Growth correlations and Physiological performance of Sunflower (Helianthus annuus L.) by applying biostimulant materials

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Article

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Abstract

This study investigated the physiological and biochemical responses of sunflower (*Helianthus annuus* L.) to foliar spray with algae extract, potassium citrate, potassium sulfate, boron, and paclobutrazol. The treatments significantly affected vegetative growth parameters, including stem length, stem diameter, and number of leaves, with changes in growth correlations as relative growth rate (RGR), absolute growth rate (AGR), and net assimilation rate (NAR). Applications of algae extract, potassium and boron enhanced photosynthetic efficiency with promoting the assimilation of Co_2. These physiological enhancements related with increasing accumulation of total sugars, total carbohydrates and crude protein, as well as metabolism activity. In addition, enhanced macro- and micronutrient accumulation uptake. Moreover, significantly increase endogenous phytohormone were observed, with algae extract, whereas paclobutrazol altered hormonal content through gibberellin inhibition. Generally, results showed that 6 ml L^{-1} of algae extract, potassium citrate 1000 mg L^{-1} increased vegetative growth, chlorophylls, minerals, photosynthesis efficiency, metabolism, and endogenous phytohormone of sunflower plants.

Keywords: Co_2 assimilation; physiological responses; photosynthetic efficiency.

Introduction

Sunflower is an oil crop from family Asteraceae can be divided into two types (non-oilseed and oilseed). The first type is (non-oilseed): used for human as snacks and for birds feed and the second is the oilseed grown primarily for oil extraction which containing minimum 40% oil [1]. Sunflower is an annual plant mainly grows in spring-summer season young plants are an excellent agricultural substance, and green sunflower plants consider a valuable source of animal feeding it has high fat and protein contents [2,3]. Climate change has become one of the major problems around the world in last few years. The growth and yield of many crops, especially oilseed crops, which the source of edible oils and nutrients. Also, the growing demand for vegetable oils and the fact that oilseed crops don't grow very well in many places there by made up the gap between production and consumption even bigger. So, we need quickly to investigate the effective methods that can help plants grow and improve yield and oil production even when the environmental changes from these methods nutrition factors starts with Potassium considered one of the most important macronutrients, along with phosphorous (P) and nitrogen (N) [4]. It plays many essential roles in different metabolic processes including photosynthesis, protein synthesis, enzyme activation, osmoregulation, phloem loading, energy transfer, stomatal conductance , stress resistance and cation-anion balance and etc. [5]. Potassium is an essential key in activation of many enzymes which play roles in protein and carbohydrate synthesis led to increase in plant growth, development and yield and crop. (ATP) Adenosine triphosphate is an essential energy source for many different types of chemical reactions that occur in plants required K for ATP synthesis and activate and helps maintain the cationic-anionic balance, facilitates the flow of water, and facilitates the transmission of energy. It also controls the osmoregulation of water and other salts in plant tissues and cells. [6] mentioned that stomatal regulation (opening and closing) stomata essential for plant cooling, continuous generation of energy during the photosynthesis, water translocation, nutrient transport. When K^+ is present guard cells are swollen and increase in size by absorbing water and stomatal opening and allow of gaseous exchange between plants and air. [7] certified that potassium in high concentration helps for recovery of water stress. Under water irrigation potassium used for improving growth, yield, and quality parameters. The average of achene weight, achene yield, biological yield, oil, and protein contents. According to[8] Potassium improved stem girth, stalk yield and biological yield might be during increasing CO_2 assimilation rate, stomata regulation and enzymes activation led to increase of photosynthesis, more carbohydrates formation more biological yield. [9] revealed that Potassium requires for improving quality production and increase grain yield, potassium and sulphur enhanced plant height, leaves number plant^{-1}, diameter head, grains number head^{-1}, thousand grain weight, biological yield, grain yield, oil percentage % and oil yield. Using algae extract led to an increase in total photosynthetic pigments (chlorophyll a, chlorophyll b, chlorophyll a+b, carotenoids, and total photosynthetic pigments) both under stress conditions and normal conditions. It also contaning phytohormones Indoleacetic Acid (IAA), Gibberellic Acid (GA_3), Cytokinins (CKs; Zeatin (Z) and Benzyl adenine (BA), and Jasmonic Acid (JA) [10]. Application of algae extract achieved a significant stimulatory effect on all growth parameters (root length, shoot length, number of pods per plant, average leaf area, fresh and dry weight of sprout, and fresh and dry weight of roots) of canola plants [11]. [12] demonstrated that growth and yield characteristics of sunflower plants were considerably improved by foliar application of the algae extracts. Plants treated with algae extracts had the highest number of leaves and the largest stem diameter, indicating an increase in leaf area and vegetative growth, resulting in a positive increase in biological yield and highest harvest index%. According to, [13] sunflower plants growing under saline stress conditions in calcareous soil had the greatest values of all parameters examined when algae extract and micronutrients were applied topically. It outperforms the control treatment by 111% in stem diameter, 40% in plant height, 76% in leaf count, 11% in chlorophyll index, 55% in head diameter, and 38% in weight of 100 seeds. Boron (B) among microelements is very important to crop [14]. It affected many physiological processes, IAA metabolism, synthesis of cellular walls, translocation of sugars, maintenance of membrane integrity, accelerating flowering and fruit-bearing processes in sunflower head [15]. Also, effected in pollen viability, abortion of stamens and sunflower pistils [16]. Plants need very small quantities of microelements, including boron and other microelements, which are considered essential for growth and the completing plant life cycle , activate enzymes and chlorophyll formations[17]. Deficiency of boron can be one of the factors resulting in empty seeds in the proximal and distal regions of the capitulum [18]. [19] mentioned that foliar application of boron resulted in higher chlorophyll content, leaf fluorescence also, improved the length of vascular bundles, increased the percentage of dry matter partitioned in seed and reduced dry matter partitioning to stem. indicating the role of boron in remobilization of reserves and translocation of photosynthates. [20] Mentioned that paclobutrazol(PBZ) application produces positive effect on vegetative growth of sunflower plants (plant height and stem diameter) parameters and yield parameters including increasing flower diameter, the age of flower appearance and the yield (number of seeds, total seed weight and 100 seed weight). Paclobutrazol altered morphology and growth of sunflower plants. [21] reported that sunflower plants treated with (PBZ), characterized by short stem, dark green, glossy leaves enriched with chlorophylls, carotenoids, and epicuticular wax. It elicited root morphological traits such as a more fibrous root system, enhanced root volume, and higher root dry weight. It also modified the root-to-shoot ratio and the height-to-girth ratio. The augmentation of 100-seed weight and seed output per plant in PBZ-treated sunflower specimens resulted from a modified root–shoot ratio and enhanced dry matter allocation, attributable to superior root system growth [20]. This study was conducted to enhance sunflower growth by increasing the production of photosynthetic pigments, improving photosynthetic efficiency, promoting vegetative growth attributes, and increasing the plant's nutritional value by applying biostimulant materials.

Material and methods

Experimental design

A field experiment was conducted over two consecutive growing seasons (2024 and 2025). Eleven treatments with three replicates of each treatment were used in the randomized complete block design (RCBD) experiment. Every experimental unit had five rows and measured 10.5 m^2 (3 × 3.5 m). The same agronomic techniques were applied to all treatments to determine the effects of foliar application of algae extract, potassium citrate, potassium sulfate, boron, and paclobutrazol on growth parameters and some biochemical constituents of sunflower plants (*Helianthus annuus* L.)cv. Sakha 53.

Plant material and cultivation

Sunflower seeds were obtained from the Sakha Agriculture Research Station, Agriculture Research Center, Doki Governorate, Egypt. Certified sunflower seeds were sown on April 1st of every seasons. The distance between each hill was 30 cm, and width of row was 70 cm on each hill, two seeds were sown. All normal farming guidelines of soil preparation, fertilizer, irrigation, and pest control were performed to make sure that all plants were grown and established evenly.

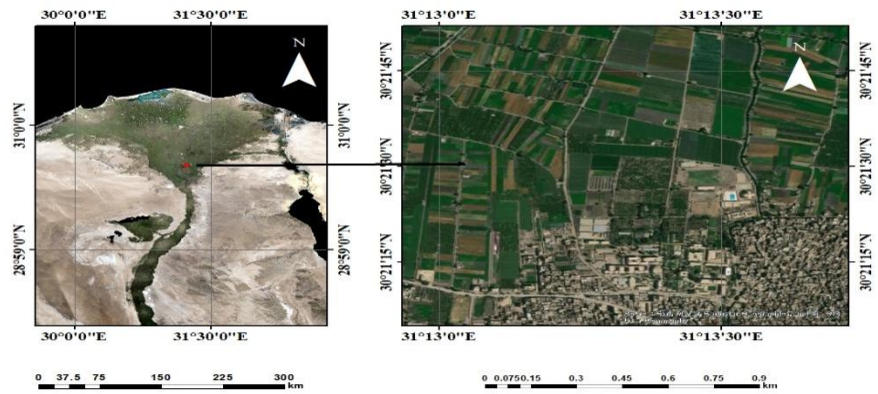


Figure (1): Location map for the studied area

Managements through plant growth

Foliar application treatments were applied three times during the vegetative and early reproductive stages: the first at 30 days after sowing (DAS), followed by two times at 15-day intervals. Treatments consisted of: Algae extract: 3 and 6 ml L^{-1}, Potassium citrate: 500 and 1000 mgL^{-1}, Potassium sulfate: 500 and 1000 mgL^{-1}, Boron: 25 and 50 mgL^{-1}, Paclobutrazol: 50 and 100 mgL^{-1} and Control (distilled water).All solutions were freshly prepared in distilled water and applied until runoff using a calibrated hand sprayer.

Treatment sources:

Algae extract was obtained from Algae Biotechnology Unit, National Research Center, Doki ,Giza , Egypt, was prepared from the early isolated blue green alga Spirulina platensis described by El-Sayed et al., (2001). Tripotassium citrate monohydrate, M.F.:C6H5K3O7,H2O, M.W.: 324.42g/mol, Assay 99.5%. Potassium sulfate, M.F: K2SO4 , M.W.: 174.3 g/mol, Assay 99.5%. Boric acid (Trihydrooxidoboron) M.F.: H3BO3, M.W.: 61.8 g/mol, Assay 99.9%min, were imported from Pioneers for chemicals (Piochem): area 269A,1, Industrial zone, 6 October city, Giza, Egypt. Paclobutrazol, M.F: C15H20ClN3O, M.W.:293.80, Assy NLT-59% were imported from TITAN BIOTEH LTD.

Sampling and collecting data:

Vegetative growth characteristics:

Different morphological characteristics of sunflower plants at 75 days after sowing were measured and calculated. Six plants from each treatment were randomly taken from middle rows and then separated into their organs and the following characteristics were recorded:

Plant height (cm) /plant, stem diameter (cm), number of leaves /plant, dry weight of stems (g) /plant, dry weight of leaves (g) /plant, head diameter (cm), total leaf area (cm^2)/plant by using the disk methods according to (**Derieux et al., 1973)**[43], specific leaf area (SLA), leaf area ratio (LAR), leaf area index (LAI), absolute growth rate (AGR), crop growth rate (CGR) and net assimilation rate (NAR). The samples of the above ground vegetative parts were dried in the oven for 48 h in

75°C to a constant weight and then the dry weight per plant was calculated. These dry samples of leaves were kept for chemical analysis.

Determination (Photosynthesis efficiency - Transpiration rate - Stomatal conductance):

The Photosynthesis efficiency, transpiration rate, and stomatal conductance were determined in leaves at 75th day after sowing during both seasons by using a LI-6400 portable photosynthesis system (LI-COR, Inc.).

Photosynthetic pigments:

According to the [22] method, the photosynthetic pigments (chlorophyll a, b, and carotenoids) were extracted and calculate (as mg/g fresh weight).

Determination of mineral nutrients, total carbohydrates and total sugars in leaves:

According to **(Piper, 1947)**[44] using common analytical techniques, to digest 0.1 g of dry leaves. Nitrogen and Crude protein were determined by Micro-Kjeldahl method described by [23] was used to determine total nitrogen. and calculated as dry weight of 100 g^{-1}. Then the following formula was used to determine crude protein using a conversion factor of 5.30 in accordance with [23] Crude protein (%) =Total nitrogen (%)×5.30. potassium and phosphorus According to [23] state that potassium was measured with a flame photometer and phosphorus was assessed colorimetrically [24]**.** The results were expressed as g 100 g^{-1} dry weight. Iron, Zinc and manganese by using the atomic absorption spectrophotometer Fe, Zn and Mn were determined.[25]. Total carbohydrates and total sugars were determined in sunflower leaves collected at 75 DAS, following the methods of [26] for total carbohydrates and [27] for total sugars. The concentrations were calculated as g 100 g^{-1} DW.

Endogenous phytohormones:

Endogenous phytohormones were determined quantitatively in fresh sunflower leaves at 75 DAS during the 2025 season for all treatments. By using high-performance liquid chromatography (HPLC) method of[28] (IAA), gibberellins, and abscisic acid (ABA) were determined. Meanwhile, cytokines were determined by HPLC according to[29]**.**

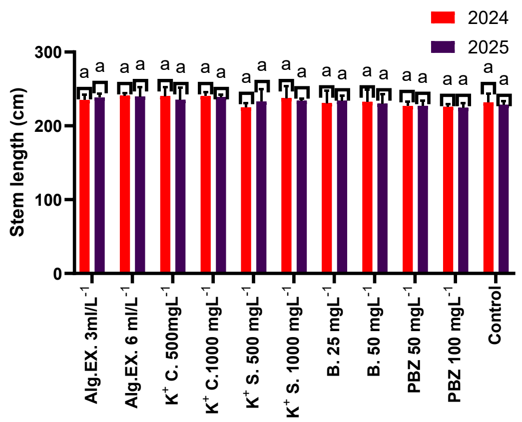
Statistical analysis: The statistical analysis was carried out using One-way ANOVA using SPSS, ver. 27 (IBM Corp. Released 2023). Data were treated as a complete randomization design according to **Steel et al. (1997)**[45]. Multiple comparisons were carried out applying Duncun test the significance level was set at < 0.05.

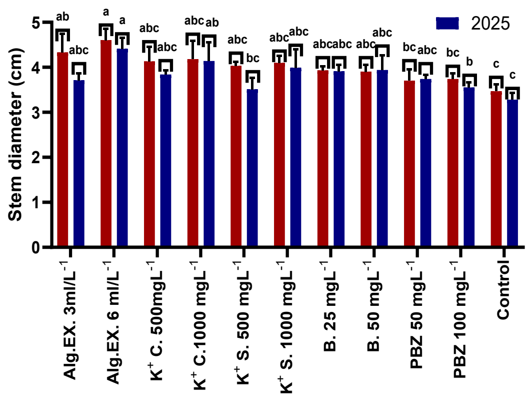
Results

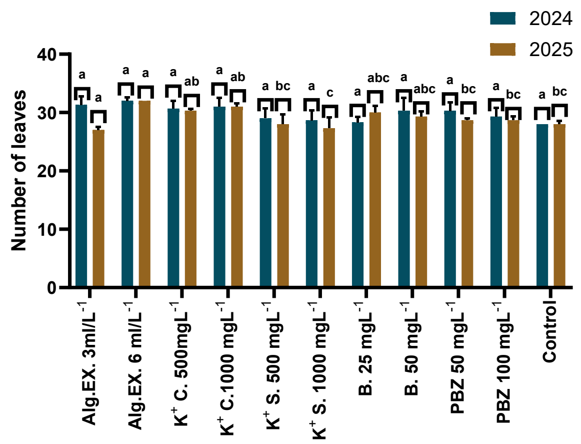
The results in **figure (2)** showed that vegetative growth parameters respond variously to foliar treatments, with some applications residing clearly superior to the control in both growing seasons.

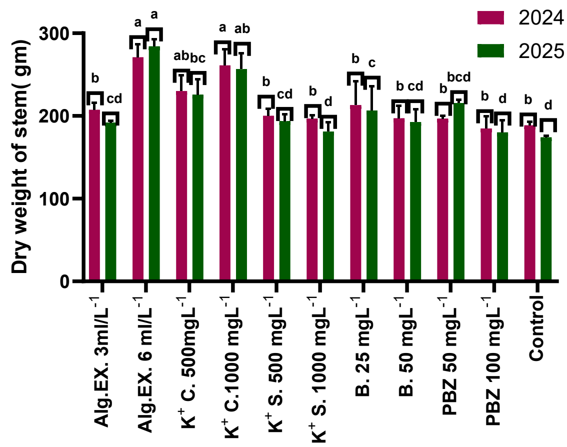
Stem length and diameter (cm): In both season, none of the treatments had an enormous impact on the height of the plants. Even though algae extract (6 ml L^{-1}) and potassium citrate (1000 mgL^{-1}) were higher than the control, these increases were not statistically significant. This means that stem elongation was stable and less affected by foliar treatments in the current. On the other hand, stem diameter showed a lot of variation. In both seasons, algae extract at 6 ml L^{-1} always had the highest values, and it was statistically better than the control. Potassium citrate at 1000 mgL^{-1} came in second and, in some cases, worked just as well as the algae extract treatment. The control and paclobutrazol (100 mgL^{-1}) produced the lowest stem thickness. The notable increase in stem diameter indicates enhanced structural development and vascular differentiation.

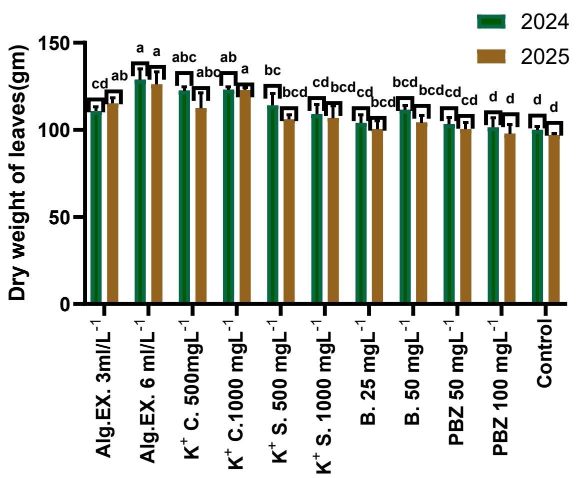
Number of leaves: showed limited response in season 2024, with no significant differences between treatments. However, in season 2025, algae extract (6 ml L^{-1}) produced the highest leaf number, whereas potassium sulfate (1000 mgL^{-1}) maintained the lowest value. Treatments containing potassium citrate or algae extract generally maintained higher vegetative growth as compared to the control. Dry weight of stem and leaves was markedly and significantly affected. In both seasons, Algae extract (6 ml L^{-1}) achieved the highest stem dry weight in both seasons and showed clear statistical superiority over the control. Potassium citrate (1000 mgL^{-1}) followed as the second most effective treatment. Conversely, paclobutrazol at 100 mgL^{-1} and the control recorded the lowest biomass values, particularly in 2025. Although dry weight of leaves showed a similar pattern. In both seasons, Algae extract (6 ml L^{-1}) significantly outperformed the control in both seasons. Potassium citrate treatments showed intermediate performance, while paclobutrazol (100 mgL^{-1}) and the control consistently recorded the lowest values. Head diameter: consistently increased numerically under algae extract (6 ml L^{-1}) and potassium citrate (1000 mgL^{-1}) compared to the control in both seasons. Algae extract (6 ml L^{-1}) had the highest value in 2024, followed by potassium citrate (1000 mgL^{-1}). The control and paclobutrazol (100 mgL^{-1}) had the lowest values. But these differences weren't statistically significant.

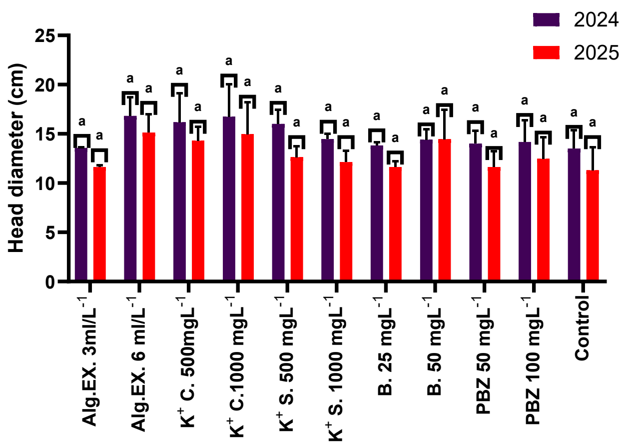










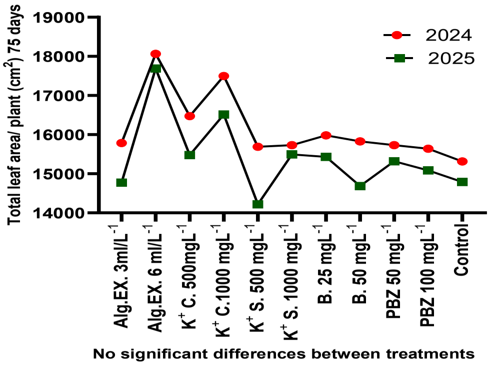


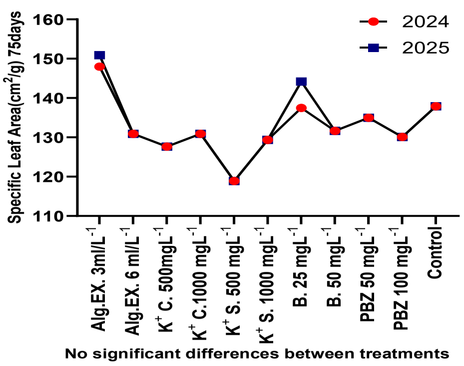
Figer (2): Effect of foliar application with Algae extract, potassium citrate, potassium sulfate, Boron, and Paclobutrazol on Stem length (cm), diameter (cm), Number of leaves, Dry weight of stem, leaves and Head diameter of sunflower plant during 2024-2025 seasons. Data are mean ± SE. a, b & c: There is no significant difference (P>0.05) between any two means, within the same column have the same superscript letter.

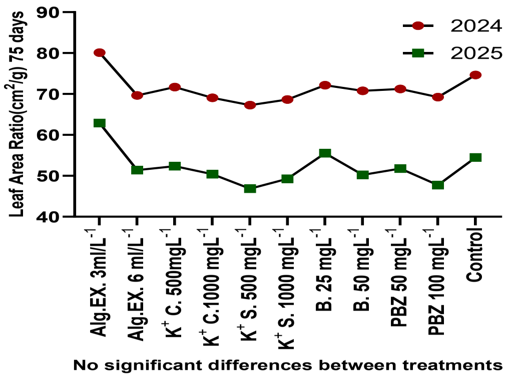
The presented data in **figure (3)** demonstrate the effect of algae extract, potassium sources, boron, and paclobutrazol on growth correlations of sunflower plants during the 2024 and 2025 seasons.

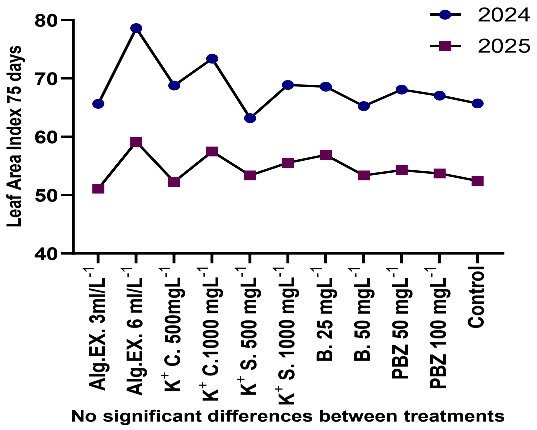
Growth correlations

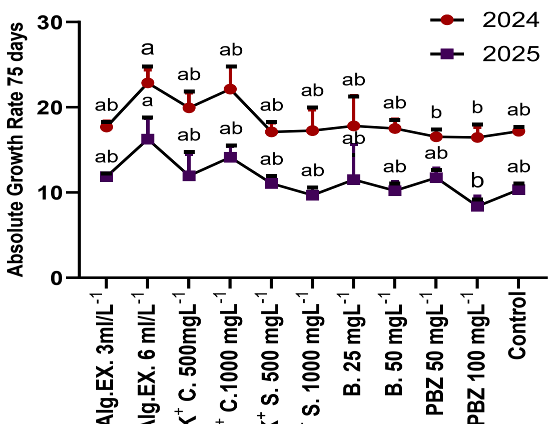
Total leaf area plant^{-1} (TLA) in both seasons (18063.76 and 17687.86 cm^2) was the highest values for algae extract at 6 ml L^{-1}. The next highest values were for potassium citrate at 1000 mg L^{-1}. The control treatment had values that were lower than the others and there were no significant variations between treatments. Specific leaf area (SLA) and leaf area ratio (LAR) were not significantly influenced by treatments in either season, suggesting that leaf thickness and biomass allocation remained relatively constant across treatments. Algae extract treatments, especially 3 ml L^{-1}, tended to give slightly higher (SLA) values, which could mean that the leaves were able to grow faster. Leaf area index (LAI) showed a similar pattern, with algae extract at 6 ml L^{-1} giving the highest numerical values in both seasons. Absolute Growth Rate (AGR) and Crop Growth Rate (CGR) both showed a good improvement when algae extract was used at 6 ml L^{-1}. This was the highest value for both seasons (22.85 and 16.26 g/day) and was much higher than all treatments. Potassium citrate at 1000 mg L^{-1} came in second. Paclobutrazol treatments (50 and 100 mg L^{-1}) exhibited the lowest AGR values, especially in 2024, demonstrating a growth-inhibiting effect. The (CGR) results showed the same pattern. The algae extract at 6 ml L^{-1} produced the highest (CGR) values (101.56 and 72.25 g·m^{-2}·day^{-1}), showing that it was better at growing biomass per unit of land area. Treatment with potassium citrate showed a moderate improvement, while treatment with potassium sulfate and paclobutrazol showed lower values. Paclobutrazol 100 mg L^{-1} had the lowest (CGR) in both seasons, which shows that vegetative growth was limited. Net Assimilation Rate (NAR). In 2024, values ranged from 1.3 to 1.7 g cm^{-2} day^{-1}. Potassium citrate at 1000 mg L^{-1} (1.7) had the highest number, followed by algae extract at 6 ml/L (1.6). This suggests that these treatments made photosynthesis more efficient per unit leaf area. Paclobutrazol at 50 ppm had the lowest number (1.3), which means that the plant's ability to take in nutrients was slightly lower. The overall NAR values in 2025 were lower (0.7–1.1 g cm^{-2} day^{-1}) than in 2024, which was due to changes in the environment over the seasons. Algae extract (6 ml/L) and potassium citrate treatments resulted in comparatively elevated numerical values (1.1), while paclobutrazol at 100 ppm exhibited the lowest value (0.7), indicating a more pronounced growth-regulating effect at this concentration.

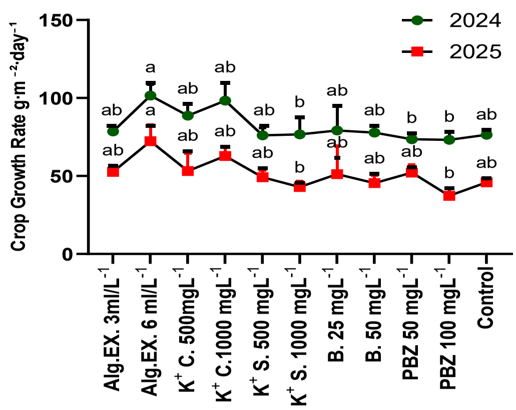


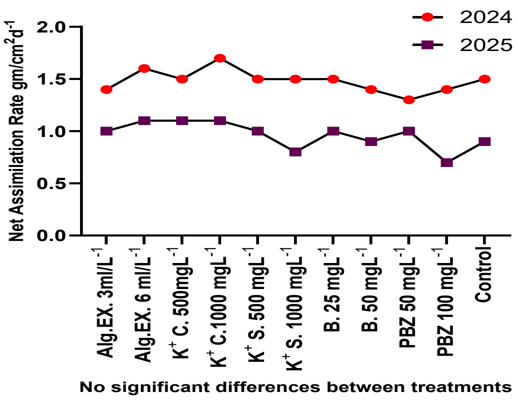












Figer (3): Effect of foliar application with Algae extract, potassium citrate, potassium sulfate, Boron, and Paclobutrazol on chemical components Total Leaf Area(TLA), specific leaf area (SLA), leaf area ratio (LAR), leaf area index (LAI), absolute growth rate (AGR), crop growth rate (CGR), and net assimilation rate (NAR)of sunflower plants during 2024-2025 seasons. Data are mean ± SE. a, b & c: There is no significant difference ($P>0.05$) between any two means, within the same column have the same superscript letter.

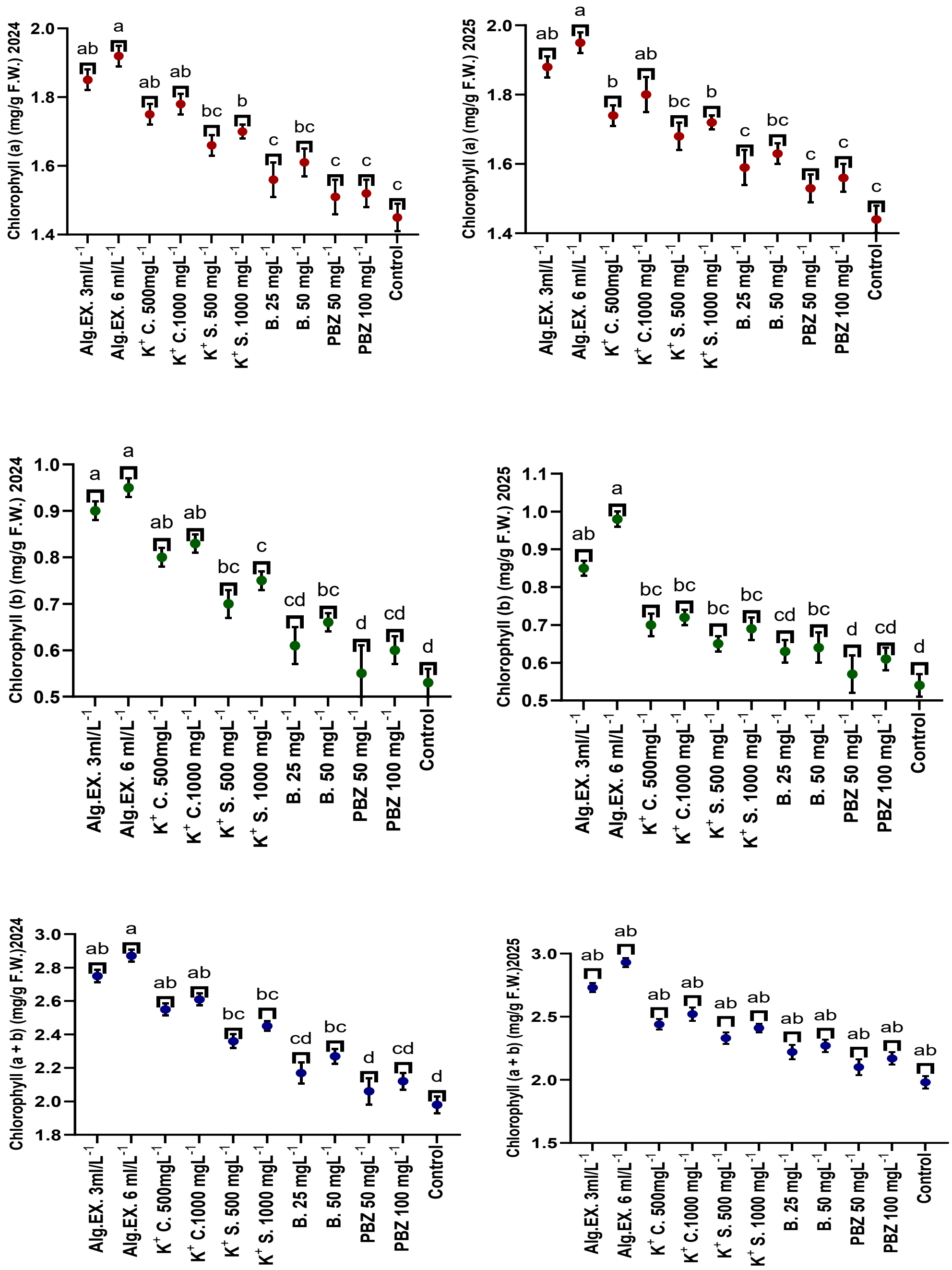
Results in **figure (4)** clarified that foliar application of algae extract, potassium sources, boron, and paclobutrazol significantly influenced the physiological and Photosynthesis efficiency of sunflower plants during the 2024 and 2025 seasons.

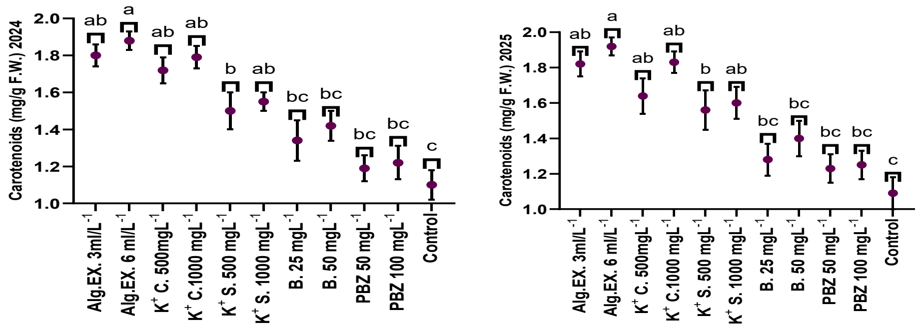
Photosynthetic pigments:

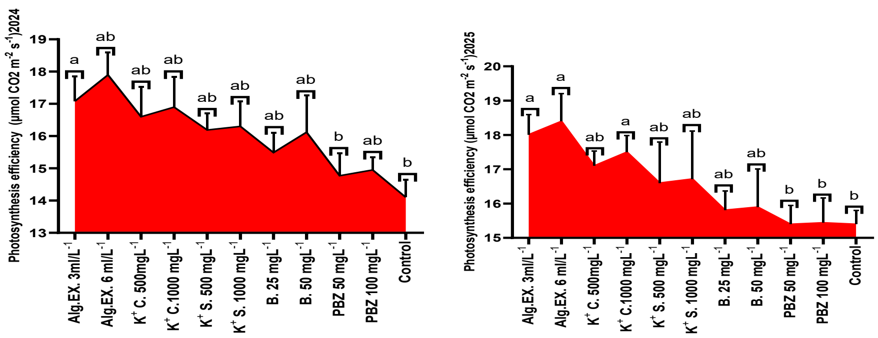
Algae extract, especially at 6 ml L^{-1}, increased the production of photosynthetic pigments, which is why both chlorophyll a and b and total chlorophyll content were at their highest levels. The 3 ml L^{-1} dose also caused big increases. Potassium citrate (especially at 1000 mg L^{-1}) raised pigment levels a little bit, and potassium sulfate (500 and 1000 mg L^{-1}) did the same. Boron treatments caused small increases, while Paclobutrazol at both doses and the control had the lowest pigment levels. This suggests that chlorophyll synthesis or stability was lower under these conditions. Carotenoid content followed similar patterns, with algae extract treatments delivering the highest values, particularly at 6 ml L^{-1}. Potassium citrate and sulfate (more so at 1000 mg L^{-1}) provided moderate increases, while boron showed only a slight effect. Paclobutrazol and the control exhibited the lowest carotenoid levels.

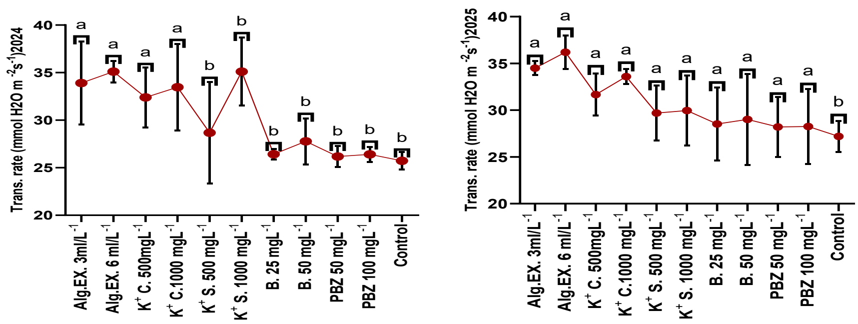
Photosynthesis measurements:

The algae extract at 6 ml L-1 had the highest Photosynthesis efficiency (μm CO_2 m^{-2} s^{-1}) of all the treatments, and the algae extract at 3 ml L-1 was very close behind. Potassium citrate at both 1000 mg L-1 and 500 mg L-1 enhanced the Photosynthesis efficiency relative to the control, however to a lesser degree than algae extract. Potassium sulfate treatments (1000 and 500 mg L-1) resulted in moderate increases, with 1000 mg L-1 exhibiting slightly superior performance compared to 500 mg L-1. The boron treatments (50 and 25 mg L-1) had only a small effect, while both doses of Paclobutrazol and the control had the lowest rates. This shows that Paclobutrazol stops photosynthesis. The highest transpiration rates (mmol H_2O m^{-2} s^{-1}) were achieved with algae extract (6 ml L-1), followed by algae extract (3 ml L-1), which confirms that they help with stomatal activity and gas exchange in leaves. Both potassium citrate treatments increased transpiration more than the control, while potassium sulfate treatments had a moderate effect, with the higher dose being slightly better. Boron applications had small positive effects, and Paclobutrazol treatments again led to the lowest transpiration rates, which were similar to or even lower than the control. This means that Paclobutrazol stops water loss by lowering stomatal conductance and/or leaf area. Stomatal conductance (mmol m^{-2} s^{-1}) was highest for algae extract treatments, especially at 6 ml L-1. This means that the stomata were working well and performing in CO_2. Potassium citrate, particularly at 1000 mg L-1, resulted in moderate enhancements, whereas potassium sulfate and boron treatments exhibited insignificant increases relative to the control. The control groups and Paclobutrazol had the lowest stomatal conductance, which shows that Paclobutrazol stops stomatal opening and gas exchange.









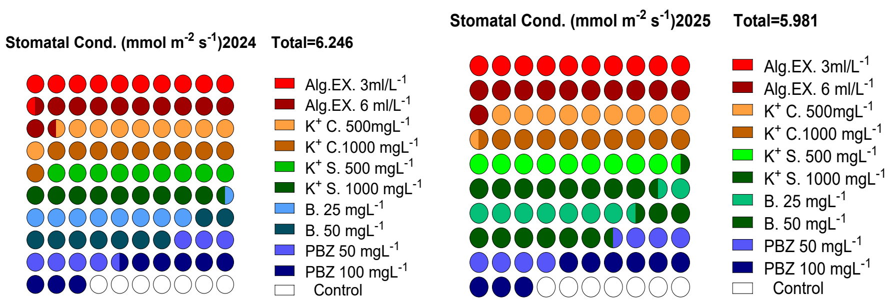


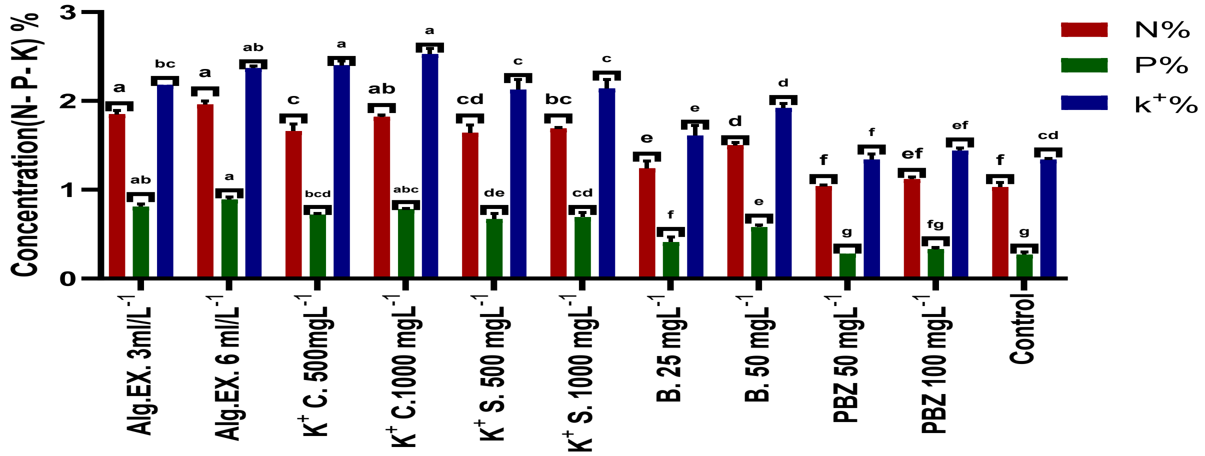
Figure (4): Effect of foliar application with Algae extract, potassium citrate, potassium sulfate, Boron, and Paclobutrazol on (Photosynthesis efficiency (µm CO_2 m^{-2} s^{-1})-Transpiration Rate (mmol H_2O m^{-2} s^{-1})-Stomatal Conductance (mmol m^{-2} s^{-1})-Chlorophyll Content Chlorophyll a, b, and total, (mg/g F.W.)-Carotenoid Content (mg/g F.W.) of sunflower plants during 2024-2025 seasons. Data are mean ± SE. a, b & c: There is no significant difference (P>0.05) between any two means, within the same column have the same superscript letter.

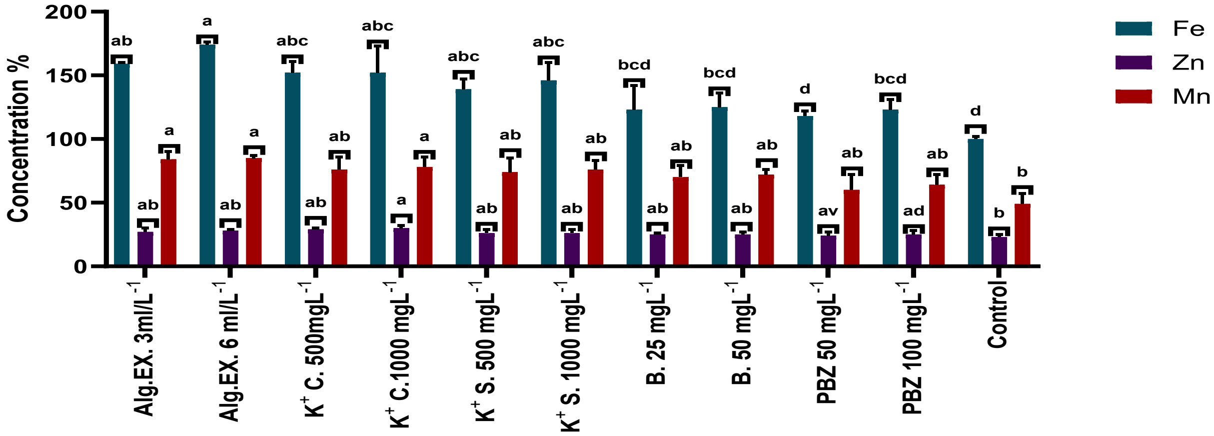
Macro and micronutrients content:

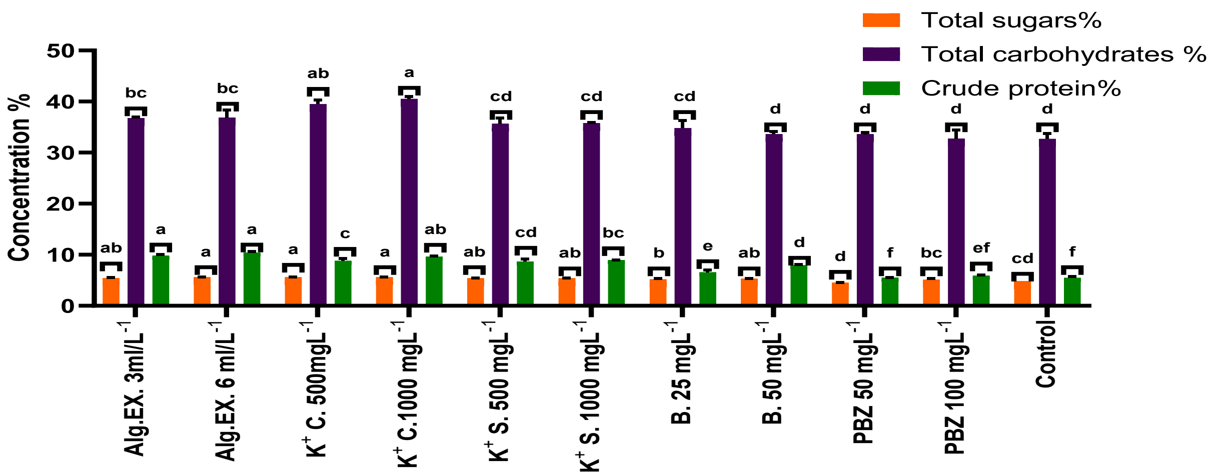
The results **in figure (5)** showed that the macronutrient levels were very different from those in the control group. The nitrogen concentration went up a lot with algae extract, especially at 6 ml L^{-1} (1.96%), then at 3 ml L^{-1} (1.85%), and finally at 1.03% (the control). The phosphorus levels were about the same (0.89%) in the algae extract at 6 ml L^{-1} and the lowest level (0.27%) in the control. The increase suggests that the body is better at absorbing nutrients and speeding up metabolism. The highest level was found in algae extract at 6 ml/L (0.89%), while the control group had the lowest level (0.27%). The rise means that nutrients are being absorbed more efficiently and metabolism is being activated more quickly. Potassium citrate treatments raised potassium levels a lot, reaching 2.53% at 1000 ml L^{-1} and 2.40% at 500 ml L^{-1}. This was higher than both potassium sulfate treatments and the control (1.34%). This shows that potassium citrate is better at helping tissues hold on to potassium. The levels of micronutrients were very different between the treatments. The algae extract had the best iron (Fe) concentration, with 174 ppm compared to 100 ppm in the control. Under potassium citrate at 1000 ml L^{-1}, zinc (Zn) levels reached their highest level (30 ppm). Under algae extract treatments, manganese (Mn) levels reached their highest level (85 ppm). Boron and potassium sulfate showed some improvements, but paclobutrazol and the control always had lower micronutrient levels.

Bio constituent contents:

Total sugars were markedly increased under potassium citrate (1000 ml L^{-1}, 5.63%) and algae extract (6 ml L^{-1}, 5.60%) compared with the control (4.81%). A pronounced response was observed in total carbohydrates, which were significantly affected by different applied treatments. Potassium citrate at 1000 ml L^{-1} recorded the highest value (40.50%), followed by 500 ml L^{-1} (39.52%), whereas the control exhibited the lowest percentage (32.67%). Crude protein percentage showed a good parallel to nitrogen concentration. The highest protein content was recorded with algae extract at 6 ml L^{-1} (10.39%), followed by 3 ml L^{-1} (9.81%), compared with 5.46% with the control.





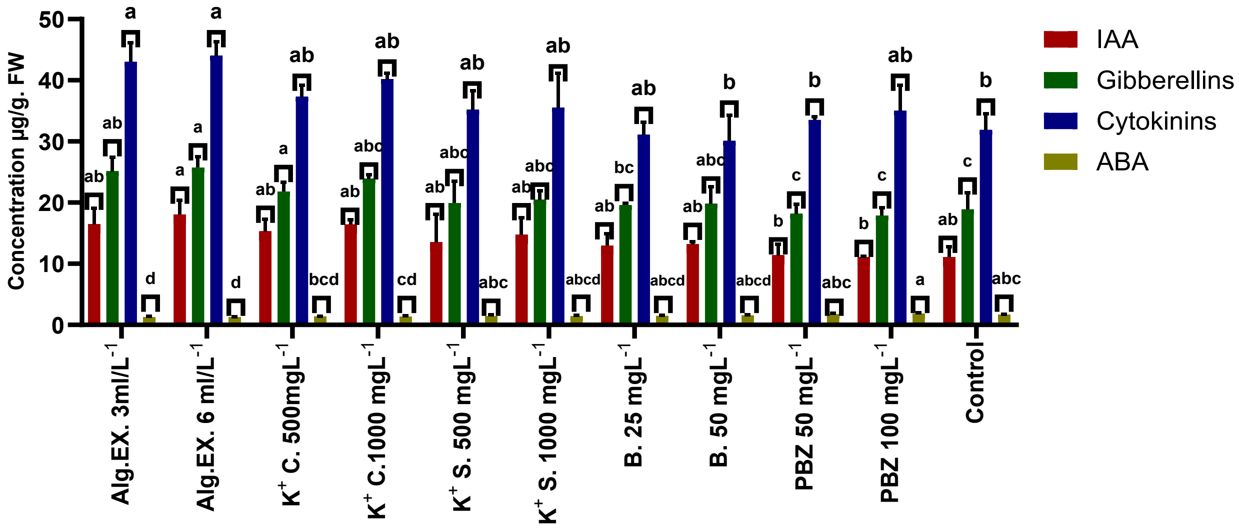


Figer (5): Effect of foliar application with Algae extract, potassium citrate, potassium sulfate, Boron, and Paclobutrazol on chemical components (minerals %N-P-K-Fe-Zn-Mn) - (Total carbohydrates%- Total sugars - Crude Protein) of sunflower leaves during season 2025. Data are mean ± SE. a, b & c: There is no significant difference (P>0.05) between any two means, within the same column have the same superscript letter.

Data presented in **figure (6)** demonstrate that the treatments significantly influenced in endogenous phytohormone balance, particularly plant growth promoters (IAA, gibberellins, and cytokinins) and Abscisic acid (ABA) compared with the control.

Endogenous phytohormone contents:

The highest concentrations of IAA (18.08 μg g^{-1} FW), gibberellins (25.73 μg g^{-1} FW), and cytokinins (44.0 μg g^{-1} FW) were obtained by foliar application of algal extract, particularly 6 ml L^{-1}. As a result, total promoters increased by 141.88% compared to the control, reaching 87.81 μg g^{-1} FW. Growth promoters were moderately increased by potassium treatments (citrate and sulfate forms) at both concentrations when compared to the control. A dose-dependent response was suggested by the superior performance of potassium citrate at 1000 mg L^{-1} compared to 500 mg L^{-1}. Potassium's crucial function in enzyme activation and carbohydrate metabolism, which indirectly promotes hormone biosynthesis, may be the cause of these increases. Total promoters were only slightly improved by boron treatments, with relative increases that were roughly 102–103% of the control. This implies that rather than significantly promoting promoter synthesis, boron mostly preserved hormonal homeostasis. The ABA content increased significantly with paclobutrazol treatments (50 and 100 mg L^{-1}; 1.79 and 1.84 μg g^{-1} FW, respectively), surpassing the control (1.70 μg g^{-1} FW) and reaching 105–108% relative values. This is in line with Paclobutrazol's known mechanism of action, which involves reversing the hormonal balance toward growth inhibition and blocking gibberellin biosynthesis. Algae extract, on the other hand, dramatically decreased ABA levels (1.27–1.29 μg g^{-1} FW), reaching only 74–76% in comparison to the control, indicating improved vegetative growth potential. One important measure of growth activity is the ratio of ABA to total promoters. The highest ratio was reported by algal extract at 6 ml L^{-1} (69.14; 189.81% relative to control), followed by algae extract at 3 ml L^{-1} (180.18%). This ratio was also improved (163.89%) by potassium citrate (1000 mg L^{-1}). By rebalancing hormones in Favor of inhibition, paclobutrazol treatments, on the other hand, decreased the ratio to 95–97% in comparison to control, indicating its growth-retarding impact.



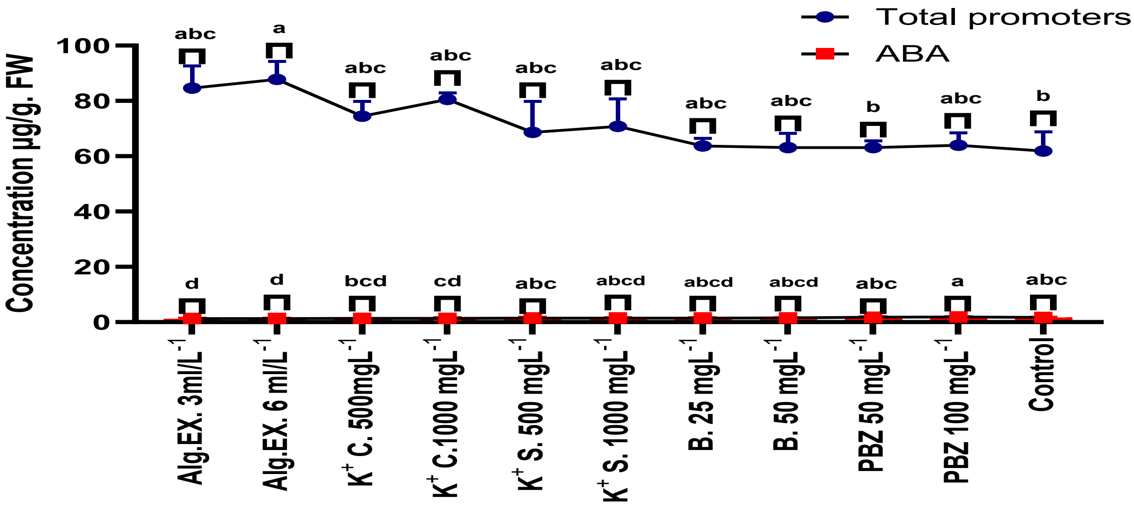


Figure (6): Effect of foliar application with Algae extract, potassium citrate, potassium sulfate, Boron, and Paclobutrazol on endogenous phytohormone contents IAA, Gibberellins, Cytokinins, and ABA on sunflower leaves on 75 days after sowing during season 2025. Data are mean ± SE. a, b & c: There is no significant difference (P>0.05) between any two means, within the same column have the same superscript letter.

Discussion:

Algae extract improved metabolic activity and enhanced nutrient uptake by using their naturally occurring bioactive compounds, such as phytohormones, amino acids, and vitamins. This led to higher protein content and enzymatic activity in plant tissues by promoting amino acid biosynthesis and nitrogen assimilation. The increase in chlorophyll and carotenoid levels increased photosynthesis efficient and net assimilation rate, which led to more sugar accumulation. As a result, higher Co_2 fixation and assimilate partitioning led to higher absolute growth rate, crop growth rate, and biomass production. This was shown by big changes in vegetative growth parameters like stem length and diameter, number of leaves, total leaf area, specific leaf area, leaf area ratio, and leaf area index. these results indicated with [10] who mentioned that using algae extract increased the photosynthetic pigments and stimulated phytohormones like IAA, GA_3, cytokinins, and ABA. Also,[30] indicated that foliar application of algal extract increased vegetative growth in terms of height, stem diameter, number of leaves, head diameter, and seed weight. [31] indicated that sunflower plants treated with seaweed extracts achieved the maximum shoot dry weight per plant.[32] reported that seaweed extract enhanced photosynthetic capacity by 43.3% and decreased transpiration rate by 26.5%. also, enhanced the specific leaf area to 247.3 cm^2 g^{-1}, increased the net CO_2 assimilation rate by 43% (μmol CO_2 m^{-2} s^{-1}), and reduced transpiration (mmol H_2O m^{-2} s^{-1}). Additionally, a maximum stomatal conductance of 0.359 mol H_2O m^{-2} s^{-1}).[33] clarified that the application of seaweed extract on Calotropis procera enhances shoot weight, achieving an increase of 122.4% compared to the control, and augmented specific leaf area about 64.6%. Although seaweed exhibited a 59% enhancement in photosynthetic rate.[34] showed that concentrations of (N, P, K, Fe, Zn and Mn) on sunflower shoot were significantly increased with increasing algae and potassium concentration foliar spray application. The enhancement in total carbohydrates and soluble sugars in treatment 1000 mgL^{-1} potassium citrate may be improved photosynthetic performance and activation of enzymes involved in carbohydrate metabolism under adequate potassium supply and biostimulant application. Our results in a line with [35] said that Potassium activated numerous enzymes that specialized in carbohydrate and protein synthesis, resulting in enhanced plant growth, development. Adenosine triphosphate (ATP) is a crucial energy source for several chemical reactions in plants, necessitating potassium (K) for ATP synthesis. It regulates the osmoregulation of water and other salts in plant tissues and cells. K also influences the absorption of water by plant roots and its loss through stomata. [36] concluded that foliar application of 500 mgL^{-1} potassium improved growth, physiological parameters, gas exchange measurements, antioxidant levels, also, increases K^+ level which provides turgidity to guard cells and stability to membranes. This treatment promoted healthy growth for sunflower plants. The metabolic function of boron in nitrogen absorption and carbohydrate metabolism may have positively influenced. Boron contributes to leaf functionality by enhancing photosynthetic oxygen evolution, and the efficiency of PS II electron transport [37]. The application of boron may have enhanced the cell wall structure, resulting in a temporary elevation in the elasticity modulus, subsequently followed by diminished secondary thickening and an increase in plasma membrane-bound reductase activity, facilitating improved partitioning to sinks and ultimately leading to greater dry matter allocation to seeds [19]**.** The use of boron enhanced crop productivity compared to the control, attributed to greater photosynthesis throughout the reproductive phase and improved differentiation of vascular bundles in sunflowers [38]. Paclobutrazol (PBZ) inhibit gibberellin biosynthesis, which makes stems grow shorter and plants shorter and thicker because cell division and cambial activity are boosted [39]. High concentration may suppress vegetative growth and reduce leaf number [40]**.** A moderate application of PBZ (2.5 g/plant) significantly increased the accumulation of carbohydrates and reallocating assimilates toward reproductive growth [21]. But too much of it can lower the yield[41]. Plants treated with PBZ had more chlorophyll and carotenoids, but their photosynthetic rate was lower because their stomatal conductance was lower and their stomatal pores were smaller. This could make them more resistant to drought. PBZ slows down growth and helps roots grow better, which moves more biomass toward seed filling and increases seed yield. This is also seen in mango[42]**.**

In summary, these findings validate the physiological function of algae extract as an effective biostimulant that promotes plant growth and productivity by influencing metabolic processes, photosynthetic activity, and nutrient availability.

Conclusion:

This study illustrates that the growth, physiological, and biochemical performance of sunflower plants significantly affected by foliar application of algae extract, potassium citrate, potassium sulfate, boron, and paclobutrazol. Algae extract (6 ml L^{-1}) enhanced vegetative growth characteristics, including stem length, stem diameter, and leaf number. In addition, photosynthetic pigments, photosynthesis measurements, and bio constituents including total sugar, crude protein, and carbohydrate accumulation were all significantly enhanced. Also, relative growth rate, absolute growth rate, and net assimilation rate pertain to the treatments. Moreover, macro- and micronutrient of the treated plants was enhanced, indicating augmented internal translocation and nutrient assimilation. Potassium citrate, the secondary treatment, positively influenced these characteristics. Endogenous phytohormones exhibited substantial regulation, as paclobutrazol synthesis and modified hormonal equilibrium, while biostimulant and nutrient applications enhanced growth-promoting hormones. In summary, the integration of biostimulants, mineral nutrients, and growth regulators can effectively enhance the physiological efficiency and metabolic activity of sunflower plants, providing a feasible approach to increase source sink relationship and allow the increase in photosynthesis allocation and partitioning which qualifies the plants to increase growth and productivity.

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