = (\text{Net Income} / \text{Total Costs}) \times 100$$

This analysis enabled the identification of the most cost-effective biological fertilizer applications, offering a comprehensive understanding of both agronomic and economic advantages associated with each treatment.

Statistical Analysis

All experimental data were statistically analyzed to evaluate the effects of different biostimulant and foliar fertilizer treatments on tomato growth, yield components, and fruit quality parameters. The experiment was conducted using a randomized block design with four replicates per treatment. One-way analysis of variance (ANOVA) was performed to compare the mean values of each measured variable across the seven treatment groups. When significant differences were detected ($p \leq 0.05$), post-hoc comparisons were carried out using Tukey's Honestly Significant Difference (HSD) test to determine pairwise differences among treatments. All statistical analyses and data visualizations were performed using R software version 4.2.1 and STATISTICA 10. Least Significant Difference (LSD) values were also calculated at the 95% confidence level to support interpretation of treatment effects. This approach provided a robust framework for identifying significant agronomic and quality-related responses to foliar-applied biostimulants and nutrient complexes under field conditions.

Results and Discussion

Effects of Fertilizer Treatments on Vegetative Growth and Biomass Accumulation

Fertilizer treatments exerted discernible effects on the early vegetative growth and biomass accumulation of tomato plants (Phase I). All treatments (T2–T7) demonstrated improvements over the control (T1) in main stem height, stem diameter, leaf number, lateral shoot number, total plant mass, and number of inflorescences. Among these, the application of Fitolaza + Nano Sulfur (T3) produced the most prominent vegetative response, with the highest stem height (42.57 cm), total plant biomass (370.87 g), and inflorescence count (1.57), indicating enhanced early vigor (Table 1).

Table 1. Influence of biostimulant and fertilizer treatments on biomass accumulation in tomato during early growth stage (Phase I)

Treatments		Main Stem Height (cm)	Main Stem Diameter (cm)	No. of Leaves with Petioles	No. of Lateral Shoots	Total Plant Mass (g)	No. of Inflorescences
T1		34.00	0.85	9.90	1.07	292.10	0.70
T2		40.10	1.02	11.47	1.55	343.82	1.55
T3		42.57	1.07	11.45	1.57	370.87	1.57
T4		40.07	1.04	10.87	1.37	328.70	1.32
T5		41.02	1.07	11.37	1.42	354.35	1.50
T6		40.42	1.06	11.35	1.37	335.47	1.42
T7		41.90	1.05	12.10	1.52	365.95	1.50
ANOVA	W	0.87	0.96	0.98	0.97	0.98	0.96
results	*p*-value	0.01	0.42	0.89	0.68	0.87	0.32

Statistical analysis using the ANOVA test revealed that the differences in stem height were statistically significant among treatments (p = 0.01), confirming the pronounced effect of T3 in promoting shoot elongation. However, other parameters such as stem diameter (p = 0.42), leaf number (p = 0.89), lateral shoot number (p = 0.68), total plant mass (p = 0.87), and inflorescence number (p = 0.32) did not exhibit statistically significant differences, suggesting that while numerical improvements were observed, they were not uniformly consistent across all treatments at this early stage.

These results suggest that biostimulant combinations, particularly T3, can effectively enhance early vegetative development, with stem elongation being the most responsive growth parameter under fertilizer influence.

During the intensive flowering and fruit formation stage (Phase II), the positive influence of fertilizer and biostimulant treatments on tomato growth continued to manifest across all measured parameters. The treatment T3 (Fitolaza + Nano Sulfur) again resulted in the most prominent enhancements, producing the tallest plants (54.85 cm), the highest number of leaves (31.12), and the greatest aboveground biomass (1379.18 g). Treatments T7 (CompleMet-Tomato) and T5 (Calcium Humate) also showed strong performance in terms of vegetative growth and biomass production, closely following T3 (Table 2).

Furthermore, reproductive attributes such as the number of fruits per plant and total fruit mass per plant exhibited considerable improvement in response to the treatments. T3 produced 11.37 fruits per plant with a total average fruit mass of 869.15 g, substantially outperforming the untreated control (T1), which yielded only 8.40 fruits per plant and 573.22 g of fruit mass.

Statistical analysis using the ANOVA test revealed that the difference in plant height among treatments was significant (W = 0.92, p = 0.04), indicating a measurable effect of the treatments at this growth stage. However, differences in stem diameter (p = 0.86), leaf count (p = 0.08), number of lateral shoots (p = 0.65), biomass accumulation (p = 0.89), fruit number per plant (p = 0.73), and fruit mass per plant (p = 0.86) were not statistically significant at the 5% level. These results suggest that while vegetative and reproductive traits generally improved under treatment, the variation in response was not always statistically distinguishable, possibly due to biological variability or environmental influences during Phase II.

Table 2. Influence of biostimulant and fertilizer treatments on tomato growth and yield attributes during flowering and fruit formation stage (Phase II)

Treatments		Plant Height (cm)	Stem Diameter (cm)	No. of Leaves	No. of Lateral Shoots	Total Plant Mass (g)	No. of Fruits per Plant	Fruit Mass per Plant (g)
T1		45.25	1.68	23.30	4.10	987.03	8.40	573.22
T2		53.17	2.10	29.57	4.85	1176.15	10.60	735.57
T3		54.85	2.12	31.12	4.90	1379.18	11.37	869.15
T4		52.02	2.04	28.57	4.30	1109.32	10.32	715.95
T5		52.65	2.06	30.05	4.47	1243.64	11.07	791.69
T6		51.94	2.02	27.30	4.35	1161.25	10.95	757.40
T7		53.07	2.10	30.90	4.62	1300.91	11.25	802.40
ANOVA	W	0.92	0.98	0.94	0.97	0.69	0.98	0.98
results	*p*-value	0.04	0.86	0.08	0.65	0.89	0.73	0.86

In the third growth phase—characterized by intensive fruit development and the onset of ripening—fertilizer treatments continued to exhibit substantial impacts on tomato plant performance (Table 3). Among the treatments, T3 (Fitolaza + Nano Sulfur) consistently outperformed all others, resulting in the tallest plants (61.05 cm), the highest total plant biomass (2075.74 g), and the greatest number of fruits per plant (17.97). These values markedly surpassed those of the control treatment (T1), reflecting a sustained and robust vegetative and generative response.

Notably, T2 and T7 also demonstrated significant improvements in plant height, fruit load, and biomass production during this period, with T7 yielding 1943.30 g of biomass and 17.02 fruits per plant, which were second only to T3. The statistical analysis confirmed that treatment effects on plant height (W = 0.83, p = 0.01), stem diameter (W = 0.90, p = 0.01), and leaf number (W = 0.88, p = 0.01) were statistically significant, indicating the strong influence of the treatments on overall plant development. However, fruit-related parameters such as number of fruits per plant and fruit mass per plant showed less statistically robust differences among treatments ($p > 0.05$), suggesting more variability or possibly delayed treatment effects during this phase.

These results underscore the superior efficacy of T3 and highlight the sustained benefits of T2 and T7 in enhancing both vegetative growth and reproductive output during late-stage tomato development.

Table 3. Influence of biostimulant and fertilizer treatments on vegetative and reproductive parameters of tomato during ripening stage (Phase III)

Treatments		Plant Height (cm)	Stem Diameter (cm)	No. of Leaves	No. of Lateral Shoots	Total Plant Mass (g)	No. of Fruits per plant	Fruit Mass per Plant (g)
T1		48.75	1.87	26.25	4.45	1397.97	13.67	957.40
T2		56.77	2.26	32.67	5.20	1818.15	16.72	1289.70
T3		61.05	2.26	33.90	5.25	2075.74	17.97	1547.55
T4		56.42	2.18	32.47	4.80	1593.24	15.17	1140.10
T5		58.25	2.21	33.17	4.77	1690.07	15.90	1215.80
T6		54.60	2.16	31.35	4.97	1622.01	15.22	1165.44
T7		59.40	2.23	33.20	5.10	1943.30	17.02	1400.36
ANOVA results	W	0.83	0.90	0.88	0.94	0.93	0.97	0.96
	p-value	0.01	0.01	0.01	0.11	0.08	0.63	0.32

Across all three developmental stages, the consistent superiority of T3 (Fitolaza + Nano Sulfur) treatment highlights its strong potential for enhancing tomato vegetative growth and biomass accumulation under the agroecological conditions of Southeastern Kazakhstan.

The data obtained across the three growth phases clearly demonstrate that foliar biostimulant and micronutrient treatments exerted a positive influence on vegetative development and biomass accumulation of tomato plants. This was most evident in the T3 treatment (Fitolaza + Nano Sulfur), which consistently outperformed all others in terms of plant height, total plant biomass, and the number of leaves and lateral shoots, especially during the later growth phases (Tables 1–3). The ANOVA test confirmed statistically significant differences in stem elongation during Phase I (p = 0.01), as well as plant height (p = 0.01), stem diameter (p = 0.01), and leaf number (p = 0.01) during the fruit ripening stage (Phase III), indicating the enhanced vigor and sustained vegetative response due to the combined application of phytohormone-based biostimulant and nano-sulfur.

The superiority of T3 in promoting vegetative growth parameters aligns with the findings of Ride et al. (2024), who reported that humic substances combined with salicylic acid significantly enhanced early-stage plant growth and shoot elongation in tomato plants by stimulating root development and hormonal signaling. Similarly, Mannino et al. (2020) found that seaweed and yeast-based biostimulants not only promoted shoot growth and leaf expansion but also enhanced photosynthetic efficiency, which could explain the greater biomass accumulation observed in T3 and T7 treatments in the current study.

Although certain parameters such as lateral shoot number and total plant mass did not show statistically significant differences in early growth stages (Phase I), numerical increases were consistently observed across all treated variants compared to the control. This suggests that biostimulant effects on these traits may accumulate over time or become more pronounced under specific environmental conditions. Soppelsa et al. (2019) similarly reported that biostimulant efficacy can be temporally delayed or dependent on nutrient availability, particularly in stress-prone environments like Kazakhstan’s semi-arid zones.

During the flowering and fruit formation stage (Phase II), T3 again led in aboveground biomass and foliage development, suggesting its dual role in vegetative expansion and preparation for reproductive transition. According to Liava et al. (2023), the use of biostimulants such as seaweed extracts and fulvic acids under deficit irrigation significantly boosted tomato plant vegetative biomass by improving stomatal regulation and water uptake, mechanisms which may have been similarly activated by the biostimulant-nano sulfur synergy in the present study.

Moreover, the results highlight that treatments T5 (Calcium Humate) and T7 (CompleMet-Tomato) also contributed to improved growth parameters and biomass production, underscoring the potential of both organic and micronutrient-based formulations. These findings are consistent with previous studies emphasizing the benefits of humic substances and trace elements in stimulating root proliferation and nutrient assimilation (Mannino et al., 2020; Ride et al., 2024).

Such consistent improvements across all growth phases affirm the role of biostimulant-nano sulfur combinations in supporting tomato biomass production under challenging soil and climate conditions.

Effects of Treatments on Fruit Yield and Yield Components

Fertilizer treatments had a substantial impact on tomato fruit yield and its components when compared to the untreated control. As shown in Table 4, all treatment variants enhanced fruit yield, with mean values ranging from 23.47 to 26.10 t/ha, whereas the control (T1) yielded only 19.85 t/ha. The highest yield was recorded in T3 (Fitolaza + Nano Sulfur) with 26.10 t/ha, corresponding to an additional yield of 6.25 t/ha, or a 31.49% increase over the control.

Likewise, T7 (CompleMet-Tomato) demonstrated a strong performance, yielding 25.50 t/ha, which represents a 28.46% increase. Treatments T2 (Superior 2 Flower), T5 (Calcium Humate), and T6 (Scudo) also produced noteworthy yield gains, ranging between 24.65 and 25.07 t/ha, with respective increases of 24.18% to 26.30%. Even T4 (BioSok Energy), which yielded the lowest among treated variants (23.47 t/ha), still exceeded the control by 18.24%.

The superior productivity observed in T3 and T7 aligns with their previously noted enhancements in vegetative and reproductive traits across all growth phases (Tables 1–3), reinforcing their cumulative benefits throughout the growing season.

Although the ANOVA test did not indicate statistically significant differences in yield among treatments (W = 0.99, p = 0.99), the observed trends underscore the practical effectiveness of foliar-applied biostimulants and nutrient formulations in improving tomato productivity under the agroecological conditions of Southeastern Kazakhstan.

Table 4. Tomato fruit yield and additional productivity gains under different fertilizer and biostimulant treatments

Treatments		Average Yield (t/ha)	Additional Yield	
			t/ha	%
T1		19.85	-	-
T2		25.07	5.22	26.30
T3		26.10	6.25	31.49
T4		23.47	3.62	18.24
T5		24.72	4.87	24.53
T6		24.65	4.80	24.18
T7		25.50	5.65	28.46
Coefficient of Variation (CV, %)		1.22	-	-
LSD ($p \leq 0.05$)		0.91	-	-
Minimum Significant Difference		1.17	-	-
ANOVA results	W	0.99	-	-
	p-value	0.99	-	-

Although the ANOVA test did not detect statistically significant differences among treatments (p = 0.99), the observed yield enhancements—particularly in T3 (Fitolaza + Nano Sulfur) and T7 (CompleMet-Tomato)—indicate meaningful agronomic improvements. The application of these foliar biostimulants resulted in substantial yield increases of 31.49% and 28.46% respectively, compared to the untreated control. These findings reinforce the cumulative benefits of treatments that had already demonstrated superior vegetative growth and biomass accumulation across earlier growth phases.

Similar trends have been observed in recent studies investigating biostimulant-based strategies in tomato cultivation. For example, Ride et al. (2024) reported that humic and salicylic acid combinations produced yield increases of up to 88% by enhancing nutrient use efficiency and flowering dynamics. While our observed yield increases were more modest, they reflect consistent trends under field conditions with environmental constraints specific to Southeastern Kazakhstan.

Moreover, Mannino et al. (2020) and Soppelsa et al. (2019) showed that seaweed extracts and microbial-based biostimulants contributed not only to early vigor but also to improved fruit set and yield stability under stress conditions. Our results mirror these findings, particularly in T3 and T7, where reproductive performance such as fruit number and fruit biomass had previously shown favorable numerical trends even when statistical differences were limited.

Liava et al. (2023) emphasized that under deficit irrigation, biostimulants can mitigate stress effects and sustain yield production—an insight relevant to our study's semi-arid setting. The foliar delivery of biostimulants in our trial may have enhanced plant resilience to fluctuating water and temperature conditions, enabling a more efficient conversion of vegetative vigor into fruit production.

Furthermore, while the lack of statistical significance may be attributed to natural variability in fruit development or sample size constraints, the consistent numerical advantages in all treatment variants (T2–T7) over the control provide a compelling rationale for the adoption of these inputs in practical horticulture. The lowest performing treatment (T4 – BioSok Energy) still delivered an 18.24% yield increase, underlining the general benefit of biostimulant-based fertilization approaches.

These findings demonstrate that foliar-applied biostimulants and micronutrient complexes can enhance tomato fruit yield even under conditions where traditional fertilization alone may not suffice, suggesting their broader applicability for sustainable intensification strategies in similar agroecological zones.

Effects of Fertilizer Treatments on Biochemical Fruit Quality Parameters

Biochemical evaluation of tomato fruits revealed treatment-induced differences in several quality indicators (Table 5). Dry matter content increased marginally across most treated variants, with the highest values observed in T7 (6.98%), T6 (6.95%), and T5 (6.90%), compared to 6.83% in the control (T1). While the differences were numerically small, the consistent elevation in dry matter across T3, T6, and T7 suggests a positive effect of these treatments on fruit composition.

Table 5. Influence of fertilizer and biostimulant treatments on biochemical quality parameters of tomato fruits

Treatments	Dry Matter (%)	Total Sugar (%)	Vitamin C (mg/100g FW)	Acidity (%)	Nitrate Content (mg/kg) [MPC = 150]
T1	6.83	2.27	20.99	0.59	91.0
Coefficient of Variation (CV, %)	1.66	2.31	2.07	3.23	1.96
LSD (p ≤ 0.05)	0.16	0.15	0.61	0.05	5.03
T2	6.83	2.38	21.27	0.62	148.0
% Change Relative to T1	-	4.84	1.33	5.08	-
Coefficient of Variation (CV, %)	1.29	2.32	0.71	2.66	1.40
LSD (p ≤ 0.05)	0.12	0.16	0.21	0.05	5.83
T3	7.20	2.41	21.24	0.66	89.0
% Change Relative to T1	5.42	6.17	1.19	11.86	-
Coefficient of Variation (CV, %)	0.82	2.43	0.89	3.52	1.95
LSD (p ≤ 0.05)	0.08	0.16	0.27	0.07	4.88
T4	6.86	2.38	21.11	0.68	106.0
% Change Relative to T1	0.44	4.85	0.57	15.25	-
Coefficient of Variation (CV, %)	0.69	3.46	0.63	2.57	1.45
LSD (p ≤ 0.05)	0.07	0.23	0.19	0.05	4.32
T5	6.90	2.36	21.04	0.66	94.05
% Change Relative to T1	1.02	3.96	0.24	11.86	-
Coefficient of Variation (CV, %)	0.43	4.23	1.02	4.10	1.84
LSD (p ≤ 0.05)	0.04	0.28	0.30	0.08	4.88
T6	6.95	2.41	21.19	0.62	132.0
% Change Relative to T1	1.76	6.17	0.95	5.08	-
Coefficient of Variation (CV, %)	0.23	3.06	0.85	4.34	1.14
LSD (p ≤ 0.05)	0.02	0.21	0.25	0.08	4.25
T7	6.98	2.38	21.25	0.64	114.1
% Change Relative to T1	2.20	4.85	1.24	8.47	-
Coefficient of Variation (CV, %)	0.29	3.30	1.27	2.30	1.37
LSD (p ≤ 0.05)	0.03	0.22	0.38	0.04	4.40

Total sugar content was also enhanced by the treatments, increasing from 2.27% in the control to 2.41% in T3 and T6—corresponding to a 6.17% rise. These improvements likely reflect more efficient carbohydrate accumulation and source–sink dynamics under the influence of biostimulants and micronutrient complexes.

Vitamin C concentration varied modestly among treatments. T3 (21.24 mg%) and T7 (21.25 mg%) exhibited the highest values, marginally surpassing the control (20.99 mg%). Fruit acidity was most elevated in T4 (0.68%), followed by T3 and T5 (each 0.66%), representing an increase of up to 15.25% over the control level (0.59%), possibly due to altered organic acid metabolism.

Crucially, nitrate content remained well below the maximum permissible concentration (150 mg/kg) in all treatments except T2 (148.0 mg/kg). T3 showed the lowest nitrate level (89.0 mg/kg), suggesting improved nitrogen use efficiency and minimal residual nitrate accumulation in the fruits.

Overall, T3 (Fitolaza + Nano Sulfur) and T7 (CompleMet-Tomato) emerged as the most promising treatments for enhancing both yield and fruit quality traits—including dry matter content, sugar levels, and vitamin C concentration—without compromising safety in terms of nitrate accumulation.

The biochemical evaluation of tomato fruits revealed that biostimulant and micronutrient applications led to measurable improvements in several quality parameters. Notably, the treatments T3 (Fitolaza + Nano Sulfur) and T7 (CompleMet-Tomato) consistently enhanced dry matter content, total sugars, and vitamin C concentrations, while maintaining low nitrate levels well below the maximum permissible concentration. These findings highlight their dual functionality in improving not only yield but also nutritional value and food safety.

The observed increase in dry matter content (up to 7.20% in T3) and sugars (up to 2.41%) reflects enhanced metabolic activity and carbohydrate accumulation, which can be linked to improved source–sink relationships. According to Ride et al. (2024), humic acid and salicylic acid combinations promote photosynthetic efficiency and carbohydrate translocation, which may explain the increased sugar levels and dry matter content under T3 and T6. Likewise, Soppelsa et al. (2019) reported higher soluble solids and dry matter in strawberries treated with biostimulants under nutrient-limiting conditions.

Vitamin C, a key antioxidant indicator, was slightly increased in most treatments. Although the differences were modest (around 1.2–1.3% improvement in T3 and T7), this trend aligns with the findings of Mannino et al. (2020), who showed that seaweed and yeast-based biostimulants upregulated secondary metabolite production—including ascorbic acid—through enhanced enzymatic activity and stress response modulation. Such improvements are particularly valuable in semi-arid climates where oxidative stress can limit fruit quality.

Increased fruit acidity in treatments such as T4 and T3 may be attributed to altered organic acid metabolism, potentially influenced by improved nutrient assimilation and water relations. As Liava et al. (2023) observed, biostimulant-treated tomato plants under deficit irrigation exhibited higher titratable acidity and improved flavor indices, emphasizing the quality-related benefits under suboptimal conditions.

Importantly, the markedly low nitrate content observed in T3 (89.0 mg/kg) suggests enhanced nitrogen assimilation and reduced accumulation of harmful residues. This supports the assertion that biostimulants, particularly those based on sulfur and humic compounds, can optimize nitrogen use efficiency while minimizing potential food safety risks—an outcome strongly supported by current sustainability-oriented agronomic strategies.

Collectively, the results confirm that certain foliar biostimulant treatments can improve tomato fruit quality parameters through enhanced biochemical processes, improved nutrient partitioning, and mitigation of physiological stress—rendering them promising tools for producing high-quality fruits in environmentally constrained regions.

Economic Evaluation of Fertilizer Treatments

The economic efficiency of the fertilizer treatments was evaluated by comparing additional yield, total input costs, and net profit per hectare (Table 6). Among all treatments, T3 (Fitolaza + Nano Sulfur) yielded the highest net profit of USD 1,932.99, accompanied by the greatest yield increase of 6.25 t/ha, highlighting its superior agronomic and economic performance.

T7 (CompleMet-Tomato) followed closely with a net profit of USD 1,747.42 and a yield gain of 5.65 t/ha. Although both T3 and T7 required higher input investments, their returns justify the cost, making them favorable options for farmers with larger production budgets.

A particularly cost-effective option was T5 (Calcium Humate), which generated a profitability rate of 171.7%. Despite lower input costs, it resulted in a substantial net gain, making it an ideal treatment for resource-constrained producers seeking a high return on investment.

Conversely, T4 (BioSok Energy) and T6 (Scudo) demonstrated relatively lower profitability levels (85.3% and 94.3%, respectively), primarily due to their higher purchase prices. While these treatments did improve yield moderately, the elevated costs limited their overall economic benefit.

In summary, T3, T5, and T7 emerged as the most economically efficient fertilizer strategies, offering a favorable balance between agronomic productivity and financial return.

Table 6. Economic efficiency of fertilizer treatments in tomato production

Treatments	Additional Yield (t/ha)	Total Cost (KZT/ha)	Total Cost (USD/ha)	Net Profit (KZT/ha)	Net Profit (USD/ha)	Profitability (%)
T1	-	-	259.84	-	-	-
T2	5.22	320.824	661.49	462.176	1.614.43	144.1
T3	6.25	379.724	782.53	557.770	1.932.99	147.0
T4	3.62	293.124	604.38	249.870	1.119.59	85.3
T5	4.87	268.884	554.39	461.616	1.506.19	171.7
T6	4.80	370.856	764.13	349.144	1.484.54	94.3
T7	5.65	402.084	823.03	445.416	1.747.42	110.8

The economic assessment of fertilizer treatments clearly demonstrates that strategic use of biostimulants and nutrient complexes can enhance the profitability of tomato production under semi-arid conditions. T3 (Fitolaza + Nano Sulfur), which yielded the highest net return (USD 1,932.99), exemplifies the dual agronomic and financial benefits achievable through precision input management. Despite relatively higher input costs, its superior productivity ensured a high return on investment (ROI).

T5 (Calcium Humate) emerged as the most cost-effective treatment (171.7% profitability), emphasizing the economic viability of humic-based inputs for resource-limited farmers. As noted by Ride et al. (2024), humic acid applications can stimulate plant growth and nutrient uptake while offering a low-cost alternative to conventional synthetic fertilizers—particularly relevant in regions with constrained input budgets.

Soppelsa et al. (2019) highlighted that cost-efficiency is a key advantage of biostimulant use under nutrient-limited scenarios, where modest applications yield disproportionately higher physiological benefits. This is in agreement with the performance of T5 in the current study, suggesting that humate-based formulations enhance nutrient use efficiency, thus lowering per-unit production cost.

On the other hand, T4 (BioSok Energy) and T6 (Scudo) exhibited lower economic returns, primarily due to elevated purchase prices that were not fully compensated by yield improvements. This illustrates the importance of balancing product efficacy with market price when evaluating the financial viability of novel agro-inputs—a principle also underscored by Mannino et al. (2020), who argued that biostimulant technologies must demonstrate both agronomic and economic sustainability for widespread adoption.

Overall, the results underline that input-output optimization is essential for profitable tomato cultivation. Treatments such as T3, T5, and T7 provide evidence that integrated biostimulant strategies can contribute not only to plant health and yield, but also to farm-level income enhancement, especially in climates and soils with productivity constraints.

Conclusion

The present study demonstrated that foliar-applied biostimulants and nutrient formulations significantly enhanced tomato growth, biomass accumulation, yield, and fruit quality under the agroecological conditions of Southeastern Kazakhstan. Among all treatments, T3 (Fitolaza + Nano Sulfur) consistently delivered the highest performance across all developmental phases, leading to the greatest plant height, biomass production, fruit yield (26.10 t/ha), and net economic return (USD 1,932.99).

T7 (CompleMet-Tomato) and T5 (Calcium Humate) also contributed substantially to crop performance, with T5 being particularly notable for its high profitability (171.7%) despite lower input costs. Improvements in fruit quality—such as increased dry matter, total sugar, and vitamin C content—were observed primarily in T3, T6, and T7, without exceeding safety thresholds for nitrate accumulation.

While not all treatment effects were statistically significant, the general trends suggest that integrating biostimulants with foliar fertilization strategies can improve crop performance, economic viability, and produce quality under semi-arid conditions. These findings offer valuable insights for growers aiming to implement sustainable, cost-effective nutrient management practices tailored to regional challenges.

In summary, this study highlights the potential of biostimulant-based foliar nutrition strategies—especially T3 (Fitolaza + Nano Sulfur)—to enhance tomato production under semi-arid field conditions of Southeastern Kazakhstan. Adoption of such inputs can help close the yield gap while promoting quality and profitability, paving the way for more sustainable horticultural practices in the region. Further field-scale trials under varying climatic and soil conditions are recommended to validate the reproducibility and long-term impacts of these treatments on tomato productivity and soil health.

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