

Integrated application of granular and liquid bioorganic fertilizers improves corn productivity and soil fertility in light chestnut soils

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Abstract. Karabayev K, Suleimenov B, Songulov Y, Akhmurzin U, Smanov A. 2025. Integrated application of granular and liquid bioorganic fertilizers improves corn productivity and soil fertility in light chestnut soils. *Cell Biol Dev* 9: 54-63. This study evaluated the effectiveness of integrated granular and liquid bioorganic fertilizers in enhancing soil fertility and corn (*Zea mays*) productivity on light chestnut soils in the Agopark Ontusik region. Field experiments were conducted using three rates of granular organic fertilizer (0, 1000, and 2000 kg ha⁻¹) combined with four concentrations of a humic-based foliar biostimulant (0, 2, 4, and 6 mL L⁻¹). Agronomic performance was assessed through vegetative traits, biomass accumulation, yield components, and grain productivity. Soil fertility parameters and economic profitability were also evaluated. The results showed that both fertilizer types significantly improved plant height, leaf area, and biomass, with the highest values recorded under the combined treatment of 2000 kg ha⁻¹ + 6 mL L⁻¹. Grain yield increased from 7.4 t/ha in the control to 13.5 t/ha in the best treatment. Available phosphorus (P₂O₅) in the topsoil rose from 14.0 to 26.0 mg/kg, while exchangeable potassium (K₂O) declined due to high plant uptake. Economic analysis revealed that the most intensive treatment produced the highest net income (339,520 tenge/ha) and lowest cost per 100 kg of grain (2,519 tenge). Correlation analysis confirmed strong associations between biomass and yield, highlighting the importance of balanced nutrient supply. These findings demonstrate that bioorganic fertilization strategies are effective in restoring fertility and improving productivity on marginal soils, offering a sustainable alternative to conventional inputs in dryland cropping systems.

Keywords: Bioorganic fertilizer, corn, dryland, humic substances, soil fertility, sustainable agriculture

INTRODUCTION

Sustainable intensification of agricultural production remains a central challenge in semi-arid and dryland regions worldwide, where land degradation, declining soil fertility, and climatic variability threaten crop productivity and food security (Tefera et al. 2024). In such environments, soils are often characterized by poor physical structure, low organic matter, and limited nutrient retention capacity, making them marginal for intensive farming. These constraints are particularly pronounced in Central Asia, where vast areas are dominated by light chestnut soils with inherently low humus content, poor buffering capacity, and rapid nutrient leaching. Managing crop production in these soils requires targeted interventions that enhance both soil fertility and plant resilience to abiotic stress (Pankova and Chernousenko 2018).

Corn (*Zea mays* L.) is a globally important cereal crop with wide ecological adaptability and high economic value (Edmeades et al. 2017). Its cultivation has expanded into marginal zones, including light chestnut soil areas of Kazakhstan, Uzbekistan, and other Central Asian countries (Samenova 2024). However, the success of maize production in such fragile environments depends on improving nutrient availability, rooting conditions, and soil biological activity. Traditional approaches relying on high rates of mineral fertilizers have shown diminishing returns in these

systems, with growing evidence of long-term soil degradation and ecological disruption. Therefore, there is a growing interest in bioorganic fertilization approaches that combine the benefits of organic matter input and biologically active compounds to restore soil functionality and support crop productivity (Wu et al. 2024).

Bioorganic fertilizers, particularly those containing humic substances, have been widely recognized for their ability to improve soil fertility and plant growth through multiple mechanisms (Gao et al. 2020). Humic acids, fulvic acids, and associated organic compounds function as natural biostimulants that enhance nutrient uptake, promote root elongation, improve cell permeability, and regulate hormone-like activity in plants. These substances also stimulate microbial activity and soil enzymatic functions, creating favorable conditions for nutrient cycling and organic matter stabilization. Several studies have reported that humic-based amendments increase photosynthetic efficiency, improve drought tolerance, and accelerate reproductive development in cereals and other field crops (Rigobelo 2024).

In addition to soil application, foliar delivery of humic-based liquid bioorganic formulations has shown promise in enhancing nutrient absorption and plant vigor, particularly under limiting soil conditions. Foliar-applied humic substances can bypass root zone constraints and directly influence metabolic processes in leaves, leading to improved chlorophyll

synthesis, stomatal conductance, and assimilate partitioning (Tambhekar 2013). When applied in combination with soil-applied organic fertilizers, such strategies may yield synergistic effects by concurrently enhancing soil structure and nutrient mobility while promoting efficient nutrient use aboveground (Srivastava and Nguillie 2009).

Despite the growing body of evidence supporting the use of humic-based biofertilizers, field-level studies evaluating their combined impact with granular organic inputs on maize productivity, soil nutrient dynamics, and economic returns remain limited especially in the context of light chestnut soils. These soils, common across the dry steppe zones of Central Asia, are known for their low Cation Exchange Capacity (CEC), weak structural stability, and rapid moisture loss. Their management requires inputs that not only supply nutrients but also improve organic matter retention and biological functioning. Previous findings suggest that organic fertilizers can gradually increase soil humus and microbial biomass, while humic-based foliar applications provide immediate physiological benefits to plants (Lumactud et al. 2022). However, studies quantifying the interaction of both approaches under field conditions, particularly on marginal soils, are scarce.

Furthermore, the long-term sustainability of any fertilization strategy must be assessed in relation to its economic feasibility. Smallholder and commercial farmers alike require solutions that improve yields without imposing excessive costs or labor burdens. Although organic inputs are often perceived as more expensive than conventional fertilizers, they may offer better cost-effectiveness over time by improving input-use efficiency and reducing environmental risks. Therefore, assessing profitability indicators such as net income, input-output ratios, and unit production cost is essential for informing adoption decisions (Tellarini and Caporali 2000).

In this study, we investigate the agronomic and economic effects of integrating granular organic fertilizer with a humic-based liquid biostimulant on corn growth, yield, soil fertility, and profitability in the Agropark Ontusik Region, which is representative of light chestnut soil agroecosystems. Specifically, this study aims to (i) assess the response of vegetative and reproductive traits of maize to different treatment combinations, (ii) evaluate changes in topsoil nutrient availability and organic matter following fertilization, (iii) determine correlations between biomass and yield performance, and (iv) analyze economic viability of each fertilization regime. The results are expected to inform best practices for maize cultivation in dryland areas with similar soil limitations and contribute to broader efforts in agroecological intensification.

MATERIALS AND METHODS

Study site description

The experiment was conducted at Agropark Ontustik, located in the Almaty region of Southeast Kazakhstan (coordinates: 43.2589° N, 76.9151° E). The area experiences a semi-arid continental climate characterized by distinct seasonal temperature variations and limited precipitation.

The average annual temperature is approximately 7.8°C, with July as the warmest month averaging 22.1°C, and January as the coldest with an average of -7.9°C. Total annual rainfall averages 494 mm, with the majority falling during spring (April-May), while late summer and early autumn are relatively dry (Ualiyeva et al. 2022).

The soil in the experimental area is classified as light chestnut soil, a common soil type in Central Asian semi-arid steppes. These soils exhibit a loamy texture with low organic matter content, typically ranging from 1.8% to 1.9% humus in the topsoil. The soil pH is alkaline, between 8.8 and 8.9, reflecting high base saturation but also indicating limited nutrient availability in certain forms. Light chestnut soils generally have low Cation Exchange Capacity (CEC) and poor moisture retention, contributing to rapid nutrient leaching and posing challenges for sustainable crop production (Chatzistathis et al. 2021).

Such edaphic characteristics render these soils vulnerable to degradation under intensive cropping systems, necessitating tailored fertility management strategies to maintain soil health and productivity (Khan 2024). The experimental site's climatic and soil conditions make it representative of marginal dryland agroecosystems where innovative bioorganic fertilization methods may offer agronomic and environmental benefits.

Experimental design and treatment structure

The field experiment was arranged in a factorial Randomized Complete Block Design (RCBD) with three replications. Two factors were tested: Granular Organic Fertilizer (GOF) and Liquid Bioorganic Fertilizer (LBF). The GOF was applied at three rates: G0 (0 kg ha⁻¹, control), G1 (1000 kg ha⁻¹), and G2 (2000 kg ha⁻¹). The LBF factor consisted of four concentrations of BioEcoGum: P0 (0 mL L⁻¹, control), P1 (2 mL L⁻¹), P2 (4 mL L⁻¹), and P3 (6 mL L⁻¹).

BioEcoGum is a commercial liquid bioorganic fertilizer characterized by a humic substance content of 60 g L⁻¹ humic acids, 20 g L⁻¹ fulvic acids, and 40 g L⁻¹ potassium oxide (K₂O), with total organic matter content ranging from 80 to 85%, a pH between 9.5 and 10.0, and a density of approximately 1.10 to 1.15 g cm⁻³. This product was applied as a foliar spray at three critical growth stages of maize: V4 (four-leaf stage), tasseling, and early grain filling.

Each experimental plot measured 3 m by 4 m, with 1-m buffer zones separating plots to minimize nutrient and moisture interference. Granular organic fertilizer was uniformly incorporated into the soil prior to planting, while the foliar applications of BioEcoGum were performed using a backpack sprayer in the early morning to maximize absorption.

This factorial design allowed the evaluation of both main effects and interaction effects between soil-applied granular fertilizer and foliar bioorganic fertilization on corn growth, yield, soil fertility, and economic performance.

Crop management practices

Maize hybrid Porumbene 458, known for its adaptability to semi-arid environments (Andriucă et al. 2016), was used in the experiment. Seeds were sown manually at a spacing

of 70 cm between rows and 25 cm between plants, with one seed per hill, resulting in a planting density of approximately 57,000 plants per hectare. Planting occurred in early May, corresponding to the beginning of the growing season in the region.

Irrigation was applied daily during the first four weeks after sowing to ensure uniform germination and early establishment, followed by biweekly irrigation until physiological maturity. Weed control was conducted twice using mechanical weeding and manual hoeing. Pest and disease management followed Integrated Pest Management (IPM) principles, with applications of environmentally safe insecticides only when pest populations exceeded economic thresholds.

Fertilization followed the treatment regimen described in Experimental design and treatment structure section, with granular organic fertilizer incorporated into the soil before sowing, and BioEcoGum applied as foliar sprays during key growth stages. Other agronomic practices, such as thinning and earthing up, were standardized across all plots to minimize variability.

Harvesting was carried out approximately 102 days after planting, at physiological maturity, by manually cutting the ears from five representative plants per plot for yield and biomass assessments.

Agronomic measurements

Growth parameters were recorded at critical growth stages to assess the effects of treatments on maize development. Plant Height (PH) was measured from the soil surface to the tip of the tallest leaf on five randomly selected plants per plot at the tasseling stage. The Number of Leaves (NL) was counted on the same plants. Leaf area (LA) was estimated using a portable leaf area meter (Model LI-3000C, LI-COR Biosciences) on fully expanded leaves sampled from five plants per plot.

Reproductive parameters included days to Male Flowering (MF) and Female Flowering (FF), recorded as the number of days from sowing until 50% of plants in a plot exhibited tassel emergence and silking, respectively. At physiological maturity, Ear Weight (EW) and Grain Weight per ear (GW) were determined by harvesting and weighing ears from five representative plants per plot. Aboveground biomass was sampled by cutting the five plants at ground level; fresh biomass was recorded immediately, and subsamples were oven-dried at 70°C until constant weight to determine dry biomass (Total Dry Biomass/TDB). All measurements were performed following standard agronomic protocols, ensuring accuracy and repeatability. Data were averaged per plot for subsequent statistical analysis.

Soil sampling and laboratory analysis

Soil samples were collected from the 0-20 cm depth before planting and immediately after harvest to assess changes in soil fertility parameters. For each plot, five subsamples were taken at random points and composited into a single representative sample. Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter. Organic matter content (humus) was determined by the Walkley-Black dichromate oxidation method. Hydrolyzable

nitrogen (N) was measured using alkaline hydrolysis diffusion techniques. Available phosphorus (P_2O_5) was analyzed using the Bray I extraction method, and exchangeable potassium (K_2O) was extracted with ammonium acetate and measured by flame photometry.

The liquid bioorganic fertilizer used in this study (BioEcoGum) is a humic-based formulation designed to enhance nutrient availability and plant vigor, as previously described (Lavanya 2022). All soil analyses were performed at the certified Soil Testing Laboratory of Kazakh Research Institute of Agriculture and Plant Growing, following standardized protocols to ensure data accuracy and reproducibility.

Economic evaluation

An economic analysis was conducted to evaluate the profitability and cost-effectiveness of the different fertilizer treatments. Input costs included expenses for seeds, labor, Granular Organic Fertilizer (GOF), liquid bioorganic fertilizer (LBF, BioEcoGum), irrigation, pest control, and other cultural practices. All costs were calculated based on local market prices prevailing during the 2021 growing season.

Gross revenue was estimated by multiplying grain yield per hectare by the average market price of maize at harvest time. Net income was determined by subtracting total production costs from gross revenue. Additional economic indicators calculated included the Benefit-Cost (B/C) ratio and the production cost per 100 kg of grain.

Economic data were analyzed to provide insights into the financial feasibility of applying integrated granular and liquid bioorganic fertilizers in maize cultivation on light chestnut soils.

Statistical analysis

All experimental data were subjected to two-way analysis of variance (ANOVA) to examine the effects of Granular Organic Fertilizer (GOF), Liquid Bioorganic Fertilizer (LBF), and their interaction on growth, yield, soil properties, and economic parameters. Mean comparisons were conducted using the Least Significant Difference (LSD) test at significance levels of 5% ($p < 0.05$) and 1% ($p < 0.01$).

Pearson correlation coefficients were calculated to assess relationships among agronomic traits, biomass accumulation, and grain yield (Ayoubi et al. 2009). Statistical analyses were performed using SPSS version 25 (IBM Corp., Armonk, NY, USA). Data visualization was done using Microsoft Excel 2019 and GraphPad Prism 8 software. Assumptions of normality and homogeneity of variance were verified prior to analysis, and data transformations were applied when necessary.

RESULTS AND DISCUSSION

Growth response of corn to bioorganic fertilizer treatments

The application of bioorganic fertilizers significantly influenced several vegetative growth parameters of corn, including plant height, number of leaves, stem diameter,

and leaf area. As shown in the ANOVA results, granular organic fertilizer had a significant effect on plant height ($p < 0.05$), with the highest values recorded under G2 treatment (2000 kg ha⁻¹). Similarly, BioEcoGum liquid fertilizer showed a significant impact on the number of leaves and leaf area ($p < 0.05$), particularly at concentrations of 4 and 6 mL L⁻¹ (Table 1).

Leaf area was especially responsive to the interaction between granular and liquid fertilizer treatments. As visualized in Figure 1, the control treatment (G0-P0) produced the smallest leaf area (419.4 cm²), while the highest value (648.9 cm²) was recorded under the G0-P3 treatment (6 mL L⁻¹ BioEcoGum without granular fertilizer). In contrast, the G1 and G2 groups exhibited a more stable leaf area response across BioEcoGum concentrations, suggesting a buffering effect of the organic matter on foliar nutrient uptake. Although granular fertilizer alone contributed positively to overall leaf expansion, the enhancement due to BioEcoGum foliar application was more prominent in plots with limited soil nutrient amendment.

Stem diameter showed no statistically significant differences across treatments ($p > 0.05$), indicating that this trait may be less responsive to external nutrient inputs under the given environmental conditions. However, the combined use of both fertilizer types tended to promote uniform vegetative development, supporting a more robust canopy structure and potential improvement in early-stage light interception. These findings demonstrate the capacity of BioEcoGum to enhance early vegetative growth even under limited soil fertility input, especially through increased photosynthetically active surface area. This suggests its potential as a strategic foliar supplement in low-input or degraded soil systems.

Flowering time and reproductive traits

The timing of male and female flowering in corn was moderately affected by fertilizer treatments. Although granular

and liquid bioorganic fertilizers did not significantly alter the flowering time at the 5% significance level (Table 1), slight trends in developmental acceleration were observed under higher BioEcoGum concentrations. Specifically, male flowering occurred earlier by approximately 1-2 days in treatments with 4-6 mL L⁻¹ BioEcoGum, particularly when combined with the 2000 kg ha⁻¹ granular dose (G2-P2 and G2-P3). These shifts, although not statistically significant, may reflect enhanced nutrient assimilation and hormonal balance during the pre-reproductive phase.

Female flowering followed a similar trend but exhibited slightly lower sensitivity to the treatments. The average reduction in flowering time across BioEcoGum-treated plots was about one day compared to the control (G0-P0), indicating improved synchrony between vegetative and reproductive development. This effect is ecologically advantageous, as more uniform flowering can lead to better pollination efficiency and kernel set (Uribelarra et al. 2008).

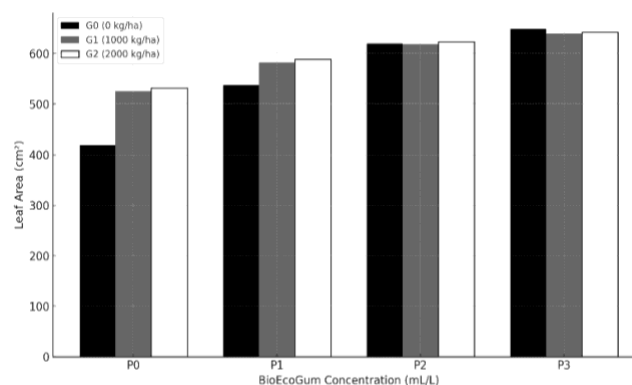


Figure 1. Effect of BioEcoGum and granular organic fertilizer on corn leaf area

Table 1. Results of analysis of variance (ANOVA) for the effects of granular and liquid bioorganic fertilizers on corn growth, yield components, and biomass traits

Variable	GOF (F)	LBF (F)	GOF × LBF (F)	CVA (%)	CVB (%)
Plant height (cm)	127.71	74.39	30.95	4.05	2.45
Number of leaves (no.)	0.23	1.09	0.57	2.19	4.40
Stem diameter (cm)	ns	ns	ns	5.28	2.26
Leaf area (cm ²)	10,256.44	21,083.13 **	9,008.70 *	15.59	9.59
Male flowering age (days)	0.86	1.30	0.71	2.69	1.67
Female flowering age (days)	0.58	0.25	1.36	1.07	2.04
Ear weight (g)	58.54 *	6.61 *	1.08	18.96	14.18
Grain weight per cob (g)	7.06	2.80 *	0.63	12.94	9.56
Grain yield (t/ha)	**61.82 ***	**9.73 **	**4.39 * **	8.44	6.27
Harvest index (ratio)	ns	ns	ns	12.33	8.14
Fresh stem biomass (g plant ⁻¹)	37,632.69 *	730.91	1,250.30	11.87	9.26
Dry stem biomass (g plant ⁻¹)	4,979.19 **	84.60 *	25.65	18.37	11.16
Fresh leaf biomass (g plant ⁻¹)	8,153.81 *	1,673.10	608.34	16.54	15.41
Dry leaf biomass (g plant ⁻¹)	449.20 **	226.45 **	13.68	6.81	5.01
Total fresh biomass (g plant ⁻¹)	196,749.11 **	14,169.93	7,005.33	14.15	13.31
Total dry biomass (g plant ⁻¹)	5,274.38 **	237.08 **	60.01	12.13	6.41

Notes: GOF: Granular Organic Fertilizer; LBF: Liquid Bioorganic Fertilizer (BioEcoGum); CVA: Coefficient of variation for GOF treatment; CVB: for LBF treatment; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ indicate significant differences based on the Least Significant Difference (LSD) test; ns: not significant ($p > 0.05$)

Reproductive structure development, particularly ear weight, showed a statistically significant response to both granular ($p < 0.05$) and liquid ($p < 0.05$) fertilizer treatments (Table 1). The highest ear weight values were recorded under combined G2-P3 treatment, suggesting a synergistic effect between soil and foliar nutrient sources in promoting reproductive biomass accumulation. This aligns with prior findings that reproductive traits in maize are highly responsive to nutrient availability, especially under conditions that support sustained photosynthate allocation to developing ears (Maiti and Singh 2017). These findings imply that, while flowering time may not be significantly shifted under current treatment levels, reproductive output in terms of ear development can be effectively enhanced through integrated fertilization approaches.

Biomass accumulation and yield performance

The combined application of granular and liquid bioorganic fertilizers had a pronounced effect on biomass accumulation and grain yield in corn (Alfarisy et al. 2021). As indicated in Table 1, both fertilizer types significantly influenced several biomass components, including fresh and dry biomass of stems and leaves, as well as total plant biomass ($p < 0.05$ or $p < 0.01$).

Dry stem biomass showed the strongest response to granular organic fertilizer (GOF), with G2 (2000 kg ha⁻¹) producing significantly greater values than G0 and G1. Similarly, dry leaf biomass increased with both GOF and BioEcoGum concentrations, reaching maximum values under the G2-P3 combination. These responses suggest improved nitrogen and potassium availability for structural growth when both soil amendment and foliar supplementation were applied.

Total dry biomass exhibited a significant increase under all treatment combinations involving BioEcoGum, with the G2-P3 treatment outperforming others (Table 1). This highlights the additive or possibly synergistic effects of humic substances and organic matter in supporting whole-plant productivity. Fresh biomass patterns followed similar trends, reinforcing the consistency of treatment effects across multiple parameters.

Grain yield, as estimated from grain weight per ear (GW), responded strongly to both fertilizer sources, with the highest grain weights observed in P2 and P3 treatments. Although not all combinations produced statistically distinct yield differences, grain weight was positively correlated with both dry stem biomass ($r = 0.34$) and total dry biomass ($r = 0.60$), as visualized in Figure 2. This suggests that improved biomass accumulation translates into higher sink strength and better assimilate partitioning into grains.

The consistent increase in dry matter accumulation, particularly in the reproductive organs, reflects improved photosynthetic capacity, possibly due to enhanced root vigor, foliar nutrient uptake, and hormonal modulation stimulated by BioEcoGum (Bhattachary 2021). These findings demonstrate that integrated bioorganic fertilization can

substantially enhance biomass productivity and yield potential in light chestnut soils, which are typically low in fertility.

Correlation among agronomic traits

To better understand the relationships among growth, biomass, and reproductive traits, a Pearson correlation analysis was conducted across all treatment combinations. The results are presented in Table 2. Grain weight per ear exhibited the strongest positive correlation with ear weight ($r = 0.81$), confirming the direct association between cob size and grain productivity. Moreover, grain weight was significantly correlated with total dry biomass ($r = 0.60$), dry stem biomass ($r = 0.34$), and dry leaf biomass ($r = 0.41$), indicating that vegetative vigor and assimilate storage are key determinants of reproductive success.

These patterns are further illustrated in Figure 2, where grain weight demonstrates a positive linear relationship with all three biomass components. The trend lines show that increases in biomass particularly total dry matter are associated with higher grain yields, although with differing slopes. This supports the notion that total biomass serves as a reliable proxy for sink strength and assimilate availability in grain-filling stages.

Interestingly, vegetative parameters such as plant height and number of leaves were only moderately or weakly correlated with grain yield ($r = 0.57$ and $r = 0.04$, respectively), suggesting that morphological size alone may not predict yield performance under these treatments. In contrast, physiological indicators like leaf area showed a negative or inconsistent correlation with yield, potentially due to trade-offs between vegetative expansion and reproductive resource allocation.

These correlations reinforce the role of dry biomass, particularly that of the stem and total plant, as a key intermediate variable linking nutrient availability with final grain yield. Therefore, treatments that promote efficient biomass production without excessive vegetative overhead are likely to be the most effective for improving productivity in light chestnut soils.

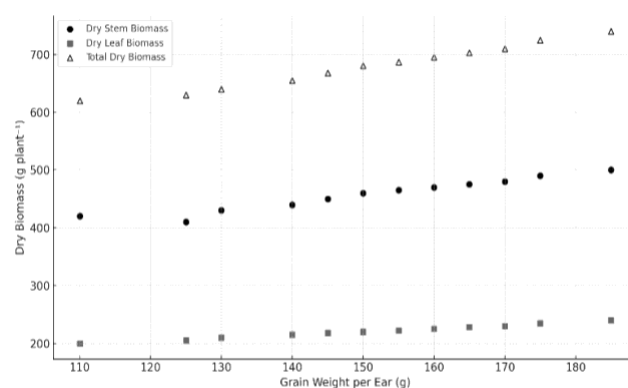


Figure 2. Relationship between grain weight and biomass components in corn

Soil fertility dynamics

The application of granular and liquid bioorganic fertilizers was found to moderately alter the chemical properties of light chestnut soils, particularly in the surface layer (0-20 cm). As presented in Table 3, soil organic matter (humus) content remained relatively stable across the two years of study, declining slightly from 1.93% to 1.83%. This modest change suggests that while organic amendments supported microbial activity and nutrient cycling, a longer application period may be needed to effect significant changes in soil organic carbon pools.

More pronounced shifts were observed in the availability of key macronutrients. Notably, available phosphorus (P_2O_5) increased substantially from 14.0 to 26.0 mg/kg in the surface soil layer, likely as a result of the combined input of soluble phosphates from the granular fertilizer and microbial mobilization enhanced by BioEcoGum. This improvement is particularly important given that phosphorus is often a limiting nutrient in alkaline soils like those of the study area.

In contrast, exchangeable potassium (K_2O) declined from 585 to 420 mg/kg, as shown in Figure 3. This reduction may reflect rapid uptake by vigorously growing plants, which outpaced the soil's replenishment capacity. While total potassium content remained relatively stable, the depletion of exchangeable forms indicates the need for balanced nutrient replenishment strategies to maintain long-term productivity. Hydrolyzable nitrogen (available N) levels decreased only slightly, from 35.0 to 33.6 mg/kg, indicating moderate biological nitrogen turnover during the

growing season. This stability may be due to the buffering effect of microbial communities stimulated by humic substances, which improve nitrogen use efficiency.

Overall, the data suggest that bioorganic fertilization enhances soil fertility through improved phosphorus availability and nutrient cycling, although potassium management may require additional attention in subsequent planting seasons. These findings support the strategic use of humic-based biostimulants and composted organics in sustainable nutrient management programs.

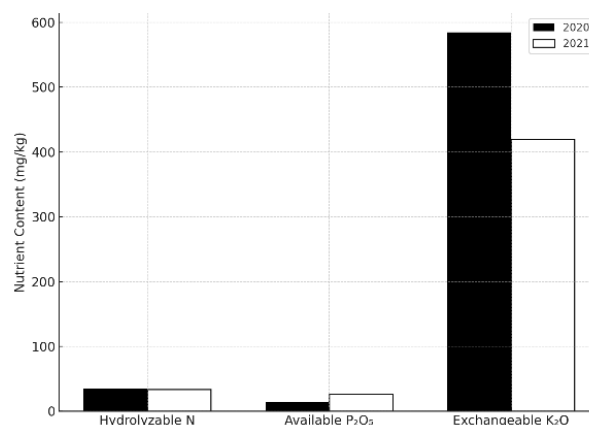


Figure 3. Changes in soil available nutrients (0-20 cm) before and after treatment

Table 2. Pearson correlation coefficients among selected agronomic traits of corn under different fertilizer treatments

Variable	PH	NL	LA	MF	FF	EW	GW	TDB	Yield
Plant height (PH)	1	0.48	-0.38	0.39	0.31	0.45	0.57	0.37	-0.05
Number of leaves (NL)		1	-0.31	0.33	0.11	0.38	0.57	0.39	0.04
Leaf area (LA)			1	-0.52	-0.40	-0.54	-0.54	-0.37	-0.07
Male flowering age (MF)				1	0.62	0.57	0.56	0.51	-0.02
Female flowering age (FF)					1	0.44	0.56	0.49	0.08
Ear weight (EW)						1	0.81	0.76	0.01
Grain weight per ear (GW)							1	0.60	-0.14
Total dry biomass (TDB)								1	0.10
Yield (final harvest weight)									1

Note: PH: Plant height; NL: Number of leaves; LA: Leaf area; MF: Male flowering age; FF: Female flowering age; EW: Ear weight; GW: Grain weight per ear; TDB: Total dry biomass; Yield: Final harvest weight per plant or plot. Values in bold (not shown here) indicate significant correlations at $p < 0.05$. Only the upper triangular matrix is shown, as the correlation matrix is symmetrical.

Table 3. Agrochemical characteristics of light chestnut soils before and after bioorganic fertilizer application

Year	Depth (cm)	Humus (%)	pH (H_2O)	Total N (%)	Total P_2O_5 (%)	Total K_2O (%)	Hydrolyzable N (mg/kg)	Available P_2O_5 (mg/kg)	Exchangeable K_2O (mg/kg)
2020	0-20	1.93	8.84	0.154	0.190	2.50	35.0	14.0	585
	20-40	1.46	8.90	0.112	0.216	2.44	30.8	9.0	340
2021	0-20	1.83	8.81	0.168	0.212	2.43	33.6	26.0	420
	20-40	1.46	8.87	0.112	0.212	2.37	28.0	10.0	260

Note: Soil samples were taken from the top 0-20 cm layer before treatment (early May) and after harvest (late August). P_2O_5 and K_2O are expressed in mg/kg, N as hydrolyzable N (mg/kg), and humus content in percentage (%). Values represent mean concentrations across treatment replicates.

Table 4. Economic performance of corn and broccoli production in 2021 under different treatments

Crop	Yield (t/ha)	Gross Revenue (tenge/ha)	Production Cost (tenge/ha)	Net Income (tenge/ha)	Cost per 100 kg (tenge)	Profitability (%)
Broccoli	24.9	883,000	454,496	428,504	18,253	94.3
Corn (control)	7.4	515,667	308,045	207,622	4,162	67.4
Corn (best yield)	13.5	945,000	605,480	339,520	2,519	56.1

Note: Total cost includes inputs, labor, and field operations. Net income was calculated as total revenue minus total cost. Cost per 100 kg refers to production cost per unit yield. All values are expressed in tenge per hectare (₸/ha) or per 100 kg of grain.

Economic performance and profitability

Economic analysis was conducted to assess the feasibility of integrating bioorganic fertilizers into corn production on light chestnut soils (Imran 2024). As shown in Table 4, the use of the highest-performing treatment combination (G2-P3) resulted in a corrected grain yield of 13.5 t/ha, producing a gross revenue of 945,000 tenge/ha. Although production costs under this treatment reached 605,480 tenge/ha due to the dual application of granular and foliar inputs, the resulting net income was 339,520 tenge/ha, with a profitability rate of 56.1%.

In comparison, the control treatment (no fertilizer input) yielded only 7.4 t/ha, with net income of 207,622 tenge/ha and a lower profitability rate of 67.4%. Interestingly, although the profit margin percentage appears higher in the control, the absolute profit was substantially lower than that of the best treatment. This reflects the classic trade-off between input investment and yield return, and highlights that high-efficiency treatments, despite greater initial cost, may be more advantageous in terms of total income generated.

Broccoli, included in the comparison as a high-value crop, produced a yield of 24.9 t/ha with a net income of 428,504 tenge/ha and the highest profitability rate (94.3%). While this demonstrates the economic potential of alternative crops, corn remains a staple with broader agronomic resilience and post-harvest market demand.

The cost of production per 100 kg of corn was lowest under the best treatment (2,519 tenge), compared to 4,162 tenge in the control. This reduction in unit production cost reinforces the economic efficiency of integrated fertilization and the contribution of BioEcoGum in improving both biological productivity and cost-effectiveness. Overall, these results demonstrate that the combined use of granular and liquid bioorganic fertilizers not only enhances agronomic performance but also provides tangible economic benefits, justifying their adoption under semi-arid soil conditions.

Discussion

Enhanced vegetative growth through bioorganic fertilization

The application of bioorganic fertilizers significantly enhanced vegetative growth parameters in corn, particularly plant height, leaf area, and number of leaves. These improvements are consistent with the observed statistical significance in the ANOVA results (Table 1) and reflect the capacity of humic-based liquid formulations, such as BioEcoGum, to stimulate early plant development through multiple physiological pathways. The pronounced expansion of leaf area under foliar BioEcoGum treatment (Figure 1)

indicates improved chlorophyll content and photosynthetic surface, which are critical during the rapid vegetative phase of corn.

Humic substances, the active component of BioEcoGum, are known to influence membrane permeability, enhance nutrient uptake, and activate hormonal pathways such as auxin-like responses, leading to increased cell elongation and division (Suleimenov et al. 2019). In this study, even in the absence of granular organic inputs (G0), foliar BioEcoGum application at 6 mL L⁻¹ (P3) resulted in a 54.7% increase in leaf area compared to the untreated control (P0), suggesting that foliar pathways are effective routes for nutrient and biostimulant assimilation under nutrient-limited soil conditions.

Granular organic fertilizer further supported vegetative growth by improving soil structure and microbial activity, contributing to sustained nutrient release (Tian et al. 2022). However, the response was more gradual compared to the liquid treatment, indicating complementary modes of action. Treatments combining both fertilizer types generally showed the most stable and consistent improvements, suggesting a synergistic effect. These findings underscore the potential of integrated bioorganic strategies in enhancing early plant vigor, especially in low-fertility or degraded soils such as light chestnut types. Improved vegetative growth lays the foundation for better reproductive development, which is discussed in the following sections.

Modulation of reproductive development and yield formation

Reproductive development in corn is sensitive to both nutrient availability and timing of assimilate allocation, and this study demonstrates that bioorganic fertilization contributes to improved yield formation through multiple mechanisms. Although flowering time did not differ significantly across treatments (Table 1), a consistent trend of earlier male and female flowering was observed under higher BioEcoGum concentrations, particularly in combination with granular fertilizer. Such shifts, though subtle, are agronomically relevant, as synchronized and timely flowering supports optimal pollination and kernel set.

The most notable reproductive improvement was observed in grain yield components, particularly grain weight per ear and ear weight. Both parameters showed statistically significant responses to fertilizer application (Table 1). Treatments involving higher BioEcoGum levels (P2 and P3) produced heavier ears, with the best performance under the G2-P3 combination. This suggests that nutrient uptake and hormonal stimulation through humic substances not

only enhance vegetative vigor but also improve reproductive sink strength.

Increased leaf area under BioEcoGum treatments (Figure 1) likely contributed to enhanced assimilate production during the critical grain-filling period. Improved photosynthetic efficiency, driven by broader leaf surfaces, may have supported a larger carbohydrate pool for grain development. This is further supported by the strong positive correlation between grain weight and total biomass components, discussed in the next section.

Importantly, the combined application of granular and foliar bioorganic fertilizers did not merely additively increase yield; rather, the interaction appeared synergistic, as the highest grain weights were not observed under single-source treatments. This implies that both soil and foliar nutrient pathways must be simultaneously optimized to fully unlock the reproductive potential of corn, particularly under conditions of moderate soil fertility.

Correlation between biomass and yield potential

Understanding the relationship between vegetative biomass and grain yield is critical for optimizing input strategies in maize cultivation. In this study, correlation analysis revealed that grain weight per ear had a strong and significant positive relationship with ear weight ($r = 0.81$), as well as moderate correlations with dry stem biomass ($r = 0.34$), dry leaf biomass ($r = 0.41$), and total dry biomass ($r = 0.60$) (Table 2). These findings confirm that robust vegetative growth contributes to grain yield not merely through structural size, but through effective source-sink dynamics.

The relationships are further visualized in Figure 2, where the linear trends suggest that as biomass accumulation increases, grain weight improves proportionally especially with total dry biomass. This underscores the importance of assimilate availability during the grain-filling period, which is driven by cumulative photosynthetic output and internal remobilization of stored carbohydrates.

Interestingly, plant height and number of leaves, while often considered basic indicators of vigor, showed weaker correlations with grain weight ($r = 0.57$ and $r = 0.04$, respectively). This suggests that sheer plant size or morphology alone may not be a reliable predictor of yield, especially in systems influenced by organic amendments where physiological efficiency matters more than physical dimensions.

These results emphasize that total dry matter particularly stem biomass, which functions as both a structural support and a reservoir for remobilized carbohydrates is a more reliable yield predictor than superficial growth traits. Consequently, fertilization strategies that promote biomass accumulation without excessive vegetative expansion can lead to improved yield efficiency, especially under resource-limited conditions.

Such insights align with the findings in other organic and semi-arid production systems, where biomass-to-grain conversion efficiency becomes a key trait under fluctuating environmental and nutrient conditions.

Soil fertility restoration in light chestnut soils

Soil fertility restoration is a major challenge in light chestnut soils due to their low organic matter content, limited cation exchange capacity, and often alkaline pH (Vittori Antisari et al. 2013). The application of bioorganic fertilizers in this study resulted in moderate but meaningful changes in soil chemical properties, particularly in the upper 0-20 cm layer, where root activity is concentrated. As shown in Table 3, the most substantial improvement was observed in the availability of phosphorus (P_2O_5), which increased from 14.0 to 26.0 mg/kg. This change is likely attributable to the combined effects of mineral inputs from the granular fertilizer and the solubilization of bound phosphorus by humic substances and microbial activity stimulated by BioEcoGum.

In contrast, a marked reduction in exchangeable potassium (K_2O) was recorded, decreasing from 585 to 420 mg/kg over the same period. This decline, visualized in Figure 3, may be explained by high plant uptake during vigorous biomass accumulation and possible leaching losses not fully compensated by the fertilizer treatment. Although potassium is generally abundant in many soils, its readily available form can be rapidly depleted without adequate replenishment highlighting the need for balanced nutrient management in organic systems.

Nitrogen levels, measured as hydrolyzable N, decreased only slightly from 35.0 to 33.6 mg/kg, indicating a relatively stable N pool likely supported by microbial mineralization of organic matter. Meanwhile, soil humus content declined marginally (from 1.93% to 1.83%), suggesting that one season of organic application is not sufficient to build up stable organic carbon in light-textured soils. Overall, these findings point to the partial restoration of soil fertility, with improved phosphorus availability as a key benefit, while highlighting potassium as a potentially limiting factor in repeated cropping cycles. Long-term studies and nutrient budgeting are needed to ensure sustainable soil health under intensive bioorganic fertilizer use.

Economic implications of integrated bioorganic fertilizer use

Economic viability is a critical determinant in the adoption of sustainable agricultural technologies (Ochieng et al. 2022). In this study, the combined application of granular and liquid bioorganic fertilizers not only improved agronomic performance but also enhanced profitability, as reflected in the cost-benefit analysis summarized in Table 4. The best-performing treatment (G2-P3) resulted in a grain yield of 13.5 t/ha and generated a net income of 339,520 tenge/ha, despite higher production costs compared to the control. This represents a 63.5% increase in net return over the non-fertilized treatment (G0-P0), which yielded only 7.4 t/ha.

Interestingly, while the profitability ratio of the control was higher (67.4%) due to minimal input costs, the absolute profit was significantly lower. This highlights a common economic trade-off: low-input systems may appear efficient per unit cost, but high-input systems often produce greater net returns due to yield maximization. Moreover, the cost per 100 kg of corn was lowest under the G2-P3 treatment

(2,519 tenge), indicating greater cost efficiency per output unit.

The inclusion of broccoli as a reference high-value crop illustrates that, while alternative crops may offer superior economic margins (94.3% profitability), corn remains a strategically important commodity for both food security and market stability in semi-arid regions. Thus, enhancing its productivity through bioorganic means is a viable strategy for resource-limited farmers. From a broader perspective, these findings validate the economic rationale for adopting integrated fertilization practices. Although initial costs are higher, returns in both yield and profitability justify the investment, especially when external inputs are derived from renewable or locally available organic sources. Long-term implementation may also reduce dependency on synthetic fertilizers, contributing to both economic resilience and environmental sustainability.

Comparison with previous studies and agroecological relevance

The results of this study are largely consistent with previous research demonstrating the agronomic and ecological benefits of integrating organic and bio-based fertilizers. Similar yield enhancements following humic substance application have been reported in maize by Song et al. (2022) and Verlinden et al. (2009) who attributed the improvements to increased nutrient uptake efficiency and enhanced photosynthetic activity. The observed increase in leaf area and biomass in the current study corroborates these findings, indicating that humic-rich foliar applications can play a significant role in boosting vegetative growth under nutrient-limited conditions.

In terms of yield formation, the synergistic effect of combined granular and liquid organic fertilizers aligns with studies conducted in dryland and degraded soils, such as those by Liu et al. (2021) and Tian et al. 2022, where integrated organic fertilization improved not only yield but also soil structure and microbial function. The modest changes in humus content and nitrogen levels in this study reflect the need for longer-term applications, a limitation frequently noted in organic soil fertility programs.

Soil phosphorus availability showed significant improvement, paralleling findings from Habib (2021) in semi-arid soils, where humic acids enhanced phosphate solubilization and plant uptake. However, the depletion of exchangeable potassium observed here highlights a divergence from studies in heavier soils, where organic matter often contributes to greater K retention. From an agroecological standpoint, the adoption of bioorganic fertilizers offers a sustainable intensification pathway for marginal lands such as the light chestnut soils of the Ontusik Region. These systems typically suffer from poor nutrient retention, low microbial biomass, and erratic rainfall. The use of biostimulants and organic amendments not only supports crop productivity but may also build resilience to climatic and edaphic stressors over time. Together, the findings validate the integration of organic and humic-based inputs as a promising approach for environmentally sound and economically viable maize cultivation in resource-constrained agroecosystems.

In conclusion, the integration of granular and liquid bioorganic fertilizers significantly improved the growth, yield, and economic performance of corn cultivated on light chestnut soils. BioEcoGum foliar application enhanced vegetative development, particularly leaf area expansion, while granular organic fertilizer contributed to overall biomass accumulation and yield stability. The combined treatments not only increased grain weight and total dry matter but also promoted earlier and more synchronized flowering, supporting reproductive efficiency. Soil fertility improvements were evident through increased phosphorus availability, although potassium depletion highlights the need for balanced nutrient management. Economically, the most intensive treatment (G2-P3) yielded the highest net income and lowest cost per unit output, confirming its viability for adoption despite higher input costs. These outcomes are consistent with previous studies on humic substances and organic amendments, reaffirming their effectiveness in semi-arid and nutrient-limited environments. The findings underscore the potential of integrated bioorganic fertilization as a sustainable intensification strategy that addresses both productivity and soil health challenges in marginal agroecosystems. While short-term gains are promising, longer-term trials are recommended to assess cumulative effects on soil quality and nutrient dynamics. Overall, this study provides a practical and ecologically sound basis for scaling up the use of bioorganic inputs in dryland maize production systems.

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