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Biostimulant and Silicon Synergistically Enhance Potato Physiology, Water Use Efficiency, and Tuber Yield under Field Conditions

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ABSTRACT

Potato (*Solanum tuberosum* L.) production in arid and semi-arid regions is increasingly constrained by water scarcity, heat stress, and associated oxidative damage. Therefore, sustainable strategies that enhance crop performance and improve water-use efficiency are essential. This study evaluated the effects of foliar-applied of a biostimulant and nano silicon, applied individually and in combination, on potato growth, physiological responses, antioxidant defense, water relations, and yield under semi-arid conditions in Egypt. A two-season field experiment (2024 and 2025) was conducted using a randomized complete block design with four treatments: control, biostimulant, nano silicon, and biostimulant + nano silicon.

All treatments significantly improved chlorophyll content, leaf area index, plant growth, antioxidant enzyme activities, plant water status, and yield compared with the untreated control. Across most measured traits, treatment performance consistently followed the order: control < biostimulant < nano silicon < biostimulant + nano silicon. Treated plants showed increased proline accumulation and higher activities of superoxide dismutase, catalase, and peroxidase, indicating enhanced oxidative stress tolerance. Applications also reduced canopy temperature and increased water-use efficiency.

Yield components, including tuber number, tuber weight, total yield, and marketable yield, were significantly enhanced, with the combined treatment producing the highest productivity in both seasons. These findings demonstrate a synergistic interaction between biostimulant and nano silicon, integrating metabolic stimulation with structural and physiological protection.

The combined application of biostimulant and nano silicon represents a practical, environmentally sustainable, and effective strategy to improve potato productivity and resilience under water-limited conditions typical of arid agricultural regions.

Keywords: silicon, antioxidant enzymes, water-use efficiency, drought stress, tuber yield.

INTRODUCTION

Potatoe (*Solanum tuberosum* L.) is one of the most important food crops worldwide and plays a vital role in food security due to its high productivity nutritional value, and adaptability to diverse agroecological conditions. In Egypt, they are especially important, serving both local markets and export demands. However, their productivity is increasingly threatened by environmental issues like water shortages, high evaporation rates, and rising temperatures caused by climate change.

These plants are particularly vulnerable to water stress during key growth phases like tuber formation. Several studies demonstrating significant genotypic variability in drought tolerance and emphasizing the importance of selecting adapted cultivars and stress-mitigation technologies (Ștefan et al., 2020; Tican et al., 2021). When water is scarce, potatoes struggle with photosynthesis and nutrient absorption, leading to lower yields. Drought also causes oxidative stress due to a buildup of harmful molecules called reactive oxygen species (ROS), which damage cells and disrupt photosynthesis. Because of this, finding ways to improve the plant's ability to tolerate stress and use water more efficiently is a top research priority, especially in dry regions.

In recent years, plant biostimulants have attracted increasing attention as environmentally

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sustainable inputs capable of enhancing crop performance under abiotic stress conditions (Hamed, 2026). Biostimulants, including seaweed extracts, amino acids, and humic substances, are known to stimulate plant metabolic activity, improve nutrient uptake and assimilation, enhance photosynthetic efficiency, and activate antioxidant defense systems (Farouk, 2015; Rouphael and Colla, 2020). Accumulating evidence indicates that biostimulant application can significantly enhance potato growth, tuber yield, and quality by modulating key physiological and biochemical processes, particularly under stress-prone environments (Trawczyński, 2020; Alowaiesh et al., 2024).

Silicon (Si), although not classified as an essential plant nutrient, is widely recognized as a beneficial element that enhances plant tolerance to multiple abiotic stresses. Silicon application improves plant water status by reducing transpirational water loss, strengthening cell wall structures, and regulating stomatal behavior. In addition, silicon plays a pivotal role in alleviating oxidative stress through the enhancement of antioxidant enzyme activities, including superoxide dismutase, catalase, and peroxidase (Mahmoud et al., 2022). In potato, silicon supplementation has been reported to improve chlorophyll content, photosynthetic performance, water use efficiency, and tuber yield under drought and salinity stress conditions (Wadas, 2021; Al-Selwey et al., 2023).

Recent studies further suggest that the combined application of biostimulants and silicon may exert synergistic effects on plant growth and stress tolerance. While biostimulants primarily enhance metabolic activity and hormonal regulation, silicon provides structural reinforcement and physiological protection against stress-induced cellular damage. This complementary interaction can promote osmolyte accumulation, strengthen antioxidant capacity, and improve the maintenance of cellular homeostasis under unfavorable environmental conditions (Ma et al., 2016; Melo-Sabogal and Contreras-Medina, 2024). However, despite growing interest in this integrated approach, field-based studies evaluating the combined effects of biostimulants and silicon on potato performance particularly under Egyptian agro-climatic conditions remain limited.

Therefore, this study aimed to evaluate the individual and combined effects of biostimulant and nano-silicon on growth, physiological traits, antioxidant activity, water use efficency, and yield of potatoes under field conditions in Egypt.

MATERIAL AND METHODS

Experimental Site and Location

The field trials were carried out over two consecutive growing seasons 2024 and 2025, to enhance the reliability and repeatability of the results under field conditions, on a privately owned farm in Nile Delta, Beheira Governorate, Egypt (30.758528° N, 30.689093° E). This area experiences a Mediterranean climate, with mild winters and warm conditions during the growing period. Since rainfall is minimal during the potato season, irrigation was a necessary part of the farming process.

Soil Sampling and Analysis

Prior to the initiation of the experiment, composite soil samples were collected from the experimental field to characterize the physico-chemical properties of the soil. Samples were taken from the 0-60 cm soil depth, corresponding to the effective root zone, using a soil auger. At each sampling point, multiple cores were collected and thoroughly mixed to form a representative composite sample.

Soil samples were air-dried, ground, and passed through a 2-mm sieve before laboratory analysis. Soil texture was determined using the hydrometer method, while soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter. Electrical conductivity (EC) was determined in the same extract using a conductivity meter.

Soil organic matter content was determined using the Walkley-Black dichromate oxidation method, and total nitrogen was analyzed using the Kjeldahl method. Available phosphorus was determined using the Olsen method, while exchangeable potassium was measured using a flame photometer following ammonium acetate extraction.

Field capacity (FC) was determined at a matric potential of -0.033 MPa, while the permanent wilting point (PWP) was measured at -1.5 MPa, and available water content was calculated as the difference between FC and PWP. All analyses were conducted following standard procedures as described in Page et al. (1982) and FAO guidelines for soil analysis.

The average physicochemical properties of the soil were as follows: pH 7.85, electrical conductivity 1.75 dS/m, organic matter 1.15%, total nitrogen 0.085%, and available phosphorus and potassium concentrations of 17.5 mg/kg and 240 mg/kg, respectively. Field capacity was 32%, permanent wilting point was 15%, resulting in an available water content of 17%.

Experimental Design and Crop Management

The study followed a randomized complete block design (RCBD) with four different treatments, each replicated four times. The treatments included: (1) Control, (2) Biostimulant, (3) Silicon, and (4) Biostimulant + Silicon. Each experimental plot consisted of rows planted with certified seed tubers of the Spunta potato variety, approved by Egypt's Ministry of Agriculture. Tubers were uniform (35-45 mm in diameter) and free from visible damage.

Irrigation was applied using a drip irrigation system, with soil moisture maintained at approximately 50% depletion of available soil water within the effective root zone (0-60 cm). Based on the determined soil water constants and assuming an irrigation application efficiency of 90%, the total seasonal irrigation water applied was approximately 7030 m^3 ha^{-1} during the first growing season and 8200 m^3 ha^{-1} during the second growing season. The same irrigation regime was uniformly applied to all experimental treatments throughout both seasons.

Tubers were planted on October 15 in both seasons during each growing season, using certified seed tubers of uniform size and health status. Planting was performed at a spacing of 25 cm apart along rows and 60 cm between rows.

Fertilization was applied based on soil test recommendations. 120 kg N ha^{-1}, 80 kg P_2O_5 ha^{-1}, and 100 kg K_2O ha^{-1} was supplied using [urea (46% N), calcium superphosphate (15.5% P_2O_5), and potassium sulfate (48% K_2O), respectively. Phosphorus was applied entirely at planting, while nitrogen and potassium were applied through fertigation in four equal split applications at 15 day intervals, beginning 30 days after planting (DAP) and continuing at 45, 60, and 75 DAP, corresponding approximately to the early vegetative, tuber initiation, early bulking, and bulking stages, respectively.

Weed control was performed manually as needed to maintain weed-free conditions throughout the growing season. Pest and disease management practices were implemented according to standard local agricultural guidelines. All other cultural practices, including hilling and field maintenance, were conducted uniformly across all treatments to ensure that observed differences were attributable solely to the experimental treatments. Harvesting took place on February 25.

Application of Biostimulant and Silicon

The biostimulant used in this study was a commercial seaweed extract formulation (Algae Production Unit, National Research Centre, Giza, Egypt), derived from *Ascophyllum nodosum*. The product contains approximately 20% seaweed extract, enriched with natural plant growth regulators (auxins and cytokinins), amino acids, vitamins, and micronutrients, as specified by the manufacturer.

Silicon was applied in the form of a commercial potassium silicate solution (K_2SiO_3; sourced from El-Nasr Company for Intermediate Chemicals, Egypt) containing approximately 25% SiO_2 and 10% K_2O in soluble form, suitable for foliar application. Both biostimulant and silicon treatments were applied as foliar sprays using a calibrated knapsack sprayer with a spray volume of 300 L ha^{-1}, ensuring uniform canopy coverage. The biostimulant was applied at a rate of 2.5 L ha^{-1}, while potassium silicate was applied at a concentration of 1.5 g L^{-1}. Applications were conducted twice during the growing season, at: Early vegetative stage (30 days after planting), and Pre-flowering stage (50-55 days after planting). For the combined treatment, both solutions were freshly prepared and mixed immediately before application, maintaining the same individual concentrations. No surfactant was added. All foliar applications were carried out in the early morning under calm weather conditions to minimize evaporation and maximize leaf absorption.

Measurments

To ensure statistical validity, all measurements obtained from individual plants within each plot were averaged prior to analysis, and the plot was considered the experimental unit.

Growth and Physiological

Vegetative growth and physiological measurements were conducted at the mid-vegetative stage using a standardized sampling protocol. In each experimental plot, five representative plants were randomly selected from the central rows to avoid border effects, and all measurements were performed on these plants.

Plant height was measured from the soil surface to the apex of the main stem using a measuring tape, and the mean value per plot (n = 5 plants) was calculated. The number of stems per plant was recorded for the same sampled plants and averaged accordingly.

Leaf area index (LAI) was determined using a portable leaf area meter on fully expanded leaves collected from the sampled plants. Chlorophyll content was measured using a SPAD meter, with three readings per leaf taken from three fully expanded leaves per plant, and the average value per plant was calculated before computing the plot mean.

For biochemical analyses (e.g., proline content and antioxidant enzyme activity), composite leaf samples were prepared by pooling leaves from the five sampled plants within each plot, ensuring a representative sample. These composite samples were used as a single experimental unit for laboratory analysis.

Antioxidant Enzyme Activity

Leaves were collected, frozen in liquid nitrogen, and stored at -80°C. Activities of the antioxidant enzymes superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) were measured using established spectrophotometric techniques.

Yield Assessment

At harvest, yield components were determined from ten plants randomly selected from the central rows of each plot. The number of tubers per plant and average tuber weight were recorded, and the mean values per plot were calculated. Total and marketable yield were determined based on the entire plot area and expressed on a hectare basis.

Water relation and Canopy Temperature

Water use efficiency (WUE) was calculated as the ratio of total tuber yield to the total volume of irrigation water applied during the growing season and expressed as kg m^{-3}.

The total irrigation water applied was calculated based on the measured discharge rate of the drip irrigation system and the duration of each irrigation event, integrated over the entire growing season. Irrigation was scheduled according to soil moisture depletion, approximately 50% depletion of available soil water within the effective root zone (0-60 cm) before re-irrigation. The irrigation system efficiency was assumed to be 90%, and this factor was incorporated into the calculation of the total applied water. Based on these parameters, the total seasonal irrigation water applied was 7030 m^3 ha^{-1} in the first growing season and 8200 m^3 ha^{-1} in the second growing season. The same irrigation regime was uniformly applied across all treatments to ensure that differences in WUE were attributable to treatment effects rather than variation in water supply.

Relative water content (RWC) was determined using fully expanded leaves collected from five plants per plot, and the average value was calculated at the plot level.

Canopy temperature measurements were recorded at midday using an infrared thermometer. Three readings per plot were taken at different positions and averaged to obtain a single value per plot.

Statistical Analysis

Data were first examined for compliance with the assumptions of analysis of variance (ANOVA). Normality of residuals was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated using Levene’s test. When necessary, percentage data were subjected to arcsine square-root transformation, and count data were log-transformed prior to analysis to meet ANOVA assumptions. However, untransformed means are presented in the figures for ease of interpretation. The experiment followed a randomized complete block design (RCBD) with four replicates (n=4). A two-way analysis of variance (ANOVA) was performed. Mean comparisons were conducted using Tukey’s test at a significance level of $P \leq 0.05$. All statistical analyses were performed using IBM SPSS Statistics software (version 26.0; IBM Corp., Armonk, NY, USA). All statistical analyses were performed using plot means as the experimental unit, and results are presented as mean ± standard deviation (SD). Graphical abstract of expriment materials and methods is representing in Figure 1.

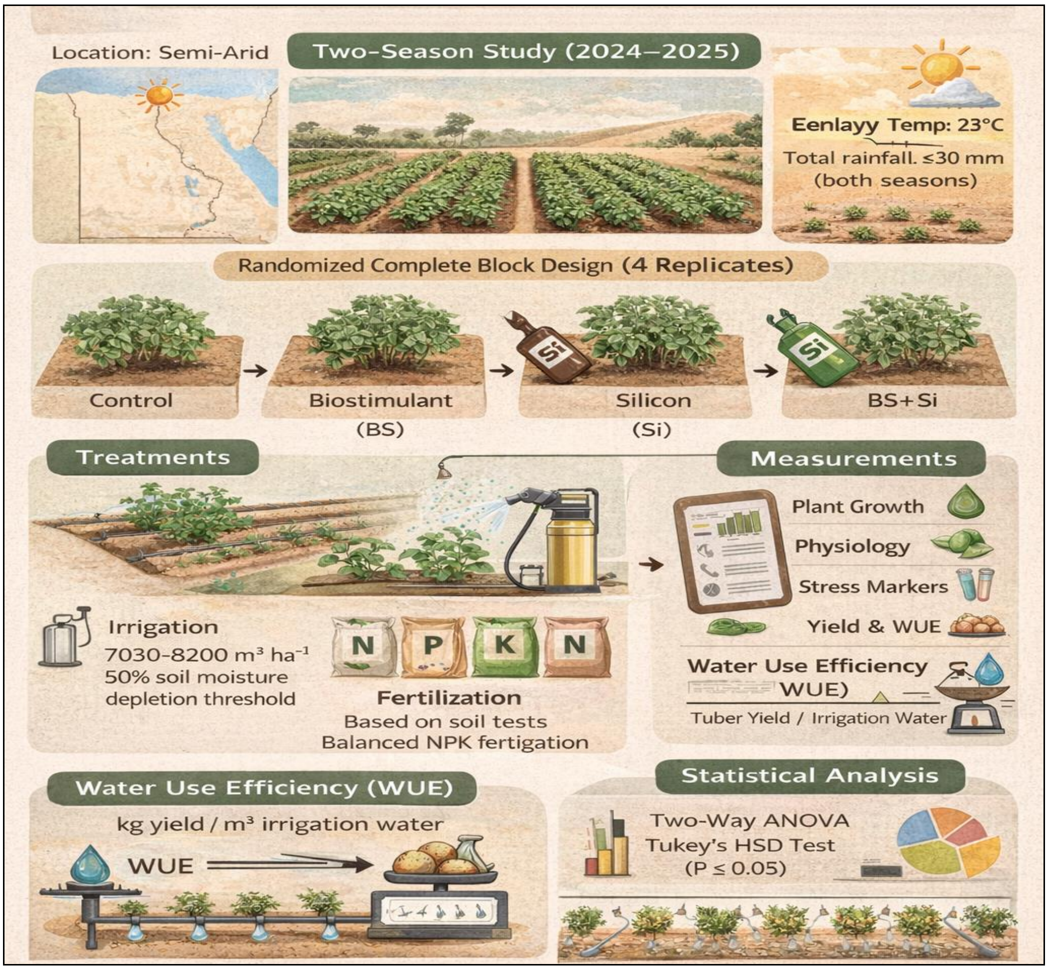

Figure 1. Graphical abstract of the experimental design.
A two-season field study evaluated the effects of biostimulant and silicon, applied individually or combined, on potato growth, physiology, water use efficiency, and yield under drip irrigation.

RESULTS AND DISCUSSION

Growth and Photosynthetic Performance

Foliar application of biostimulant, nano silicon, and their combined treatment significantly improved vegetative growth and photosynthetic traits of potato plants compared with the untreated control during both growing seasons (Figure 2). Across all measured parameters, treatment performance consistently followed the order: Control < Biostimulant < Nano silicon < Biostimulant + Nano silicon.

Leaf chlorophyll content increased significantly in response to all treatments. The enhancement under biostimulant application may be attributed to improved nutrient assimilation, hormonal stimulation, and delayed leaf senescence. Biostimulants, particularly seaweed extracts and humic-based products, are known to stimulate chlorophyll biosynthesis and improve photosynthetic metabolism under field stress conditions (Matthews et al., 2025; López-Serrano et al., 2026). Nano silicon produced a greater increase than biostimulant alone, likely because silica nanoparticles improve chloroplast stability, reduce pigment degradation, and enhance leaf structural integrity under stress (Salam et al., 2026). The combined treatment recorded the highest chlorophyll values, indicating complementary metabolic and protective effects.

Leaf area index (LAI) also increased progressively with treatment intensity. Greater canopy expansion under biostimulant treatment may reflect enhanced cell division and nutrient use efficiency, while the stronger response to nano silicon could be associated with improved turgor maintenance and leaf erectness. Similar improvements in canopy architecture have been reported in potato and other vegetable crops treated with silicon-based nanomaterials under drought-prone environments (Al-Selwey et al., 2023). The combined treatment generated the highest LAI, suggesting greater source capacity for assimilate production.

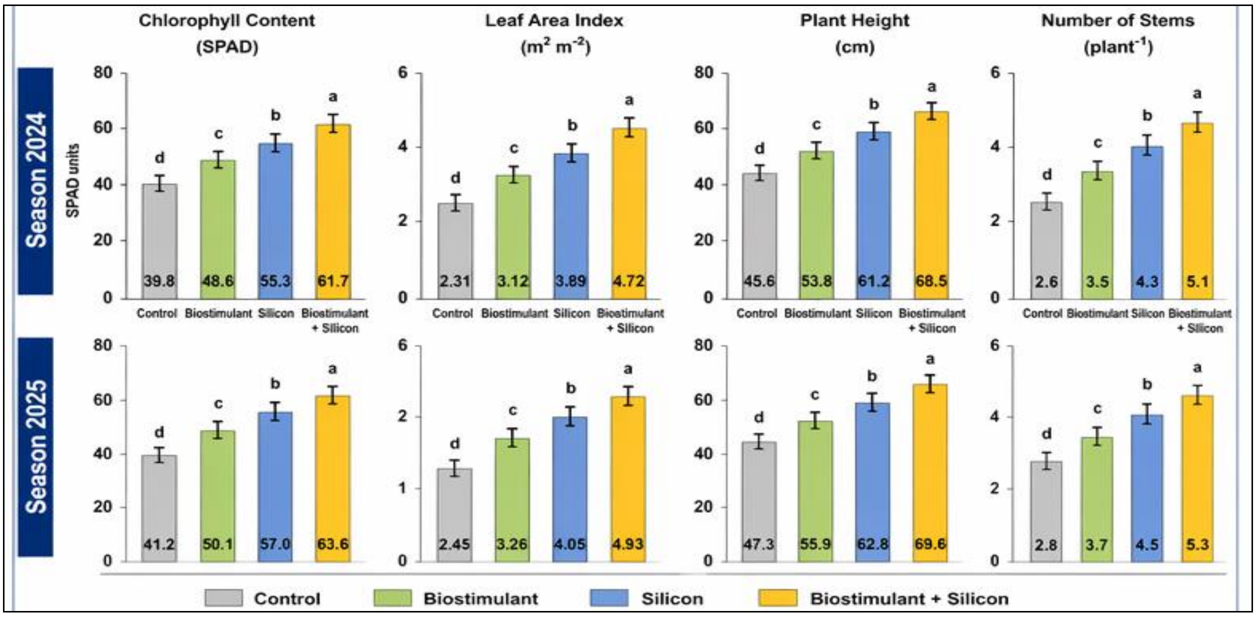

Figure 2. Effect of biostimulant, silicon, and their combined application on some groth and physiologicat traits of potato plants across two growing seasons. Bars indicate mean ± SD. Different lowercase letters denote significant differences among treatments ($p \leq 0.05$, Tukey's HSD).

Plant height and stem number followed the same trend. Increased vegetative vigor under nano silicon may result from improved water status, strengthened cell walls, and reduced oxidative damage, whereas biostimulants likely enhanced metabolic activity and root function. The integrated treatment maximized overall canopy development, confirming that simultaneous stimulation of growth processes and stress protection is more effective than either treatment alone.

Osmolyte Accumulation and Stress Mitigation

Leaf proline concentration increased significantly in treated plants relative to the control (Figure 3), with the highest values observed under the combined treatment. Proline is a well- known compatible solute involved inosmotic adjustment, membrane stabilization, reactive oxygen species (ROS) scavenging, and enzyme protection under drought and heat stress. The observed increase under biostimulant treatment may be associated with enhanced amino acid metabolism and improved nitrogen assimilation. Similar findings have been reported where foliar stimulants promoted compatible solute accumulation and improved plant stress tolerance under water deficit conditions (Abdel Latef et al., 2026).

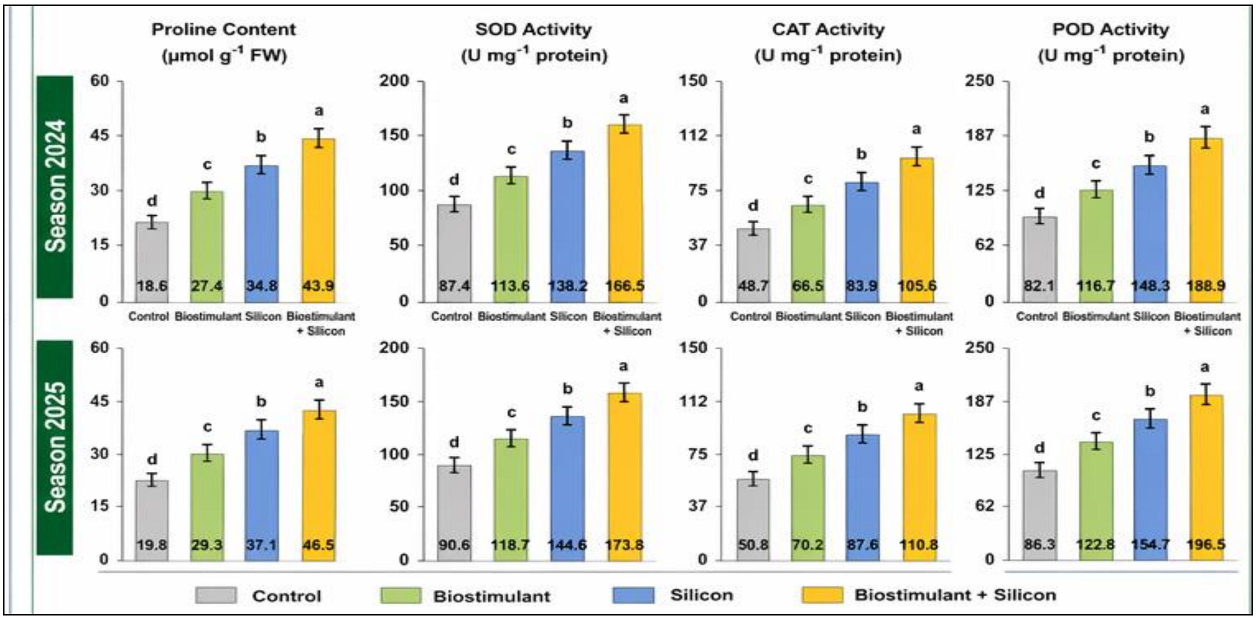

Figure 3. Effect of biostimulant, silicon, and their combined application on osmolyte content and antioxidant enzyme activities of potato plant leaves across two growing seasons. Bars indicate mean ± SD. Different lowercase letters denote significant differences among treatments ($p \leq 0.05$, Tukey's HSD).

Nano silicon induced a stronger increase in proline than biostimulant alone, which may be explained by its superior role in regulating stress signaling, preserving membrane integrity, and maintaining plant hydration. Silicon nanoparticles have been repeatedly associated with improved osmotic balance and reduced cellular injury under abiotic stress (Desoky et al., 2025). The highest proline accumulation in the combined treatment indicates superior stress preparedness and greater capacity to maintain metabolic activity under challenging environmental conditions.

Antioxidant Enzyme Activities

Activities of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) increased significantly in response to all treatments compared with the control (Figure 3). Nano silicon consistently outperformed biostimulant alone, whereas the combined treatment produced the strongest antioxidant response.

Under drought and heat stress, excess ROS accumulation can damage lipids, proteins, nucleic acids, and photosynthetic membranes. Enhanced SOD activity accelerates superoxide detoxification, while CAT and POD decompose hydrogen peroxide into harmless products. Therefore, increased antioxidant enzyme activity reflects stronger cellular defense systems.

Biostimulants can activate antioxidant metabolism through signaling compounds, phenolics, amino acids, and hormone-like substances that induce stress-responsive pathways (Matthews et al., 2025). However, nano silicon frequently exerts stronger effects because of its high reactivity, efficient uptake, and ability to modulate gene expression associated with ROS detoxification and membrane protection (Salam et al., 2026).

The superior antioxidant performance under the combined treatment suggests a synergistic interaction in which biostimulant-enhanced metabolism is protected and sustained by nano silicon-mediated structural and redox stabilization. Similar synergistic responses have recently been reported when natural extracts were combined with nano silicon under drought conditions (Desoky et al., 2025).

Water Relations and Canopy Thermoregulation

Water-use efficiency (WUE), relative water content (RWC), and canopy temperature were significantly affected by treatment application (Figure 4). All treated plants exhibited better water relations than the control, and responses followed the order: Control < Biostimulant < Nano silicon < Biostimulant + Nano silicon.

The improvement in WUE under biostimulant treatment may result from enhanced root activity, nutrient uptake, and photosynthetic efficiency. Biostimulants often promote greater biomass accumulation per unit water consumed through better metabolic coordination (López-Serrano et al., 2026). Nano silicon resulted in a greater increase in WUE, likely because silicon reduces non-productive transpiration, improves stomatal regulation, and strengthens epidermal barriers that limit water loss. This mechanism has been widely documented in water-stressed crops (Vafa et al., 2026).

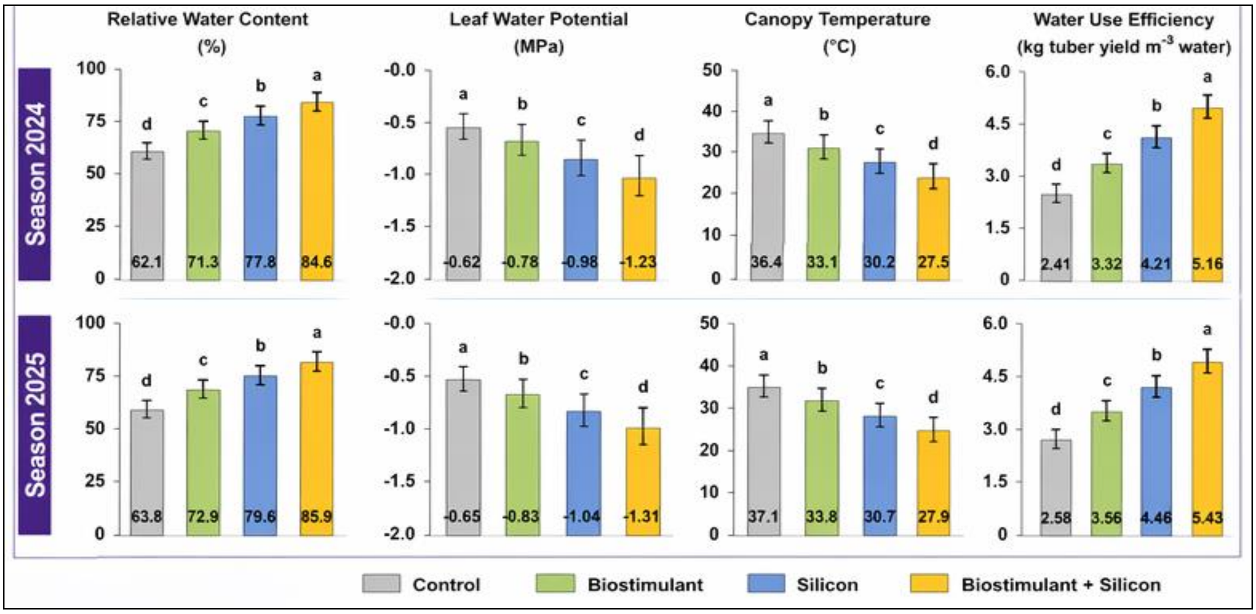

Figure 4. Effect of biostimulant and silicon treatments on water use efficiency (WUE), relative water content (RWC), and canopy temperature of potato plants under drip irrigation. Bars indicate mean ± SD. Different lowercase letters denote significant differences among treatments ($p \leq 0.05$, Tukey's HSD).

Relative water content increased significantly under all treatments, indicating improved plant hydration and turgor maintenance. Nano silicon may have improved leaf water retention through silica deposition and enhanced membrane stability, while biostimulants likely supported root water uptake and osmotic adjustment. The highest RWC under the combined treatment confirms superior internal water balance.

Canopy temperature declined markedly in treated plants, with the lowest values observed in the integrated treatment. Lower canopy temperature is a reliable field indicator of improved physiological status and more efficient cooling through transpiration. Reduced thermal load under nano silicon has been linked to better stomatal performance and stress buffering, while biostimulants contribute through improved vigor and hydraulic conductance. Collectively, these findings indicate that the combined treatment enhances drought adaptation and irrigation efficiency under Egyptian field conditions.

Yield Components and Tuber Productivity

Yield-related traits responded positively and significantly to all treatments compared with the control (Figure 5). Across both seasons. Shoot dry weight increased significantly in treated plants, reflecting greater photosynthetic productivity and assimilate accumulation. Tuber number and average tuber weight also improved, indicating enhanced tuber initiation and stronger sink development. Biostimulants likely improved carbohydrate metabolism and hormonal regulation of tuberization, whereas nano silicon further promoted tuber filling by sustaining photosynthesis, water relations, and stress tolerance during critical growth stages.

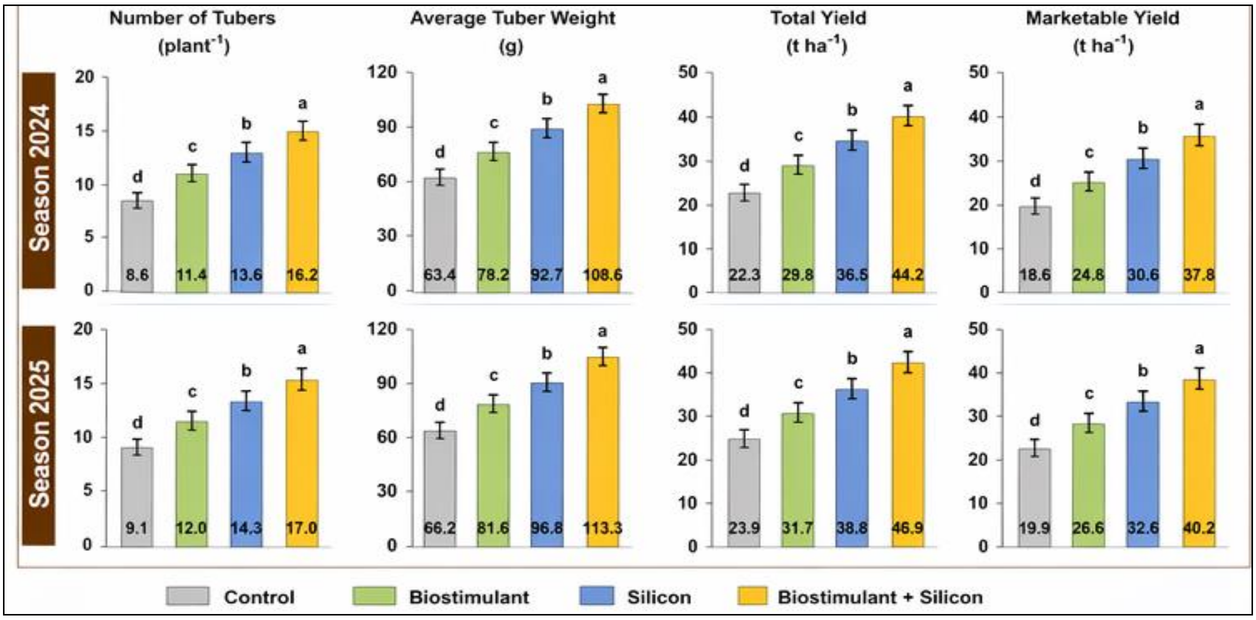

Figure 5. Effect of biostimulant and silicon application on yield and its components of potato. Bars indicate mean ± SD. Different lowercase letters denote significant differences among treatments ($p \leq 0.05$, Tukey's HSD).

The combined treatment produced the highest tuber number and the largest tubers, resulting in maximum total and marketable yield. This suggests that yield enhancement was driven by simultaneous improvements in both source strength (canopy productivity) and sink strength (tuber growth and filling).

Recent studies support these findings. Potato plants treated with silicon nanoparticles under water deficit or salinity have shown higher tuber productivity, improved marketable yield, and greater physiological stability (Alowaiesh et al., 2024). Likewise, biostimulant-based foliar programs have been associated with better tuber size distribution, higher dry matter accumulation, and improved postharvest quality (Saleh et al., 2024). From a practical perspective, the higher marketable yield under the combined treatment is particularly important because it directly determines economic returns for growers.

Radar Chart Visualization of Integrated Trait Performance

The radar chart provided a visual snapshot of how each treatment performed across all measured traits (Figure 6). The biostimulant + silicon combo had the broadest, most balanced radar shape, reflecting superior overall improvements in physiology, biochemistry, water relations, and yield. In contrast, the control showed the smallest shape, pointing to lower performance.

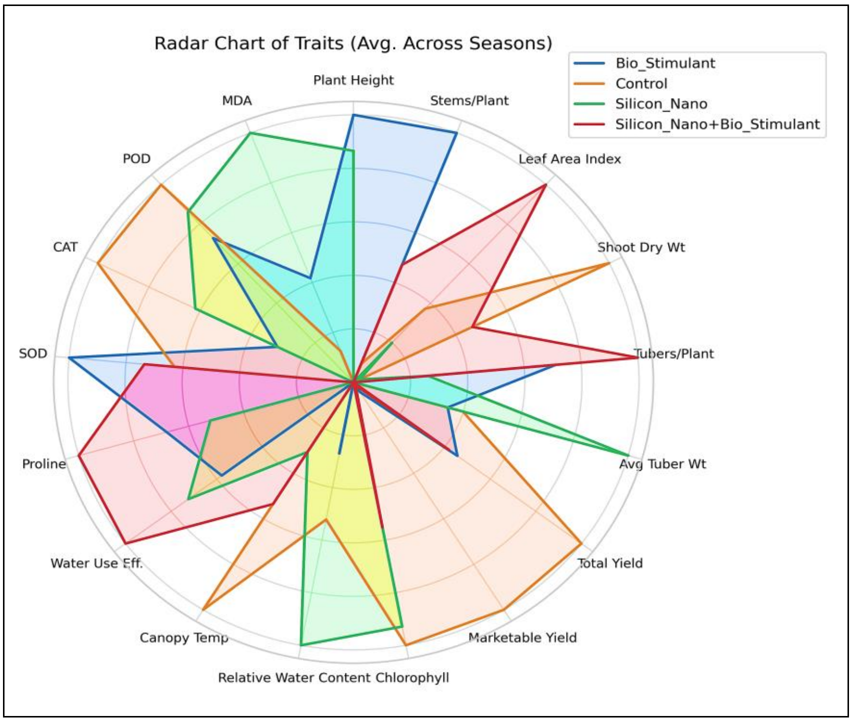

Figure 6. Radar chart comparing integrated performance of potato traits under biostimulant, silicon, and combined treatments averaged across both growing seasons

The biostimulant and silicon alone had moderate radar areas, with each treatment offering unique advantages biostimulants boosting metabolic and biochemical traits, and silicon helping more with water and antioxidant-related traits. Still, neither matched the across-the-board gains of the combined treatment.

The radar chart clearly demonstrates the added value of using both biostimulant and silicon together. This combination not only strengthens individual traits but also improves the plant's overall functionality a critical factor in real-world field conditions, where successful yield depends on how well plants can manage photosynthesis, stress, and water use in tandem. This integrative approach has been similarly illustrated in potatoes and other crops using radar charts to track stress resilience (Rouphael and Colla, 2020; Hamed, 2026).

Integrated Interpretation and Agronomic Implications

Overall, the results demonstrate that combining biostimulant with nano silicon offers the most effective strategy for improving potato growth, stress tolerance, water relations, and productivity under field conditions (Figure 7). This integrated treatment consistently enhanced chlorophyll content, canopy development, antioxidant defenses, osmotic adjustment, plant hydration, and tuber yield more than either treatment alone.

The superiority of the combined treatment can be explained by complementary mechanisms. Biostimulants primarily stimulate metabolism, nutrient acquisition, hormonal balance, and root growth, whereas nano silicon provides stronger structural protection, redox regulation, and water conservation. When applied together, these mechanisms interact to increase resilience and productivity simultaneously.

For Egyptian agriculture, where potato production increasingly faces irrigation constraints, heat stress, and climate variability, this integrated approach represents a practical and environmentally sustainable management option. It can improve yield stability, increase water productivity, and reduce the vulnerability of production systems to seasonal stress. The consistency of responses across seasons further confirms the reliability and scalability of this strategy for commercial cultivation.

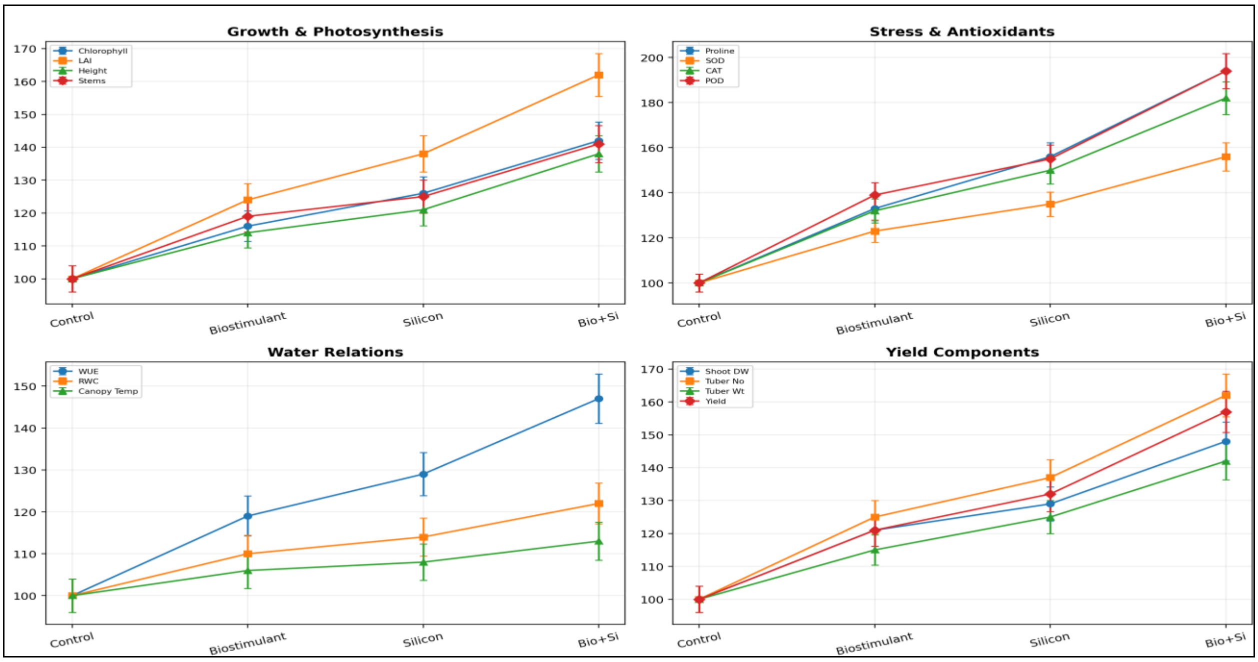

Figure 7. Integrated Effects of Biostimulant and Silicon on Growth, Stress Tolerance, Water Relations, and Yield of Potato under Field Conditions

CONCLUSIONS

This study demonstrates that foliar application of biostimulant and nano silicon, particularly in combination, markedly improves potato growth, physiological efficiency, stress tolerance, and tuber yield under Egyptian field conditions. Enhanced chlorophyll content, greater osmolyte accumulation, stronger antioxidant defense, improved plant water status, and higher water-use efficiency collectively contributed to superior crop performance, especially under water-limited environments.

The combined treatment consistently surpassed all other treatments across two consecutive growing seasons, confirming a pronounced synergistic effect between the metabolic stimulation provided by the biostimulant and the structural and physiological protection conferred by nano silicon.

From an agronomic perspective, this integrated strategy offers a practical, sustainable, and environmentally sound approach to improving potato productivity in arid and semi-arid regions facing increasing climate variability. Future studies should optimize application rates and timing, while also evaluating the long-term impacts of this practice on soil health, resource-use efficiency, and overall cropping system sustainability.

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