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SUNFLOWER (*HELIANTHUS ANNUUS* L.) LEAF AREA RESPONSE TO MINERAL FERTILIZATION GROWN IN IRRIGATED GRAY-BROWN SOILS

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SUMMARY

Agrochemical analysis of irrigated gray-brown (chestnut) soils in the Ganja-Dashkasan Economic Region, Azerbaijan, during 2022–2024 revealed low levels of plant-available nutrients, including ammonium and nitrate nitrogen, available phosphorus, and exchangeable potassium. As per national classification, these soils had poor supplies of essential nutrients and need application of mineral fertilizers to maintain soil fertility and ensure optimal growth and productivity of sunflower (*Helianthus annuus* L.). This study evaluated the effects of balanced nutrient supply on the growth and yield of sunflower under irrigated conditions**.** Field experiments conducted were in a randomized complete block design (RCBD) with three replications. Nitrogen, phosphorus, and potassium fertilizer applications were at recommended rates using split applications. The results showed mineral fertilization significantly increased leaf area. The largest leaf area was evident under the $N_{120}P_{120}K_{120}$ treatment. Furthermore, balanced fertilization improved physiological activity, resulting in an enhanced plant growth and a higher yield performance.

Keywords: Sunflower (*Helianthus annuus* L.), mineral fertilization, nutrient management, irrigated soils, crop growth, yield performance

Key findings: In sunflower (*H. annuus* L.) growth traits (leaf area and physiological processes) and yield, the highest improvement was successful by using the fertilization treatment of $N_{120}P_{120}K_{120}$.

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INTRODUCTION

Sunflower (*Helianthus annuus* L.) is one of the most pivotal oilseed crops globally and plays a crucial role in ensuring vegetable oil production and agricultural sustainability. Sunflower cultivation has considerably expanded, particularly in the Ganja-Dashkasan Economic Region, Azerbaijan, where favorable soil and climatic conditions support its growth and production. However, in this region, constraints to sunflower productivity are due to suboptimal soil fertility and imbalanced nutrient management (Akbarova and Mammadova, 2024).

Gray-brown soils widely distributed in the region were generally characterized by low availability of essential plant nutrients, including nitrogen, phosphorus, and potassium. Since sunflowers have a well-developed root system and the highest nutrient demand, the appropriate nutrient management during critical growth stages is indispensable for achieving steady yields and improving seed quality (Bayrambekov *et al*., 2013; Akhundova *et al*., 2025).

Previous studies have shown that balanced fertilization considerably enhanced plant growth and development, leaf area expansion, and yield formation, while insufficient nutrients, particularly during early growth stages, can lead to reduced growth and development, biomass accumulation, and lower productivity. Similar observations were in reports for oilseed crops under diverse agroecological conditions (Novruz *et al*., 2025; Bahram *et al*., 2026).

Among macronutrients, the nitrogen and phosphorus play a crucial role in the vegetative growth and reproductive development, whereas potassium is essential to assimilate translocation and stress tolerance. Additionally, micronutrients, such as boron, proved critical for proper flowering and seed formation. Regardless of the recognized importance of mineral nutrition, the optimization of fertilizer application rates under existing soil and climatic conditions remains unsatisfactorily studied in Azerbaijan (Ismayilov *et al*., 2025; Ikhtiyar *et al*., 2026).

Therefore, the consequent study aimed to appraise the effect of balanced mineral fertilization on the growth and development and productivity of sunflowers cultivated in irrigated gray-brown soils of the Ganja–Dashkasan Economic Region, Azerbaijan. The study hypothesized that the application of optimal rates of nitrogen, phosphorus, and potassium fertilizers would improve plant growth parameters, enhance physiological processes, and, ultimately, increase yield and agronomic performance (Oqtay *et al*., 2024; Ismayilova *et al*., 2025).

MATERIALS AND METHODS

Study area and experimental design

Field experiments on sunflower (*H. annuus* L.) began during 2022–2024 on irrigated gray-brown (chestnut) soils at the Ganja Regional Agrarian Science and Innovation Center, Ganja-Dashkasan Economic Region, Azerbaijan. The experiment was in a randomized complete block design (RCBD) arrangement with three replications. The total plot area was 100 m² (40 m × 2.5 m). The early-maturing sunflower (*H. annuus* L.) cultivar 'Lakomka' was the test crop used. The fertilizer treatments comprised the following: a) control (no fertilizer), b) $N_{60}P_{60}K_{60}$, c) $N_{90}P_{90}K_{90}$, d) $N_{120}P_{120}K_{120}$, and e) $N_{150}P_{150}K_{150}$ (Ikhtiyar *et al*., 2026).

According to crop management and fertilizer application, sowing the sunflower seeds in rows had the spacing of 50 cm × 35 cm at the seeding rate of 15 kg ha^{-1} (Mammadova *et al*., 2024). The N, P, and K fertilizer applications were in the form of ammonium nitrate (34.7% N), simple superphosphate (18.7% P_2O_5), and potassium sulfate (46% K_2O), respectively. The P and K fertilizers had an 80% application of the total rate before autumn plowing and 20% as top dressing. Nitrogen treatment was in two split doses during the growing season. All agronomic practices performed followed regional recommendations (Mirzezadeh *et al*., 2025). Phenological observations continued on 25 plants in two replications. Total leaf area,

upon determination, followed the methodology of Dospekhov (Mammadzada *et al*., 2026).

During the growing season, the experimental plots received irrigation five times using the sub-artesian water. Depending on weather conditions, the irrigation rate ranged from 800 to 1000 m^3 ha^{-1} per irrigation event, while the total seasonal irrigation amount varied between 3600 and 4500 m^3 ha^{-1}. During the study period (2022–2024), the mean air temperature in the growing season ranged from 15.2 °C to 15.7 °C, while total precipitation varied between 156.3 and 217.2 mm. Weather conditions during the experimental years differed only slightly from the long-term average values.

Soil and plant analysis

Soil samples collected before the establishment of the experiment underwent analysis using standard methods. Soil pH determination proceeded potentiometrically, with the humus content measured using the Tyurin method. Available nitrogen, phosphorus, and potassium, as detected, used standard procedures (Mammadzada *et al*., 2025). Plant samples' assessment for dry matter content received oven drying at 105 °C. Total nitrogen, phosphorus, and potassium contents, upon determination, used standard analytical methods (Bahram *et al*., 2025).

The physicochemical properties of the soil showed the distribution of soil fractions and exchangeable bases across different soil layers. The data revealed relatively stable clay and silt composition, confirming the classification of the soils as light loam. The soil structure was generally favorable for crop growth; however, it requires adequate fertilization to compensate for low nutrient reserves (Simić and Dragicevic, 2011).

According to agrochemical characteristics of the soil, for nutrient content, an apparent decline emerged with the soil depth. The highest concentrations of humus, nitrogen, phosphorus, and potassium appeared in the 0–30 cm soil layer, decreasing significantly and gradually in deeper soil layers. This vertical distribution explains the robust response of sunflowers to fertilizer application, as root-accessible nutrients were insufficient in deeper soil horizons (Smirnov *et al*., 2019).

Leaf area measurement

Sunflower leaf length and width (LW) sustained measurement to calculate leaf area (LA), often using a linear equation such as in Figure 1:

$$\text{Leaf area (LA)} = 6.72 + 0.65 \times \text{LW} \ (\text{cm}^2)$$

Leaf length measurement started from the lamina tip to the petiole intersection, while the leaf width was across the widest part, typically with 0.1 cm accuracy (Titovskaya *et al*., 2018; Nazim *et al*., 2025).

Figure 1. Measurement of leaf length and width in sunflower (*H. annuus* L.).

Statistical analysis

All the recorded data based on various parameters reached assessment using the analysis of variance (ANOVA) (Nazim *et al*., 2025). Treatment means received comparison and separation at the 5% level of significance ($p < 0.05$). Correlation analysis, when performed, evaluated relationships among the leaf area, biomass, and seed yield. However, the increased fertilizer rate (NPK_{150}) resulted in a slight decrease in leaf area, indicating that excessive fertilization could negatively affect plant growth and development due to nutrient imbalance and osmotic effects (Titovskaya *et al*., 2018).

RESULTS AND DISCUSSION

Studying the effect of mineral fertilizers on sunflower (*H. annuus* L.) leaf area and soil nutritional status in irrigated gray-brown (chestnut) soils was very relevant because the level of nutrients necessary for forage crops decreases each year. The mineral fertilizers' application significantly ($p < 0.05$) improved the total leaf area per plant at all growth stages compared with the control. In the unfertilized treatment (control), the leaf area remained minimal due to insufficient nutrients available in the existing soil. In contrast, in the fertilized treatments, a stable increase resulted in leaf area, reflecting improved plant growth and biomass conditions. Leaf area measurement occurred at the 4–6 leaf, budding, and flowering stages under irrigated gray-brown (chestnut) soil conditions. Past studies also showed plant leaves as a biogeochemical indicator of the environmental state in different regions of Azerbaijan (Nazim *et al*., 2025; Verdiyeva *et al*., 2026).

The NPK application denotes the different levels of nitrogen, phosphorus, and potassium fertilizer application (Figure 2). The dynamics of leaf surface development entailed studies at different stages of plant growth and development, where a gradual increase was noteworthy from the 4–6 leaf stage to the flowering stage. However, this trend was more noticeable under fertilized conditions, revealing enhanced photosynthetic surface formation. Among the fertilizer treatments, the recorded highest leaf area values appeared in the variant of NPK_{120}. The results suggested this fertilizer rate provided optimal nutrient balance, promoting plant vegetative growth and development. The nitrogen likely stimulated the chlorophyll formation and leaf expansion, while phosphorus and potassium supported metabolic and water regulation processes in crop plants (Nazim *et al*., 2025; Ikhtiyar *et al*., 2026).

However, a further increase in fertilizer rate (NPK_{150}) resulted in a slight decrease in leaf area, implying that excessive fertilization could negatively affect plant growth and development due to nutrient imbalance and osmotic effects. The physicochemical properties of the soil showed the distribution of soil fractions and exchangeable bases across different soil layers. The data revealed relatively stable clay and silt composition, recognizing the classification of soils as light loam. This soil structure was generally favorable for crop growth but requires adequate fertilization to compensate for the low nutrient reserves (Suleymanov *et al*., 2015). Particle-size fractions (clay, silt, and others) also gained detection at 0–30, 30–60, and 60–100 cm in the irrigated gray-brown chestnut soils (Figure 3).

According to agrochemical characteristics of the soil, the nutrient contents revealed an obvious decline with soil depth. The highest concentrations of humus, nitrogen, phosphorus, and potassium occurred in the 0–30 cm soil layer, which gradually and significantly decreased in deeper soil layers. This vertical distribution explains the robust response of sunflower plants to fertilizer application, as root-accessible nutrients lessen in deeper soil horizons (Ikhtiyar *et al*., 2026). Furthermore, the correlation analysis revealed a significant positive relationship between the leaf area, biomass accumulation, and yield, confirming that improved leaf development enhanced overall plant productivity (Figure 4).

The leaf area (LA) measurements served to assess plant growth, health, and canopy development. The coefficients of determination (R^2) ranged from 0.82 to 0.99,

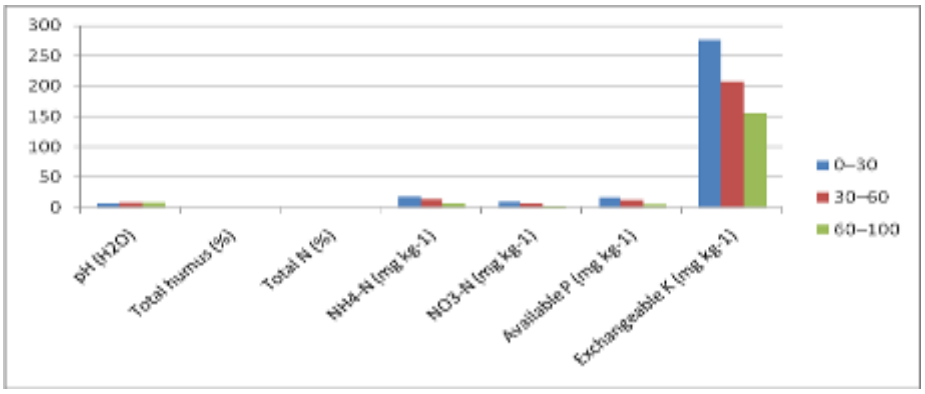
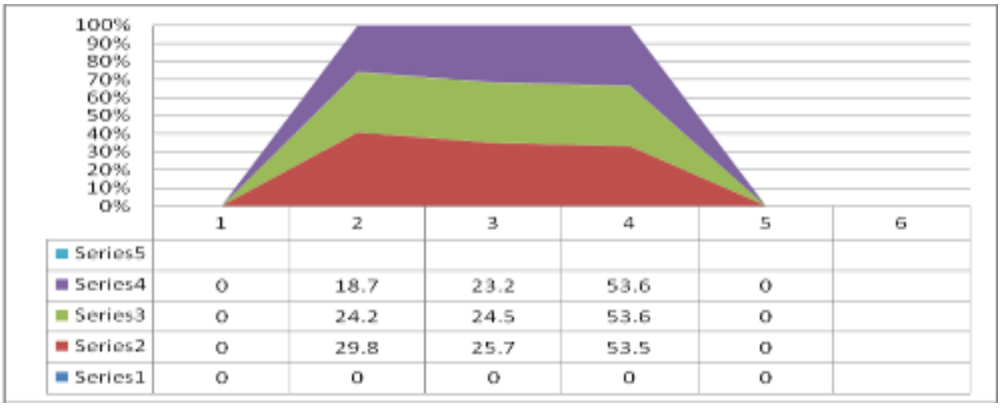
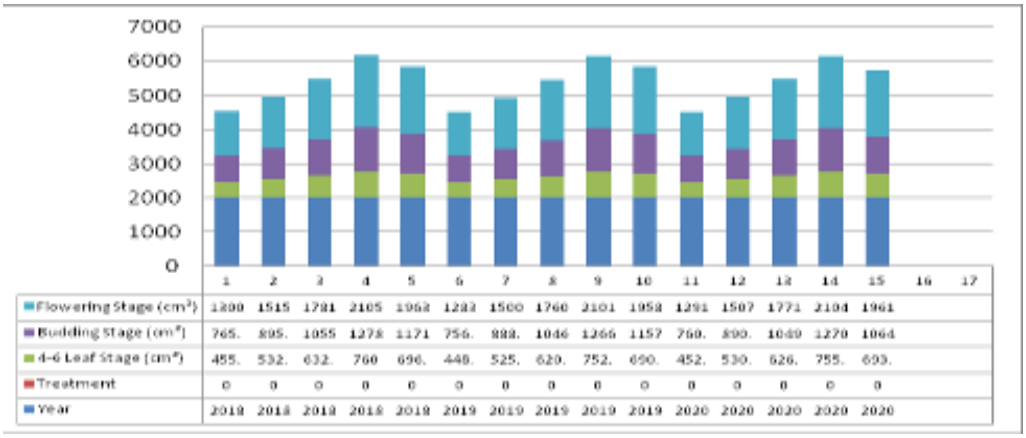


Figure 2. Effect of NPK rates on sunflower (*H. annuus* L.) leaf area at key growth. Note: Leaf area measurement was at the 4–6 leaf, budding, and flowering stages.



	1	2	3	4	5	6
Series5						
Series4	0	18.7	23.2	53.6	0	
Series3	0	24.2	24.5	53.6	0	
Series2	0	29.8	25.7	53.5	0	
Series1	0	0	0	0	0	

Figure 3. Soil particle-size distribution across depth layers. Note: Data indicate a predominantly light loam texture.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Flowering Stage (cm²)	1200	1515	1781	2165	1962	1282	1500	1760	2101	1958	1291	1507	1771	2104	1961		
Budding Stage (cm²)	765.	895.	1055	1278	1171	756.	888.	1046	1266	1157	760.	890.	1049	1270	1064		
4-6 Leaf Stage (cm²)	455.	532.	632.	760	696.	448.	525.	620.	752.	690.	452.	530.	626.	755.	693.		
Treatment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Year	2018	2018	2018	2018	2018	2019	2019	2019	2019	2019	2020	2020	2020	2020	2020		

Figure 4. Agrochemical properties by the soil depth of 0–30, 30–60, and 60–100 cm under irrigated conditions.

providing the highest degree of relationship. The leaf area values calculated from leaf characteristics emerged to be highly significant ($p \leq 0.01$), revealing that the simulated data were in better agreement with the observed data (Figure 1).

Overall, the results showed mineral fertilization plays a decisive role in improving sunflower growth under the studied soil conditions of the Ganja-Dashkasan Economic Region, Azerbaijan (Nazim *et al*., 2025). The study identified the NPK_{120} treatment as an optimal dose, ensuring maximum leaf area development without negative effects associated with excessive fertilizer application. The Pearson CC (correlation coefficient) calculation showed the statistical dependence on the agar medium on biological activity. For moldboard tillage, the CC in 2024 had a value of r = 0.9196, while for zero tillage, r = 0.9211. In a repeated study in 2025, the following values of the CC were the following results: for moldboard tillage, r = 0.8896; and for zero tillage, r = 0.6632. These results may be important for developing efficient and sustainable fertilizer management strategies for sunflower cultivation in gray-brown soils (Suleymanov *et al*., 2015; Ikhtiyar *et al*., 2026).

CONCLUSIONS

Mineral fertilizer application remarkably improved the leaf area development of sunflowers (*H. annuus* L.) across all growth stages under gray-brown soils, detailing the greater importance of balanced nutrient supply for vegetative growth. Moderate fertilizer levels showed the most favorable results, while excessive fertilizer application showed a tendency to affect and reduce growth efficiency. Enhanced leaf area was in a close association with improved biomass accumulation and yield formation, highlighting its crucial role in crop productivity. The results suggested proper nutrient management can significantly enhance sunflower performance; however, the results should entail cautious application under different soil and environmental conditions. In the study of soil bioactivity, microorganisms appeared to be more active in the upper soil layer (0.0–0.2 m). During moldboard tillage, microorganisms were active in the 0.3–0.5 m layer. Based on the findings of this study, the $N_{120}P_{120}K_{120}$ fertilizer rate can be the recommended dose for sunflower cultivation on irrigated gray-brown soils, as it provides an optimal balance of nutrient supply and plant growth. The adoption of this fertilizer management strategy could help improve crop productivity and ensure more efficient use of mineral fertilizers under local conditions.

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