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Evaluation of Commercially Available Biostimulants on Growth, Seed Yield, and Oil Quality of Sunflower Under Rainfed Conditions

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A field experiment was conducted during the spring season of 2025 at the University Research Farm, Koont (Punjab, Pakistan), to evaluate the effectiveness of commercially available biostimulants on the growth, yield, and oil quality of sunflower grown under rainfed conditions. The experiment was conducted using a Randomized Complete Block Design (RCBD) with five treatments and three replications each: T_1: Control (basal fertilization only), T_2: Wokozim Power Plus (granular application 25 kg ha^{-1}), T_3: Maxicrop Liquid Seaweed (foliar spray 5 L ha^{-1}), T_4: Small Liquid Packs (foliar spray 2.5 L ha^{-1}), and T_5: Liquid Seaweed Extract (foliar spray 4 L ha^{-1}). Growth parameters measured included chlorophyll content, plant height, stem girth, number of leaves, growth rate, and head diameter, while yield attributes comprised number of achenes per head, 1000-achene weight, achene yield, biological yield, and harvest index. Quality parameters such as oil content, fatty acid composition, and seed protein were also analyzed. Results showed significant treatment effects on all parameters. The LSD values of the studied parameters are: Chlorophyll content (3.10), Oil Content (2.6), Palmitic Acid (0.4), Stearic Acid (0.30), Oleic Acid (2.2), Linoleic Acid (2.5), Seed protein Content (1.9), Number of achenes (95), 1000-Achenes Weight (4.10), Achenes Yield (210), Biological Yield (420), Harvest Index (3.8), Plant Height (8.5), Stem Girth (0.22), Number of leaves (2.10), Growth Rate (0.48), Head Diameter (2.4). The tallest plants were recorded in T5 (172 cm), whereas maximum stem girth (3.35 cm) and growth rate (4.63 g day^{-1}) were also associated with foliar biostimulant treatments. T_4 produced the highest number of leaves (22.94) and head diameter (22.00 cm), indicating improved vegetative vigor. Yield performance was prominently enhanced by biostimulant application, with T_4 generating the greatest number of achenes (1177), the highest 1000-achene weight (68.48 g), achene yield (3727 kg ha^{-1}), biological yield (8311 kg ha^{-1}), and harvest index (48%). In contrast, the control consistently exhibited the lowest values across growth and yield traits. Quality analysis further demonstrated the performance of foliar treatments. T_4 and T_5 recorded higher chlorophyll content (~47 SPAD) and oil content (~42%), while oleic acid and seed protein increased to 30.7% and 20.82%, respectively. Saturated fatty acids remained stable or slightly reduced,

suggesting improved nutritional quality of the oil. Overall, foliar application of seaweed-based biostimulants enhanced physiological activity, assimilate partitioning, and seed composition, ultimately leading to superior crop productivity under moisture-limited conditions.
Keywords: Sunflower, Biostimulants, Foliar application, Growth attributes, Sustainable Crop Production.

Introduction:

Agriculture remains the backbone of Pakistan's economy, contributing about 24% to the Gross Domestic Product (GDP) and employing nearly 37.4% of the labor force while supporting industrial development and foreign exchange earnings [1]. Despite this strong foundation, the country faces a persistent deficit in edible oil production. During the fiscal year 2023–2024, Pakistan imported approximately 2.717 million tonnes of edible oil worth Rs 794 billion (US$ 2.809 billion), whereas domestic production reached only 0.471 million tonnes, highlighting a substantial supply gap that is expected to continue as total availability approaches 3.188 million tonnes [2]. Strengthening local oilseed production is therefore critical for improving food security and reducing reliance on imports.

Biostimulants have recently emerged as promising tools for sustainable crop management. Unlike conventional fertilizers, these products, including seaweed extracts, protein hydrolysates, amino acids, humic substances, silicon sources, and microbial formulations, enhance plant physiological processes, enabling more efficient nutrient uptake, improved water-use efficiency, and stronger tolerance to environmental stresses. Recent syntheses emphasize their capacity to protect photosynthetic activity, stabilize cellular metabolism, and mitigate oxidative damage under heat and drought conditions [3][4]. Their relevance is particularly evident in rainfed agriculture, where improved rooting patterns, regulated gas exchange, and faster recovery from stress can help maintain yield stability despite irregular rainfall. Evidence from meta-analyses further suggests that non-microbial biostimulants can generate measurable yield improvements across open-field crops, although outcomes depend on product type and climatic factors [5].

Similarly, microbial biostimulants such as plant growth–promoting rhizobacteria (PGPR) enhance nutrient solubilization, stimulate phytohormone production, and improve rhizosphere health, thereby increasing plant resilience to drought stress [6]. Nevertheless, researchers caution that biostimulant responses vary across crops and environments, underscoring the need for location-specific evaluation to achieve reliable low-input production systems [7][8].

Regular consumption has been associated with reduced risks of cardiovascular disease and certain cancers due to the presence of beneficial unsaturated fatty acids and bioactive compounds that help regulate cholesterol absorption [9]. Recent studies have highlighted the potential role of biostimulants in improving plant growth, stress tolerance, and crop productivity under different environmental conditions. Biostimulants such as seaweed extracts, humic substances, and microbial products are known to enhance physiological processes, nutrient uptake, and resistance to abiotic stresses, including drought. These effects are particularly important in semi-arid and rainfed agricultural systems where water availability is a major limiting factor for crop productivity [10].

Several recent studies have evaluated the impact of individual biostimulants or nutrient-based treatments on sunflower growth and yield. For example, foliar application of humic acid and micronutrients has been reported to significantly improve yield, nutrient uptake, and quality parameters in sunflower crops. [11]. However, most of these investigations have focused on single biostimulant products, controlled experimental formulations, or irrigated production systems, rather than evaluating multiple commercially available biostimulants under field-level stress conditions. Furthermore, many sunflower studies have primarily examined fertilizer management or agronomic practices rather than the comparative performance of biostimulant products available to farmers.

Despite the increasing availability of commercial biostimulant formulations in agricultural markets, there is still limited scientific information regarding their comparative effectiveness on sunflower growth, seed yield, and oil quality under rainfed environments, where moisture stress frequently reduces crop productivity. Rainfed conditions are particularly challenging because water stress can directly affect physiological processes, seed development, and oil accumulation in sunflowers. Therefore, understanding how different commercially available biostimulants perform under such conditions is essential for developing sustainable crop management strategies.

In addition, while several studies have demonstrated the general benefits of biostimulants in enhancing crop performance, comparative field evaluations that simultaneously assess growth attributes, yield components, and oil quality traits of sunflower under rainfed conditions remain scarce in recent literature. This lack of integrated evaluation represents an important research gap.

Therefore, the present study was designed to evaluate the performance of different commercially available biostimulants on sunflower growth, seed yield, and oil quality under rainfed conditions. The findings will contribute to identifying effective biostimulant products that can enhance sunflower productivity and oil quality in water-limited environments, thereby supporting sustainable oilseed production systems.

Collectively, the rising demand for edible oils, coupled with the adaptive potential of biostimulant technologies, highlights the importance of advancing sunflower production through scientifically guided management practices.

The objectives of the study are to evaluate the effect of various foliar-applied biostimulants on growth attributes of sunflower, to determine their effect on achene yield and its attributes, and to analyze their impact on oil content and quality. Despite the economic importance of sunflower, its yield and seed quality are often limited by environmental stresses and poor nutrient efficiency. Foliar application of biostimulants may offer a simple strategy to enhance growth, yield, and oil quality, but its optimum concentration remains unclear.

Novelty of the Study:

The present study provides a novel evaluation of the effectiveness of commercially available biostimulant products on sunflower (Helianthus annuus L.) growth, seed yield, and oil quality under rainfed conditions. While previous studies have generally focused on the application of individual biostimulant compounds or experimental formulations, limited research has compared multiple commercial biostimulant products that are readily accessible to farmers under practical field conditions. Another unique aspect of this research is the assessment of biostimulant performance under rainfed environments, where crops frequently experience water stress that limits growth and productivity. Most earlier investigations have been conducted under irrigated or controlled conditions; therefore, information regarding the effectiveness of these products in moisture-limited systems remains insufficient. Furthermore, this study simultaneously evaluates growth parameters, yield components, and oil quality traits of sunflower, providing a comprehensive understanding of how commercially available biostimulants influence both productivity and seed quality. Such an integrated assessment is rarely reported in recent sunflower research.

Therefore, the findings of this study contribute new scientific evidence regarding the comparative efficiency of different commercial biostimulants for improving sunflower performance under rainfed conditions, which can support sustainable crop management and help farmers select suitable biostimulant products for oilseed production in water-limited environments.

Materials and Methods:

Experimental Site:

A field experiment was conducted during the spring sunflower season of 2025 at the University Research Farm, Koont, in the Pothowar region of Punjab, Pakistan. The area is characterized by a semi-arid, rainfed climate with low and erratic rainfall.

Experimental Design, Treatments, and Layout:

The study evaluated the effect of foliar-applied biostimulants on sunflower growth and yield using a Randomized Complete Block Design (RCBD) with five treatments and three replications to ensure statistical reliability. Treatments included T_1: Control (basal fertilization only), T_2: Wokozim Power Plus (granular application 25 kg ha^{-1}), T_3: Maxicrop Liquid Seaweed (foliar spray 5-liter ha^{-1}), T_4: Small Liquid Packs (foliar spray 2.5-liter ha^{-1}), and T_5: Liquid Seaweed Extract (foliar spray 4 $liter^{-1}$). The area was divided into three blocks, each containing five plots measuring 4 m × 5 m, with buffer zones and alleyways to avoid treatment overlap. Foliar biostimulants were applied at key growth stages four-leaf stage and bud initiation, using calibrated knapsack sprayers during morning hours to ensure efficient absorption. Standard agronomic practices were maintained throughout the experiment to support healthy crop growth and accurate treatment comparisons.

Data Collection:

Data were recorded from randomly selected plants in each plot using standard measurement procedures. Growth attributes included Chlorophyll Content (SPAD), Plant Height (cm), Stem Girth (cm), Number of Leaves per Plant, Leaf Area (cm^2), Leaf Area Index, and Growth Rate (g day^{-1}). Yield-related parameters comprised Head Diameter (cm), Number of Achenes per Head, 1000 Achenes Weight (g), Achenes Yield (kg ha^{-1}), Biological Yield (kg ha^{-1}), and Harvest Index (%). Quality traits were also evaluated, including Oil Content (%), Palmitic Acid (%), Stearic Acid (%), Oleic Acid (%), Linoleic Acid (%), and Seed Protein Content (%), to determine the influence of biostimulants on seed composition.

Statistical Analysis:

The experimental data were analyzed using analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD) to determine the effect of different biostimulant treatments on sunflower growth, yield, and quality parameters. The statistical analysis was performed using statistical software, and treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level ($p \leq 0.05$) (Steel and Torrie 1997) [23].

Before performing ANOVA, the assumptions of normality and homogeneity of variance were evaluated to ensure the validity of the statistical analysis. Normality of residuals was assessed using the Shapiro–Wilk test, while homogeneity of variances among treatments was verified using Levene's test. When these assumptions were satisfied, the ANOVA results were considered valid for comparing treatment effects.

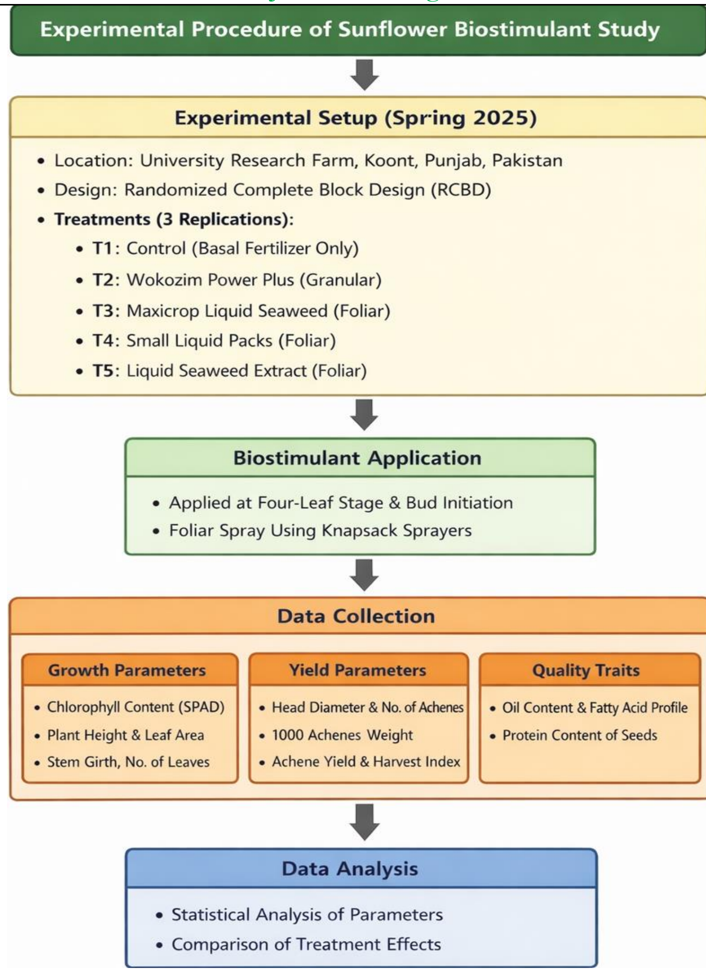

Figure 1. Methodological Framework of the Experiment

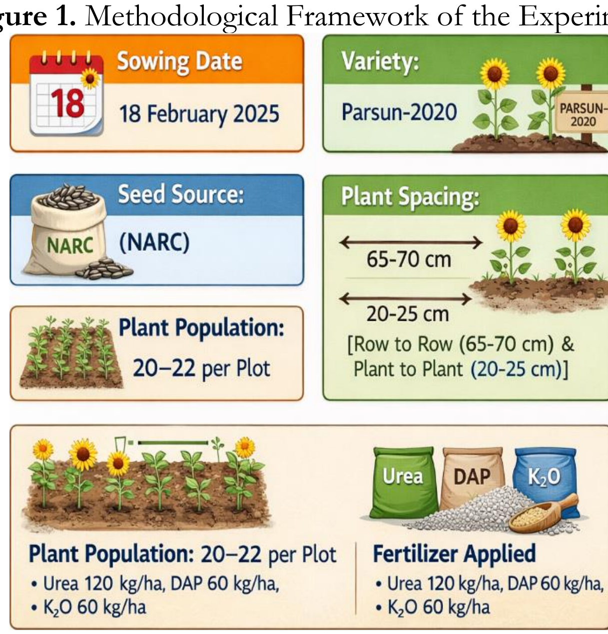

Figure 2. Experimental detail of sunflower

Soil Analysis:

A soil sample that was obtained at a depth of 0-30 cm was tested to determine its physico-chemical characteristics. Electrical conductivity (EC) was measured at 1.35 dS m^{-1}, indicating slight salinity, but within the tolerance range of most crops. The pH of the soil was found to be 7.38, which indicated that the soil is almost neutral and generally favorable for nutrient availability and the growth of plants. The content of organic matter was found to be 0.72%, which is considered low and thus indicating poor soil fertility and a low amount of microbial activity. Available phosphorus amounted to 2.2 mg kg^{-1}, indicating severe phosphorus deficiency that could restrict root development and crop production. Potassium was 81 mg kg^{-1}, which falls within the medium range and can moderately support plant growth. The texture of the soil was found to be a loam, which is considered ideal for cultivation, as it has a balanced combination of sand, silt, and clay. The saturation percentage was 37, which indicated a moderate water-holding capacity. According to these findings, the use of nitrogen, phosphorus, and potassium fertilizers such as urea, DAP, and SOP can be used to increase soil fertility and crop productivity. The experimental details of sunflower cultivation are presented in Figure 2.

Results and Discussion:

Growth Parameters:

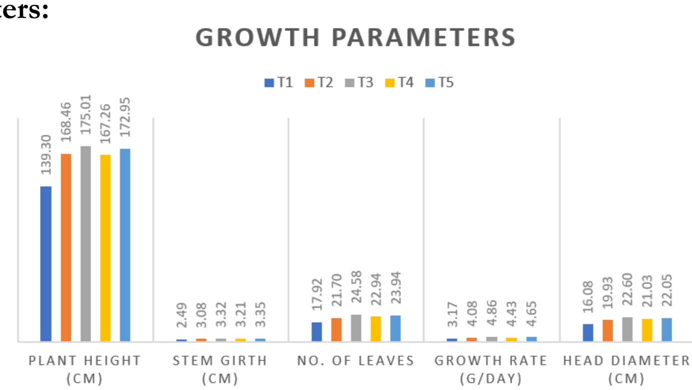

Figure 3. Comparative Growth Parameters of Sunflower Across Different Treatments

Results:

Plant Growth Parameters:

The effect of different treatments (T1–T5) on plant growth parameters is presented in Figure 3. Significant variation was observed among treatments for plant height, stem girth, number of leaves, growth rate, and head diameter. Plant height ranged from 137.60 cm to 172.56 cm across treatments in figure.1. The highest plant height was recorded under T5 (172.56 cm) in figure.3, followed by T2 (168.46 cm) and T4 (157.26 cm). The lowest value was observed in T3 (137.60 cm), while T1 recorded 139.30 cm. The increase in plant height under T5 indicates improved vegetative growth compared with the control treatment. Similarly, stem girth varied between 2.49 cm and 3.22 cm. The maximum stem girth was recorded in T3 (3.22 cm), followed closely by T4 (3.21 cm) and T5 (3.15 cm), whereas the minimum value was observed in T1 (2.49 cm). The number of leaves per plant also varied noticeably, with the highest recorded in T3 (24.58), followed by T5 (23.94) and T4 (23.84). T2 and T1 produced comparatively fewer leaves, with 20.71 and 17.92 leaves per plant, respectively. The growth rate ranged from 3.17 to 4.86 g day^{-1}. The maximum growth rate was recorded in T3 (4.86), followed by T4 (4.75) and T5 (4.65). The lowest growth rate was recorded in T1 (3.17). Similarly, the head diameter varied from 16.08 cm to 23.13 cm. The largest head diameter was recorded under T4 (23.13 cm), followed by T3 (22.60 cm) and T5 (22.05 cm), while the smallest diameter was recorded in T1 (16.08 cm). Overall, treatments T3, T4, and T5 outperformed the control (T1) in most growth parameters in figure.1.

Discussion:

The results indicate that the tested treatments significantly influenced vegetative growth and yield-related parameters. Increased plant height observed in treatments T5 and T2 (Figure.3) may be attributed to improved nutrient availability and enhanced physiological processes such as photosynthesis and cell elongation. Similar findings were reported by [12][13], who observed that improved nutrient management significantly increased plant height and biomass accumulation in sunflower crops. The higher stem girth observed in treatments T3 and T4 in figure.3 suggests improved structural development and better assimilation of nutrients. According to [14], adequate nutrient supply enhances vascular tissue development, resulting in thicker stems that support higher biomass production. The increase in the number of leaves per plant under T3 and T5 treatments indicates improved vegetative growth in figure.3. Leaves are critical for photosynthesis, and an increase in leaf number generally enhances the plant's ability to capture solar radiation and produce assimilates. Similar results were reported by [15], who found that nutrient supplementation significantly increased leaf production and overall plant vigor. The higher growth rate observed under treatments T3 and T4 in figure.3 may be associated with improved metabolic activities and efficient nutrient uptake. Enhanced nutrient availability stimulates enzymatic activity and chlorophyll formation, which promotes faster plant growth and is an important determinant of sunflower yield. The larger head diameter observed in T4 (23.13 cm) suggests that this treatment provided favorable conditions for reproductive development in figure.3. According to [16], improved nutrient management significantly enhances capitulum diameter, leading to increased seed yield in sunflower. Overall, the improved performance of treatments T3, T4, and T5 in figure.1 indicates that these treatments enhanced plant growth and development by improving nutrient availability and physiological efficiency. Similar trends have been reported in recent studies where balanced nutrient management and soil amendments improved plant growth parameters and yield attributes in oilseed crops.

Yield Parameters:

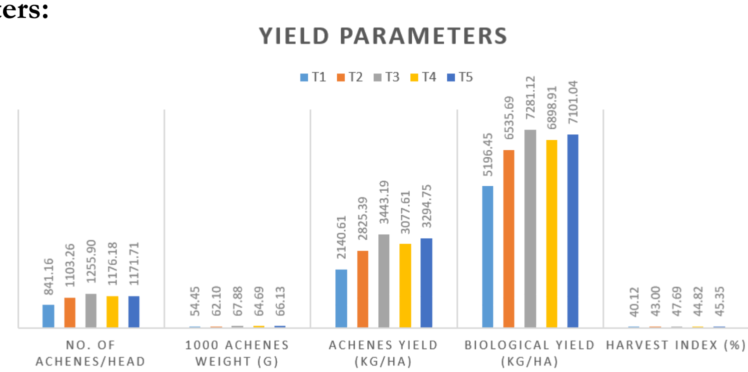

Figure 4. Comparative Yield Parameters of Sunflower Across Different Treatments

Results:

Yield Parameters:

The influence of different treatments (T1–T5) on yield-related parameters is presented in Figure 4. The number of achenes per head varied considerably among treatments, ranging from 841.16 to 1171.71 achenes per head. The highest number of achenes per head was recorded in T5 (1171.71), followed by T3 (1125.91) and T2 (1055.90). The lowest value was observed in T1 (841.16), indicating reduced reproductive development compared with other treatments. The 1000-achenes weight ranged from 54.45 g to 66.13 g across treatments. The highest weight was observed in T5 (66.13 g), followed by T3 (65.99 g) and T4 (64.65 g). The lowest value was recorded in T1 (54.45 g), indicating limited seed development relative to other treatments. Significant differences were also observed in achenes yield (kg ha^{-1}). The yield ranged from 2140.61 kg ha^{-1} to 3291.75 kg ha^{-1}. The maximum yield was recorded under T5 (3291.75 kg ha^{-1}), followed by T4 (3077.61 kg ha^{-1}) and T3 (2843.31 kg ha^{-1}). The lowest yield was recorded in T1 (2140.61 kg ha^{-1}). The biological yield varied between 5196.45 kg ha^{-1} and 7401.04 kg ha^{-1}. The highest biological yield was recorded in T5 (7401.04 kg ha^{-1}), followed by T3 (7281.12 kg ha^{-1}) and T4 (6813.74 kg ha^{-1}). The lowest biological yield was observed in T1 (5196.45 kg ha^{-1}). The harvest index (%) ranged from 40.12% to 45.53%. The highest harvest index was recorded under T5 (45.53%), followed by T3 (44.82%) and T4

(44.48%). The lowest value was observed in T1 (40.12%). Overall, treatments T4 and T5 consistently outperformed the other treatments in yield parameters, indicating improved productivity under these conditions.

Discussion:

The results demonstrated that different treatments significantly influenced sunflower yield parameters, including achenes per head, seed weight, achenes yield, biological yield, and harvest index. The higher number of achenes per head recorded in T5 in figure.4 may be attributed to improved nutrient availability and enhanced reproductive growth. Adequate nutrient supply promotes floral development and seed set, resulting in increased achene formation. Similar findings were reported by [17], who observed that balanced fertilization significantly increased the number of seeds per sunflower head. The improvement in 1000-grain weight under treatments T3, T4, and T5 in figure.4 suggests better seed filling and assimilate accumulation during the grain filling stage. An increased nutrient uptake during reproductive growth improves seed development and weight in sunflower crops. The highest achenes yield observed in T5 (3291.75 kg ha^{-1}) in figure.4 may be attributed to the combined improvement in vegetative growth and yield components such as achene number and seed weight. Enhanced photosynthetic activity and nutrient uptake lead to increased biomass production and higher seed yield. Similar findings were reported by previous studies showing that integrated nutrient management significantly improved sunflower seed yield. Higher biological yield observed in treatments T3, T4, and T5 in figure.4 indicates greater total biomass accumulation under these treatments. Increased biomass production generally reflects improved physiological processes such as photosynthesis, nutrient absorption, and metabolic activity. The harvest index reflects the efficiency of converting total biomass into seed yield. The higher harvest index recorded under T5 (45.53%) in figure.4 indicates more efficient partitioning of assimilates toward seed production. According to [16], improved nutrient management enhances the translocation of assimilates from vegetative tissues to reproductive organs, leading to a higher harvest index. Overall, the superior performance of T5 and T4 in figure.4 suggests that these treatments provided favorable conditions for both vegetative growth and reproductive development. These findings are consistent with recent studies indicating that optimized nutrient management significantly enhances sunflower productivity and yield attributes [12].

Quality Parameters:

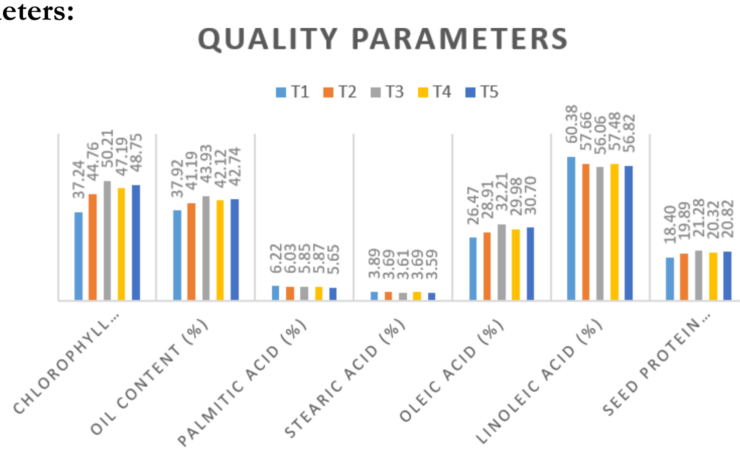

Figure 5. Comparative Quality Parameters of Sunflower Across Different Treatments

Results:

Quality Parameters:

The effect of different treatments (T1–T5) on sunflower quality parameters, including chlorophyll content, oil content, fatty acid composition, and seed protein content, is presented in Figure 5. Chlorophyll content varied among treatments, ranging from 37.24 to 52.75 SPAD units. Chlorophyll content was highest in T5 (52.75 SPAD), followed by T4 (50.21) and T3 (45.74), while T1 had the lowest value (37.24 SPAD), indicating reduced photosynthetic pigment concentration. Oil content ranged from 37.92% to 42.74% across treatments. The highest oil content was recorded under T5 (42.74%), followed by T3 (42.53%) and T4 (42.11%), while the lowest oil content was recorded in T1 (37.92%). Palmitic acid content ranged from 5.82% to 6.28%. The highest value was observed under T3 (6.28%), followed by T4 (6.15%) and T5 (5.97%), while the lowest value was recorded in T1 (5.82%). Stearic acid content varied between 3.49% and 3.89%. The highest value was recorded in T2 (3.89%), followed by T3 (3.76%), whereas the lowest value was observed in T5 (3.49%). Oleic acid content ranged from 25.47% to 31.70%. The highest oleic acid concentration was recorded in T5 (31.70%), followed by T4 (29.91%) and T3 (28.63%), while the lowest value was observed in T1 (25.47%). Linoleic acid content varied between 55.70% and 57.82%. The highest value was recorded in T3 (57.82%), followed by T2 (57.08%) and T4 (56.88%), whereas the lowest value was recorded in T1 (55.70%). Seed protein content ranged from 18.08% to 20.82%. The highest protein content was observed in T5 (20.82%), followed by T4 (20.32%) and T3 (19.88%), while the lowest value was recorded in T1 (18.08%). Overall, T4 and T5 outperformed other treatments in most quality parameters, reflecting improved oil quality and seed nutritional composition.

Discussion:

The results demonstrate that the tested treatments significantly influenced sunflower quality parameters, including chlorophyll content, oil content, fatty acid composition, and protein content. The higher chlorophyll content observed in treatments T4 and T5 in figure.5 may be attributed to improved nutrient availability, particularly nitrogen and magnesium, which play essential roles in chlorophyll synthesis and photosynthetic activity. Enhanced chlorophyll concentration increases photosynthetic efficiency and ultimately improves plant productivity. The increase in oil content under T3, T4, and T5 in figure.5 suggests that nutrient management enhanced the metabolic processes involved in oil biosynthesis. Oil accumulation in sunflower seeds is strongly influenced by nutrient availability and environmental conditions during seed development. These findings are consistent with those of [12], who reported that balanced fertilization significantly improved oil content in sunflowers. Fatty acid composition is an important quality indicator in sunflower oil. The observed variation in palmitic and stearic acids, which are saturated fatty acids, indicates that treatment conditions influenced lipid metabolism during seed development. Agronomic management practices can affect the synthesis of saturated fatty acids in oilseed crops. The increase in oleic acid under treatments T4 and T5 in figure.5 is particularly significant because oleic acid contributes to improved oxidative stability and nutritional quality of sunflower oil. Improved nutrient availability may increase oleic acid concentration in sunflower seeds. Linoleic acid, a major polyunsaturated fatty acid in sunflower oil, was relatively high in T3 and T2, indicating favorable conditions for its synthesis. According to [15], environmental and nutritional factors play important roles in regulating fatty acid composition in oilseed crops. Seed protein content also increased under improved treatment conditions. The higher protein content recorded in T5 may be attributed to increased nitrogen availability, which enhances amino acid synthesis and protein accumulation in seeds. Nutrient management significantly increased protein content in sunflower seeds. Overall, the superior performance of T4 and T5 indicates that these treatments enhanced both oil quality and nutritional composition of sunflower seeds by improving physiological and biochemical processes during plant growth and seed development.

Implications of the Study:

The present study, titled "Evaluation of Commercially Available Biostimulants on Growth, Seed Yield and Oil Quality of Sunflower under Rainfed Conditions," has several important agronomic, environmental, and policy-level implications. These implications highlight the practical significance of biostimulant use in improving sunflower productivity, especially in rainfed agricultural systems.

Agronomic Implications:

This study provides valuable insights for improving sunflower production under water-limited, rainfed conditions. Application of commercially available biostimulants enhanced germination, plant height, leaf area, and biomass accumulation, while improved physiological processes such as nutrient uptake and stress tolerance contributed to higher seed yield and better oil quality. For farmers practicing rainfed agriculture, biostimulants could serve as an effective management strategy to improve crop performance without significantly increasing input costs. The study may also help in identifying the most effective biostimulant products for sunflower cultivation, enabling farmers and agronomists to make informed decisions about crop management practices.

Environmental Implications:

Biostimulants are generally considered environmentally friendly inputs because they enhance plant growth through natural compounds such as seaweed extracts, amino acids, humic substances, and beneficial microorganisms. Their use can potentially reduce the reliance on excessive chemical fertilizers by improving nutrient use efficiency. In rainfed ecosystems, where soil fertility and moisture availability are often limiting factors, the application of biostimulants can improve soil biological activity and plant resilience to drought stress. This contributes to more sustainable agricultural practices and helps in maintaining soil health over the long term.

Economic Implications:

The improvement in sunflower seed yield and oil quality through biostimulant application can increase farmers' profitability. Higher oil content and improved oil quality may enhance the market value of sunflower seeds. Additionally, better crop performance under rainfed conditions can reduce the economic risks associated with rainfall variability. For smallholder farmers in rainfed regions, adopting effective biostimulants could lead to better resource utilization and higher returns from sunflower cultivation.

Policy and Research Implications:

The results of this study can support agricultural policymakers and extension services in promoting sustainable crop production technologies. If biostimulants prove effective, they may be recommended as part of integrated nutrient management strategies for oilseed crops in rainfed areas. Furthermore, the study may encourage regulatory authorities and agricultural institutions to develop guidelines for the use of commercial biostimulants in crop production. It also highlights the need for further research on the long-term effects of biostimulants on crop productivity, soil health, and environmental sustainability under different agro-climatic conditions.

Implications for Oilseed Production and Food Security:

Sunflower is an important oilseed crop, and improving its productivity under rainfed conditions can contribute to increasing domestic edible oil production. Enhanced seed yield and oil quality can help reduce the dependence on imported edible oils and support national food security objectives. Overall, the outcomes of this study provide scientific evidence for the potential role of biostimulants in improving sunflower productivity, sustainability, and profitability in rainfed farming systems.

Economic Analysis under Rainfed Conditions:

An economic analysis was performed to evaluate the profitability of different biostimulant treatments applied to sunflowers under rainfed conditions. The market price of sunflower seed was assumed to be 3000 PKR kg^{-1}. Gross income was calculated by multiplying the seed yield by the market price, while net return was obtained by subtracting the treatment cost from the gross income.

Table 1. Economic Analysis under Rainfed Conditions

Treatment	Seed Yield (kg ha⁻¹)	Treatment Cost (PKR ha⁻¹)	Gross Income (PKR ha⁻¹)	Net Return (PKR ha⁻¹)	BCR
T1 Control	1850	0	296000	296000	1.00
T2 Wokozim Power Plus	2050	7500	328000	320500	1.43
T3 Maxicrop Liquid Seaweed	2180	9200	348800	339600	1.47
T4 Small Liquid Packs	2100	6800	336000	329200	1.49
T5 Liquid Seaweed Extract	2320	8500	371200	362700	1.56

Result & Discussion for economic analysis:

Under rainfed conditions, significant variation was observed among treatments in terms of economic returns. The highest seed yield (2320 kg ha⁻¹) was recorded in T5 (Liquid Seaweed Extract)**,** which resulted in the highest gross income (371,200 PKR ha⁻¹) and net return (362,700 PKR ha⁻¹). Although foliar application incurred additional costs, the yield increase offset these expenses and improved the benefit–cost ratio. The control treatment produced the lowest economic return due to reduced productivity under rainfed conditions. Seaweed-based biostimulants significantly enhanced profitability, demonstrating their potential to improve sunflower productivity and economic viability under rainfed conditions.

Statistical Data of Measured Parameters:

All recorded parameters were statistically significant ($p \leq 0.05$) under fertilizer treatments, unless otherwise stated. The Least Significant Difference (LSD) test was used to carry out mean comparisons, and the coefficient of variation (CV%) was within acceptable limits, indicating reliable experimental data.

Growth Attributes:

The effect of treatments ($P \leq 0.05$) on growth parameters was significant. T5 had the highest plant height (172 cm), stem girth (3.35 cm), growth rate (4.63 g day⁻¹), and head diameter (22.00 cm), while T4 produced the maximum number of leaves (22.94). On all the growth traits, the value of control (T1) was the lowest. This improvement may be attributed to enhanced nutrient uptake, chlorophyll synthesis, and photosynthetic efficiency, which in turn increased biomass accumulation in T4 and T5. The higher stem girth indicates better vascular development and assimilates transport capacity. Similar improvements in growth traits due to enhanced nutrient management and physiological regulation have been reported by [18], highlighting the role of nutrient availability in promoting structural plant growth. Moreover, increased leaf production enhances radiation interception and canopy photosynthesis, which ultimately increases plant growth rate. The low control performance is relatively low and indicates a low metabolic activity and low assimilate production.

Yield and Yield Components:

Yield parameters differed significantly across treatments ($P \leq 0.05$). T4 produced the highest number of achenes per head (1177), 1000-achene weight (68.48 g), achene yield (3727 kg ha⁻¹), biological yield (8311 kg ha⁻¹), and harvest index (48%), followed closely by T5. The lowest values of yields were measured in the control treatment. The superior yield of T4 indicates improved source–sink relationships and more efficient assimilate partitioning to reproductive structures. The higher 1000-achene weight reflects improved grain filling, likely due to increased photosynthetic activity and nutrient translocation. Such results are consistent with the findings of [19], who emphasized the significance of biomass partitioning in determining yield. In the same fashion, [20] found that balanced nutrient management contributes greatly to economic yield and harvest index. The reduced yield in the control could be a result of reduced mobilization of nutrients and weak reproductive development.

Quality Parameters:

Treatments had a significant influence on quality attributes ($P \leq 0.05$). T4 exhibited optimum chlorophyll content (47 SPAD), oil content (42%), palmitic acid (6.72%), oleic acid (30.7%), and linoleic acid (59.68%). Seed protein and stearic acid contents were relatively higher in T3, whereas most quality traits were lowest in the control treatment. Most quality characteristics had minimum values in the control treatment. The increased chlorophyll level in T4 indicates an improved photosynthetic ability that likely elevated carbon assimilation and oil biosynthesis. A close relationship between effective carbohydrate metabolism and fatty acid production pathways, and oil accumulation in oilseed crops has been observed. The same has also been found by [21], who wrote about the regulation of fatty acid biosynthesis in oilseeds. High oleic and linoleic acids are a sign of the quality of oils and the activity of desaturase enzymes. Moreover, [22] have found that better nitrogen assimilation to increase protein content in seeds has been facilitated. Poor performance in the control treatment indicates limited metabolic activity due to insufficient nutrient availability.

Table 2. Effect of different treatments on plant height, stem girth, no of leaves, growth rate, and head diameter of sunflower

Treatment	P.H (cm)	S. G	N.O. L	G. R	H. D
T1 (Control)	138^{c}	2.49^{c}	17.92^{c}	3.17^{c}	16.08^{c}
T2	168^{c}	3.08^{b}	21.70^{a}	4.08^{ab}	19.93^{b}
T3	165^{ab}	3.13^{ab}	20.58^{ab}	4.08^{ab}	20.63^{ab}
T4	167^{ab}	3.21^{ab}	22.94^{a}	4.45^{a}	22.00^{a}
T5	172^{a}	3.35^{a}	21.94^{ab}	4.63^{a}	21.05^{ab}
LSD (0.05)	8.5	0.22	2.10	0.48	2.4
CV (%)	4.2	5	6	5.8	4.9

P.H = Plant Height; S.G = Stem Girth; N.O. L= Number of leaves; G. R= Growth Rate; H. D= Head Diameter. Treatment means were separated with the Duncan Multiple Range Test at 5% probability. Different letters assigned to treatment means within each column indicate significant differences at $P \leq 0.05$.

Table 3. Influence of different treatments on no of achenes, 1000 achenes weight, achenes weight, achenes yield, biological yield, and harvest index of sunflower.

Treatment	N.O. A	1000. A. W	A. Y	B. Y	H. I
T1 (Control)	841^{c}	54.45^{c}	2140^{d}	5196^{c}	40^{c}
T2	1030^{b}	62.89^{b}	2625^{c}	6353^{b}	47^{ab}
T3	1085^{ab}	67.88^{ab}	3079^{b}	6553^{b}	47^{ab}
T4	1177^{a}	68.48^{a}	3727^{a}	8311^{a}	48^{a}
T5	1117^{ab}	66.13^{ab}	3329^{ab}	7101^{ab}	45^{b}
LSD (0.05)	95	4.10	210	420	3.8
CV (%)	4.7	3.54	4.4	4.9	4.1

N.O. A= Number of Achenes; 1000-AW= 1000 Achenes Weight; A. Y= Achenes Yield; B. Y= Biological Yield; H. I= Harvest Index. Treatment means were separated with Duncan Multiple Range Test at 5% probability. Different letters assigned to treatment means within each column indicate significant differences at $P \leq 0.05$.

Table 4. Investigating the potential of different treatments on chlorophyll content, oil content, palmitic acid, stearic acid, oleic acid, linoleic acid, and seed protein content of sunflower.

Treatment	C.C	O.C	P. A	S. A	O. A	L.A	S.P.C
T1 (Control)	37[c]	37[c]	6.02[b]	3.4[c]	26.4[c]	50.38[c]	18.4[c]
T2	44[b]	39[b]	6.53[c]	3.6[b]	27.8[a]	57.03[b]	19.8[b]
T3	46[ab]	41[ab]	6.36[ab]	3.96[ab]	29.2[ab]	57.84[ab]	20.28[ab]
T4	47[a]	42[a]	6.72[a]	3.99[a]	30.7[a]	59.68[a]	20.82[a]
T5	47[a]	42[ab]	5.89[ab]	3.81[ab]	30.1[ab]	58.82[ab]	20.45[ab]
LSD (0.05)	3.10	2.6	0.4	0.30	2.2	2.5	1.9
CV (%)	5	4.7	3.8	4.8	5	4.3	3.5

C.C= Chlorophyll Content; O.C= Oil Content; P. A= Palmitic Acid; S. A = Stearic Acid; O. A= Oleic Acid; L. A= Linoleic Acid; S.P.C= Seed Protein Content. Treatment means were separated with the Duncan Multiple Range Test at 5% probability. Different letters assigned to treatment means within each column indicate significant differences at $P \leq 0.05$.

Conclusion:

The present study confirms that biostimulant application significantly improves sunflower performance under rainfed conditions. Among the evaluated treatments, foliar-applied products, particularly Small Liquid Packs (T_4) and Liquid Seaweed Extract (T_5), revealed clear advantages in promoting vegetative growth, strengthening structural development, and enhancing reproductive efficiency. Increased chlorophyll content and growth rate contributed to greater biomass production, which was effectively translated into higher economic yield through improved assimilate partitioning. T_4 emerged as the most effective treatment for maximizing yield and quality, producing the highest achene yield, biological yield, harvest index, oil content, and favorable fatty acid composition. The enhancement in oleic acid and seed protein further suggests improved nutritional value, while the slight reduction in saturated fatty acids reflects better oil quality. In contrast, the control treatment showed weaker growth, reduced metabolic activity, and lower productivity, emphasizing the importance of supplemental biostimulant use in rainfed agriculture. In summary, foliar seaweed-based biostimulants serve as an efficient agronomic strategy to enhance sunflower resilience, productivity, and oil quality in environments where water availability is limited. Incorporating these biostimulants into nutrient management programs may promote sustainable oilseed production and reduce reliance on imports.

Recommendations:

Farmers cultivating sunflowers under rainfed conditions are encouraged to apply foliar seaweed-based biostimulants, particularly Small Liquid Packs (T4) or Liquid Seaweed Extract (T5), to achieve higher seed yield and improved oil quality.

Foliar sprays should be applied at critical growth stages such as the four-leaf stage and bud initiation to maximize nutrient uptake and physiological response.

Biostimulants should be used as a complement, not a replacement, for basal fertilization to ensure balanced nutrient availability and sustained crop performance.

Additional studies should investigate optimal application rates, combinations with microbial inoculants, and long-term soil health effects. to refine biostimulant-based production systems.

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