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RESEARCH ARTICLE

Optimising morpho-physiological traits via micronutrient enrichment and cytokinin-mediated control in *Brassica juncea*

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Abstract

Brassica juncea, a type of rapeseed mustard, displays distinct responses to foliar applications of boron (B), sulphur (S) and phytohormones. This necessitates a thorough investigation into the resultant morphological and physiological alterations within this plant species. The application of boron and sulphur has revealed substantial enhancements in morphology and physiological functions. To elucidate these effects, a field experiment was undertaken, examining the consequences of diverse concentrations of boron (ranging from 0.5% to 1.5%) and sulphur (ranging from 0.10% to 0.20%) when applied either independently or in conjunction with the plant growth hormone, Cytokinin (at concentrations of 15 - 45 mg dm^{-3}), via foliar application. This study is designed to comprehensively evaluate their impact on growth, physiological processes and yield attributes in the mustard crop. The experiment systematically analysed morphological, physiological, biochemical and yield-related parameters at specified intervals. These findings are founded on empirical observations. Notably, the combined application of these crucial nutrients and the plant growth hormone yielded significant and statistically meaningful ($p < 0.05$) increases in plant height, leaf count, leaf area index (LAI), crop growth rate (CGR) and net assimilation rate (NAR) during the crop's maturation stage. These results underscore the discernible advantage of judiciously reducing the reliance on chemical fertilizers and concurrently integrating micronutrients and plant growth hormones. This approach contributes to environmental sustainability by mitigating the pollution associated with excessive nitrogenous and phosphatic chemical fertilizers, while also enhancing overall crop productivity.

Keywords: agriculture; boron; growth regulator; morpho-physiological; mustard; sulphur

Introduction

Brassica juncea L., commonly referred to as Indian mustard or rapeseed mustard, holds a significant role in global agriculture owing to its diverse range of uses, which include the production of edible oil, animal feed and biofuel feedstock (1). The enduring significance of this versatile oilseed crop is supported by its economic value, nutritional characteristics and ecological relevance. *B. juncea* is widely recognized for its significant contributions to the edible oil industry and the growing biodiesel sector, underscoring its crucial position within modern agricultural landscapes. Given the increasing global demand for vegetable oils and alternative energy sources, driven by growing populations and changing energy requirements, there is a pressing need to improve *B. juncea* adaptability, productivity and resilience (1-4). The imperative above is further emphasized by the enduring obstacles presented by constantly changing climatic conditions, the competition for cultivable land and the unwavering commitment to sustainable and environmentally conscientious agricultural methodologies. Therefore, optimizing morpho-physiological traits in *B. juncea* is of utmost importance, aiming to maximize crop yields, enhance oil quality and ensure the sustainability of its cultivation. Morpho-physiological traits encompass a wide array of plant characteristics and functions, from growth patterns to the utilization of nutrients and allocation of resources. These characteristics are the foundation for the crop's ability to adjust to changing environmental conditions, effectively distribute resources and establish its yield potential (2, 5-7). The complex interaction between the availability of nutrients and the regulation of hormones in determining these characteristics is a subject of great scientific fascination, particularly in the case of *B. juncea*. Micronutrients and plant growth regulators regulate morpho - physiological responses in *B. juncea*. Micronutrients, particularly boron (B) and sulphur (S) are crucial in crop uptake and assimilation processes. Extensive documentation exists regarding the involvement of boron and sulphur in plant development, encompassing processes such as root and shoot growth, flowering and seed set across a diverse range of plant species. Nevertheless, the specific mechanisms that dictate the interaction between boron and sulphur in *B. juncea* and the potential synergistic outcomes resulting from their combined application continue to be topics of considerable scientific investigation. Plant growth regulators, such as the phytohormone cytokinin, significantly impact plant development, including cell division, leaf expansion and the regulation of sink-source dynamics. Cytokinin has been shown to extensively impact crop growth and yield across various plant species (1, 7-12). The potential for manipulating the morpho-physiological traits of *B. juncea*, particularly when combined with micronutrient supplementation, offers a promising avenue for further research and exploration. The study is centred around the convergence of 2 essential components, namely micronutrients (boron and sulphur) and plant growth regulators (specifically cytokinin), which presents a significant area of interest. This study examines the separate and combined effects of boron, sulphur and cytokinin on the morpho-physiological characteristics of *B. juncea*. This investigation will yield intricate observations regarding the fundamental physiological mechanisms that govern the performance and productivity of crops. Despite the considerable research on the impacts of micronutrients and plant growth regulators on different crops, there is a noticeable gap in the scientific literature regarding comprehensive investigations, specifically on *B. juncea*. The existing body of research primarily centres around alternative crops or more generic plant species, resulting in a lack of attention towards the distinct reactions of *B. juncea* to boron, sulphur and cytokinin. Furthermore, the complex interplay among boron, sulphur and cytokinin and their possible synergistic impacts on the morpho-physiological characteristics of *B. juncea* have not been extensively investigated. Comprehending the synergistic effects is imperative to optimise the growth and development of this particular oilseed crop. Although certain studies have focused on the morphological aspects, there is still limited research on the physiological mechanisms that underlie these responses (13–15). Informed decision-making in crop management necessitates a comprehensive comprehension of the physiological processes involved. In addition, it is necessary to give further consideration to translating research findings into practical applications that can effectively benefit growers and cultivators of *B. juncea* in the field. This study aims to elucidate the complexities of these interactions, decipher the physiological mechanisms at play and offer valuable insights with practical implications for improving the adaptability, productivity and sustainability of *B. juncea* in modern agricultural practices. There are important agricultural applications for appreciating the physiological processes that underlie *B. juncea's* reactions to cytokinin, sulphur and boron. Growers can lower input costs and improve seed quality and yield by refining nutrient management techniques, such as applying sulphur and boron precisely. Furthermore, using cytokinin to control growth and enhance stress tolerance provides a technique to produce more resilient and productive crops, especially in harsh conditions. By enhancing yield stability, encouraging resource-efficient practices and eventually increasing economic returns, these insights can help farmers directly and close the gap between research and practical agricultural applications.

Materials and Methods

Planting material

The experimental study used the *B. juncea* variety "HAYOLA-405," obtained from a certified and authorised seed producer known as 'Good Grow' in Phagwara, Punjab. The selection of seeds for sowing was based on strict quality criteria, ensuring that only seeds exhibiting strong health and free from damage were chosen. The plants produced were tall, erect and compact with green foliage. They matured within 120 to 140 days, yielding approximately 6.74 quintals per acre. The seeds were round, bold and brown and appeared uniform. This variety was resistant to various soil and seed-borne diseases. The present study was conducted at the agricultural research farm of Lovely Professional University, situated in Phagwara, Punjab. The research field is located at an approximate latitude of 31° 22' 31.8" North and a longitude of 75° 23' 03.02" East. Its elevation is measured at 252 m above sea level. The experiment was conducted with meticulous organisation, adhering to the principles of a Randomized Block Design to ensure statistical rigour. The experimental site covered an estimated area of 450 m^2, carefully delineated to accommodate the size and extent of the research. The experiment was meticulously designed with a scientific approach, comprising 9 distinct treatments carefully replicated 3 times, resulting in 27 experimental plots (Table 1). To minimise bias, the researchers employed randomisation in allocating treatments to individual plots, thereby enhancing the statistical integrity of the study. Every personal subplot was carefully designed to have a length of 5 m and a width of 3 m, resulting in a total area of 15 m^2 for each subplot. The practical design deliberately incorporated distinct irrigation channels with a width of 1 m to accommodate precise and personalised irrigation needs for each experimental plot. Current field practices for mustard cultivation focus on optimal land preparation with organic amendments, timely sowing (mid-October to early November) and the use of certified, treated seeds. The research site exhibited prevailing climatic conditions characterised by an average temperature that frequently reached approximately 50 °C. The soil composition observed at the designated research site showed a sandy loam texture and an acidic pH level measuring 6.81. Subsequent soil examination unveiled an electrical conductivity (EC) value of 0.407 Deci Siemens per metre (dS/m). The nutrient content analysis revealed that there were 90 kg/acre of nitrogen (N), 75 kg/acre of phosphorus (P) and 45 kg/acre of potassium (K)

Table 1. Overall detail and layout of the field experiment

TREATMENT (T1)	Control
TREATMENT (T2)	Boron (Rec. dose at 1%)
TREATMENT (T3)	Sulphur (Rec. dose at 0.15%)
TREATMENT (T4)	Cytokinin Rec. dose at 30 mg dm^{-3}
TREATMENT (T5)	Boron at 0.5% + Cytokinin at 45 mg dm^{-3}
TREATMENT (T6)	Boron at 1.5% + Cytokinin at 15 mg dm^{-3}
TREATMENT (T7)	Sulphur at 0.10% + Cytokinin at 45 mg dm^{-3}
TREATMENT (T8)	Sulphur at 0.20%) + Cytokinin at 15 mg dm^{-3}
TREATMENT (T9)	Sulphur at 0.15% + Cytokinin at 30mg dm^{-3}

present. Balanced fertilization (80-40-40 kg N-P_2O_5-K_2O/ha) with micronutrients, 2-3 timely irrigations at critical stages and integrated weed and pest management ensure productivity. Harvesting is done at 75-80% pod maturity, followed by drying and proper storage to maintain seed quality. To meet the nutritional needs of the mustard crop, a precise application of urea, single superphosphate and muriate of potash (potassium chloride) was implemented. To fulfil the experimental objectives, a comprehensive investigation was conducted to examine the impact of 8 distinct combinations of boron (administered in the form of Boric acid), sulphur (utilised as elemental sulphur) and the plant growth hormone cytokinin (employing 6-benzyl-aminopurine or BAP) obtained from a certified and authorised seed producer known as 'Good Grow' in Phagwara, Punjab. Meticulous plant protection measures were implemented throughout the crop's growth period. Careful attention was given to the mustard crop at regular intervals, addressing pest infestations as they occurred in the experimental field. Thiomethaxam was used to control the aphid attack in the mustard crop. The treatments were carefully chosen to determine their impact on a range of morpho-physiological characteristics, such as plant height, leaf count, leaf area index (LAI), specific leaf area (SLA), specific leaf weight (SLW), crop growth rate (CGR) and net assimilation rate (NAR) of the mustard crop. The treatment combinations were carefully replicated 3 times to enhance the collected data's robustness and reliability. A Randomised Block Design (RBD) was implemented with careful attention to allocate the treatments among the experimental plots. Each property was delineated to have a length of 5 m and a width of 3 m. Implementing an advanced irrigation system necessitated the integration of irrigation channels with a width of 0.5 m between the plot replications. The provided infrastructure played a crucial role in ensuring the accessibility and continuous irrigation flow to every experimental plot, thereby enhancing the consistency of environmental conditions throughout the study. The experimental crop was carefully cultivated until it reached the stage of maturity, which is a critical phase for capturing a wide range of data and evaluating the overall effects of different treatments on the morpho-physiological characteristics of *B. juncea*.

Parameters studied in the field

The leaf samples were taken at 30-day intervals after sowing (DAS) to estimate the plant's morphological, physiological and biochemical changes. The standard procedure adopted for estimating morpho-physiological and biochemical parameters for different treatments is given below: The observations on morpho-physiological traits included plant height, no. of leaves, leaf area index (LAI), crop growth rate (CGR), net assimilation rate (NAR), specific leaf area (SLA) and specific leaf weight (SLW) which were recorded at different stages, i.e., 30 days after sowing (DAS), 60 DAS, 90 DAS of crop growth. The crop exhibited signs of some aphid attack, but no sign of disease incidence was noted. Therefore, Thiamethoxam at 4 g/L was applied to cure the problem. The crop was kept free of weeds by hand hoeing. The crop was harvested manually in the first week of April. Harvested crops were sun-dried and threshed manually. The leaf area was measured with an electronic leaf area meter.

The leaf area index was calculated using the formula given by Watson (16).

$$\text{LAI} = \frac{\text{Total Leaf Area of a Plant}}{\text{Ground area occupied by the plant}} \quad \text{Eqn.1}$$

The net assimilation rate was calculated using the formula given by Williams (17).

$$\text{NAR} = \frac{(W2 - W1)}{(t2 - t1)} \times \frac{(\text{Log}_e\, L2 - \log_e L1)}{(L2 - L1)} \quad \text{Eqn.2}$$

Where W1 and W_2 are the oven dry weights of the whole plant at time t_1 and t_2, respectively, L_1 and L_2 are leaf weights of leaf area at t_1 and t_2.

NAR is expressed as the grams of dry weight increase per unit dry weight or area per unit time (g $m^{-2}day^{-1}$).

The crop growth rate was calculated using Watson's formula (18).

$$\text{CGR} = \frac{(W2 - W1)}{t2 - t1} \quad \text{Eqn. 3}$$

Where W2 & W2 are plant oven dry weight at time t1 & t2.

The specific leaf area measures the plant's leaf area to leaf oven dry weight and is expressed in cm^2g^{-1}

$$\text{SLA} = \frac{\text{Leaf Area}}{\text{Leaf Weight}} \quad \text{Eqn. 4}$$

The Specific leaf weight measures leaf weight per unit leaf area. Hence, it is a ratio expressed as g cm^{-2}. More SLW/unit leaf area indicates more biomass and a positive relationship with yield can be expected.

$$\text{SLA} = \frac{\text{Leaf Weight}}{\text{Leaf Area}} \quad \text{Eqn. 5}$$

Data analysis

Significant distinctions between the control and treated plots prompted a segregated analysis of the data obtained from the experimental plots through one-way ANOVA. The data is presented in the format of Mean ± SD at $p<0.05$, with "DAS" denoting the days after sowing of the crop. The analysis of variance (ANOVA) was executed using SPSS software and comparisons of means were conducted through Fisher's least significant differences (LSD) test. Additionally, the interrelationships between the parameters at different time intervals and principal component analysis (PCA) were explored using XLSTAT.

Analysis of functional groups through FTIR

FTIR (Fourier-Transform Infrared Spectroscopy) was employed to analyze the functional groups of compounds. In this FTIR analysis, dried powders of each plant material were utilised. Specifically, a dried alcohol extract powder measuring 10 mg was enclosed within a 100 mg KBr pellet to produce translucent sample discs. Subsequently, each powdered sample from each plant specimen was introduced into an FTIR spectroscope, specifically the Shimadzu model 1 from Japan. Scans were conducted over a range spanning 400 to 4000 cm^{-1} with a resolution of 4 cm^{-1}.

Results and Discussion

Plant height

A thorough examination evaluated the collective and separate impacts of boron, sulphur and cytokinin nutrients on *B. juncea*, commonly called mustard. The results of this study have provided a clear understanding of significant differences in plant height observed across different treatments during the distinct phases of crop development. The data about the time intervals of 30, 60, 90 and 120 DAS are presented in Table 2. The percentage increase in plant height was determined concerning the control treatment (T0), which was used as a baseline for comparison. As a result, the percentage increase in plant height was examined at 4 different time points: 30, 60, 90 and 120 DAS. At the 30-DAS stage, the treatment with the highest percentage increase was T3, which exhibited a value of 15.74%. This was followed by T2 with a percentage increase of 10.50%, T8 with 6.34%, T7 with 5.01%, T4 with 4.62%, T9 with 2.25%, T6 with 1.29% and T5 with 0.31%. These values were compared to the control treatment (T1). It is worth mentioning that the utilisation of sulphur at the prescribed concentration of 0.15% resulted in a significant augmentation in plant height, with increments of 10.62%, 20.58% and 9.45% observed at 60, 90 and 120 DAS, respectively, in comparison to the control treatment (T1). Furthermore, at 90 and 120 DAS, Treatment T9 demonstrated the highest statistical significance level regarding plant height. This was observed when sulphur and cytokines were applied at the recommended dosage, surpassing the control treatment (T1). Treatment T6, which involved the application of boron in combination with cytokinin (boron at a concentration of 1.5% and cytokinin at a concentration of 15 mg dm^{-3}), exhibited significant increases of 16.48% and 10.13% at 90 and 120 DAS, respectively. In contrast, Treatment T4 exhibited the smallest growth in plant height, with 10.70% and 0.11% increments compared to its control (T1) at 90 and 120 DAS, respectively. This outcome occurred when Cytokinin was applied at the recommended 30 mg dm^{-3} dosage. The findings depicted in Table 1 highlight the prominence of Treatment T7 in terms of its consistent and significant impact on plant height throughout all crop growth stages, surpassing the effects observed in the other treatments. Plant growth regulators, such as cytokinin, combined with secondary macronutrients, particularly sulphur, significantly increased photosynthetic efficiency (19). The observed increase in plant height in Treatment T7 can be attributed to the substantial contribution of this phenomenon, which resulted in enhanced vegetative growth in the crop plants. cytokinin, a plant hormone renowned for its capacity to strengthen development, is crucial in stimulating branching in crops (20). As a result, the utilisation of a marginally increased concentration of cytokinin, surpassing the prescribed threshold, in conjunction with the administration of sulphur fertiliser, produced noteworthy outcomes regarding the stature of plants and the overall productivity of the crop. Increased plant height indicates more effective physiological functions and better nutrient uptake, both of which probably affect root architecture. Better water and nutrient uptake is made possible by a strong root system, which may increase biomass production. Particularly suggestive of general plant health and resource efficiency are treatments that exhibit a balanced rise in plant height and root development. This correlation emphasizes how crucial it is to assess all growth metrics in order to fully comprehend how the treatments affect crop performance.

The observation above highlights the complex relationship between the utilisation of secondary nutrients and plant growth regulators, which can substantially impact the morphological traits and vegetative growth of *B. juncea*. The increase in these crucial indicators, such as the height of plants, demonstrates the possibility of improving crop performance and productivity, which has implications for optimising agricultural methods (20-24).

Number of leaves

The number of leaves in a plant plays a pivotal role in determining crop yield. An increased leaf count has a direct and significant positive impact on crop yield and overall productivity. This increase in the number of leaves results in improved light interception, subsequently elevating the plant's photosynthesis rate. A heightened photosynthetic rate, in turn, stimulates a myriad of essential biochemical activities and activates crucial enzymes within the plant,

Table 2. Plant height (cm) and No. of leaves of mustard

Treatments	30 DAS		60 DAS		90 DAS		120 DAS	
	Plant height	No. of leaves	Plant height	No. of leaves	Plant height	No. of leaves	Plant height	No. of leaves
T1	$8.39^a \pm 1.23$	$5.78^a \pm 0.19$	$22.89^a \pm 5.07$	$9.00^a \pm 0.58$	$67.93^a \pm 9.23$	$67.93^a \pm 9.23$	$141.23^a \pm 15.64$	$29.00^b \pm 6.89$
T2	$9.37^a \pm 1.94$	$5.56^a \pm 0.51$	$25.61^a \pm 7.47$	$9.22^a \pm 1.02$	$85.54^a \pm 21.41$	$85.54^a \pm 21.41$	$155.98^a \pm 18.43$	$36.89^{ab} \pm 6.38$
T3	$9.95^a \pm 1.44$	$5.78^a \pm 0.19$	$23.78^a \pm 4.31$	$8.67^a \pm 2.03$	$82.82^a \pm 18.70$	$82.82^a \pm 18.70$	$147.28^a \pm 18.55$	$34.78^{ab} \pm 2.55$
T4	$8.12^a \pm 0.544$	$5.78^a \pm 0.19$	$20.63^a \pm 3.52$	$8.33^a \pm 1.00$	$76.07^a \pm 13.72$	$76.07^a \pm 13.72$	$141.38^a \pm 14.44$	$37.33^{ab} \pm 2.65$
T5	$8.41^a \pm 1.01$	$5.78^a \pm 0.19$	$20.70^a \pm 0.87$	$8.89^a \pm 0.19$	$77.28^a \pm 2.69$	$77.28^a \pm 2.69$	$151.52^a \pm 15.93$	$33.44^{ab} \pm 2.01$
T6	$8.50^a \pm 1.29$	$5.67^a \pm 0.33$	$23.80^a \pm 7.98$	$9.33^a \pm 1.20$	$81.34^a \pm 15.91$	$81.34^a \pm 15.91$	$157.15^a \pm 6.85$	$35.67^{ab} \pm 5.04$
T7	$8.83^a \pm 1.87$	$5.67^a \pm 0.33$	$23.35^a \pm 1.43$	$9.22^a \pm 0.69$	$90.64^a \pm 3.56$	$90.64^a \pm 3.56$	$163.68^a \pm 8.26$	$39.22^a \pm 3.24$
T8	$8.95^a \pm 1.20$	$5.67^a \pm 0.00$	$25.52^a \pm 1.35$	$9.22^a \pm 0.84$	$86.76^a \pm 5.54$	$86.76^a \pm 5.54$	$156.44^a \pm 8.42$	$38.44^a \pm 4.11$
T9	$8.58^a \pm 1.67$	$5.67^a \pm 0.58$	$25.16^a \pm 5.64$	$9.22^a \pm 1.26$	$88.28^a \pm 13.28$	$88.28^a \pm 13.28$	$166.54^a \pm 5.85$	$40.67^a \pm 5.81$

SD - standard deviation; LSD - least significant difference at 5% level.

ultimately leading to enhanced crop production. The research findings have illuminated the profound influence of the number of leaves on mustard plants across various growth stages. Variations in leaf count at 30, 60, 90 and 120 DAS are detailed in Table 2. The number of leaves directly contributes to the crop's yield potential, economic viability and the extent of intercepted light. To discern the impact of all nutrients, including boron, sulphur and the plant growth hormone cytokinin used in this experiment, compared to the control, meticulous comparisons were undertaken. At 30 DAS, no significant differences were observed in treatments compared to the control (T1). Notably, significant increases were evident in treatments T3 and T7, where either individual application of sulphur or the combined application of Sulphur and the growth hormone cytokinin were administered to the crop. Conversely, at 30 DAS, treatments T2, T6, T7, T8 and T9 exhibited slight decreases, with the percentage change amounting to 1.96% compared to the control (T1). Upon reaching the 60 DAS stage, an increase in the number of leaves became more pronounced in treatments T6, T2, T7, T8 and T9, registering percentage increments of 3.57%, 2.40%, 2.40%, 2.40% and 2.40%, respectively. In this context, treatments T2, T7, T8 and T9 displayed no significant differences. A marked increase was observed at 60, 90 and 120 DAS, with percentage changes of 3.57%, 26.62% and 18.69%, respectively, in the case of foliar application of boron in combination with cytokinin (boron at 0.5% + cytokinin at 35 mg dm^{-3}) when compared to the control (T1). At 90 DAS, the highest increase in leaf count was observed in Treatment T3, where a recommended dose of sulphur (0.15%) was applied to the crop. This was followed by T4 (Cytokinin at the recommended dose of 30 mg dm^{-3}), T2 and T5, with no significant differences between the latter 2. Subsequent treatments, T6, T9, T8 and T7, exhibited percentage increases of 27.11%, 26.62%, 26.36%, 21.53% and 19.47%, respectively, when compared to the control (T1). When the crop reached 120 DAS, a significant increase of 28.68% was observed in Treatment T9, where the combined application of sulphur and cytokinin at their recommended doses was employed. Following closely, Treatment T7 displayed a significant increase of 26.06%, wherein Sulphur (0.10%) and Cytokinin (35 mg dm^{-3}) were administered to the crop. These findings underscore the pivotal role of nutrient treatments, especially sulphur and cytokinin, in influencing the number of leaves in *B. juncea*. The augmentation of leaf count contributes significantly to the crop's growth and overall productivity, with direct implications for optimizing agricultural practices and enhancing yield potential (25-29). In Indian mustard farming, variations in leaf count between treatments at various growth stages (30, 60, 90 and 120 DAS) offer important information on the best times and methods for applying cytokinin and sulphur. A key determinant of photosynthetic ability and general plant health, leaf count has a direct impact on yield potential. Increased leaf counts in the early growth phases (30-60 DAS) imply that cytokinin and sulphur applied at the right times can optimise vegetative growth and improve nutrient absorption.

Stem girth

The circumference of the stem plays a crucial role in the growth and productivity of plants, as it provides a strong base for the stability of crops. As a medium for transporting water and nutrients to plants, soil facilitates this biological process. The xylem and phloem are essential components of the plant's vascular system, enabling the movement of water and nutrient substrates between different plant regions. The complex mechanism facilitates the transfer of water and nutrients from the soil to the upper areas of the plant while also aiding in the distribution of photosynthate from the leaves to different parts of the plant. Therefore, the stem's optimal diameter facilitates the plant's wide range of physiological and biochemical processes. In addition, a vital stem circumference enhances the plant's capacity to endure a wide range of environmental factors, thereby facilitating the establishment of a resilient crop population. To assess the impact of various treatments, measurements of stem girth were conducted at different time intervals throughout the stages of growth. The findings revealed a significant rise in the mean stem circumference, specifically by 16.12%, 27.45%, 14.56% and 27.60% at 30, 60, 90 and 120 DAS, respectively, in Treatment T3. The observed increase in growth can be attributed to the application of sulphur at its recommended dose through individual foliar application at specific intervals (15 DAS, 45 DAS, 75 DAS and 105 DAS) compared to the control group (T1). The increase in stem diameter corresponds to the plant's improved physiological functioning, ultimately leading to a rise in productivity. At 60 DAS, the stem girth increase exhibited the most prominent pattern in Treatment T3, with Treatment T8, T7, T6 and T9 closely following suit, showing no statistically significant differences. Within this particular context, it was observed that Treatment T2, T4 and T5 did not exhibit any statistically significant differences. The observed stem girth in the experimental treatments showed a substantial rise, as indicated by the respective percentage values of 27.45%, 26%, 21.27%, 19.56%, 19.56%, 17.77%, 15.90% and 15.90%, in comparison to the control group (T1). This finding highlights the positive influence of the implemented interventions on the growth and development of the stems. A supplementary analysis demonstrated a respective augmentation of 22.80%, 19.72% and 15.71% in Treatment T7 at 90 DAS, 120 DAS and the final stage of crop maturity, in comparison to the control treatment (T1). The observed increase was attained by employing a reduced dosage (0.10%) of sulphur in conjunction with an elevated dosage of cytokinin (35 mg dm^{-3}). The literature extensively documents the stimulatory effects of cytokines on the enlargement of cambium cells and the subsequent translocation of photosynthate from roots to shoots through the transpiration stream in the xylem. In contrast, during the crop's harvest phase, a minor decrease in stem circumference was noted due to plant desiccation upon reaching maturity. The collective influence of the treatments, specifically those involving cytokines, highlights their capacity to augment cambium cell function and nutrient transport, thereby leading to the observed enhancements in stem circumference. This phenomenon is consistent with existing scientific literature and provides strong evidence for the effectiveness of the applied treatments in enhancing crop growth and productivity (30-34). The administration of sulphur and cytokinin has been shown to increase stem girth, which can be explained by particular physiological processes that improve cellular growth and structural integrity. Essential amino acids like cysteine and methionine, which are necessary for protein synthesis and cell wall construction, are synthesised in large part by sulphur. This makes the stems stronger and thicker, which enhances the plant's capacity to move nutrients and water effectively. Additionally, sulphur promotes the production of lignin, which fortifies the stem and increases structural robustness. In contrast, cytokinin stimulates cambial cell division and differentiation, which increases the growth of vascular tissue. Better resource allocation and movement throughout the plant are made possible by the increased xylem and phloem capacity.

Leaf area index (LAI)

The Leaf Area Index (LAI) is a metric that quantifies the proportion of a crop's leaf area relative to the ground area during a specific period. The attainment of an optimal LAI value is associated with achieving the highest possible ground coverage, ensuring that the crop canopy receives an optimal level of solar radiation exposure. The LAI plays a crucial role in determining the amount of leaf surface area that is accessible for effective capture of solar radiation, which is a fundamental aspect of the photosynthesis process. Various treatments were applied during this mustard crop experiment at distinct stages of crop development. The findings reveal significant differences in the LAI when compared to the control group (T1) at 30, 60, 90 and 120 DAS. Percentage increases were calculated by comparing all treatments with the baseline measurement T0. These comparisons aimed to evaluate the effects of the applied nutrients, specifically boron, sulphur and the plant growth hormone cytokinin, used in the experiment compared to a control group. The experiment demonstrated a statistically significant increase of 43.14% in Treatment T9, which involved the simultaneous application of Sulphur and cytokines to the crop compared to the control group. The results are presented in Table 3. The data indicate a significant increase in LAI when the recommended doses of Sulphur and cytokines were applied together. Another noteworthy comparison can be observed in Treatment T8, which exhibited a 37.51% rise in the LAI, followed by Treatment T3, which demonstrated a 34.17% augmentation in comparison to its control (T1) at 30 DAS. The results were statistically insignificant at the 60-DAS stage, as indicated by a control value 0.94. Nevertheless, at 90 DAS, Treatment T3 exhibited a notable percentage increase of 38.38%, while Treatment T4 displayed a slightly lower increase of 36.80%. These outcomes were achieved by administering the recommended doses of cytokinin and sulphur to the crop. Treatment T6 demonstrated a significant increase of 34.95% in the LAI compared to its control group. The treatments at 90 DAS exhibited an ascending order of percentage increase as follows: T3 > T4 > T9 > T6 > T8 > T2 > T5 and T7, with increments of 38.38%, 36.80%, 36.42%, 34.95%, 33.37%, 31.82%, 28.40% and 27.95%, respectively, in comparison to the control treatment. At 120 DAS, Treatment T6 exhibited a statistically significant increase of 26.47% when boron (1.5%) and cytokinin (15 mg dm^{-3}) were applied to the crop, as compared to the control group. Another noteworthy comparison involves Treatment T9, which exhibited a significant 18.18% increase in the LAI. This increase can be attributed to the synergistic effect of applying both sulphur and cytokinin. The observed significant increase in LAI for Treatments T3, T6 and T9 can be attributed to an enhanced capacity of these plants to intercept light, which may lead to elevated rates of photosynthesis. The increased photosynthetic activity observed in these treatments played a significant role in promoting the growth of the crop plants, resulting in higher LAI values.

Plant growth hormones, such as cytokines, are crucial in coordinating diverse biochemical processes within plants, leading to improved agricultural output and efficiency. The increase in LAI values can be ascribed to the combined impacts of applying micronutrients and plant growth hormones, which exhibit synergistic effects - he treatments above enhanced nutrient availability and uptake by the crop plants while increasing light interception. The observed increase in vegetative growth can be attributed to the combined influence of these factors. Notably, the LAI exhibited a decreasing pattern during the early phases of crop growth. The observed increase in crop yield can be attributed to the progressive growth and development of the crop, potentially influenced by the synergistic effects of micronutrient supplementation and the application of plant growth hormones. These interventions likely facilitated improved nutrient accessibility and absorption by the plants. The result highlights these treatments' importance in maximising crop growth and productivity (34-37). By encouraging leaf expansion, chlorophyll synthesis and delayed senescence, the combined actions of boron, sulphur and cytokinin improve photosynthesis and the LAI as well as general physiological processes in *B. juncea*. Sulphur increases protein synthesis and

Table 3. Stem girth (cm) and leaf area index of mustard crop

Treatments	30 DAS		60 DAS		90 DAS		120 DAS	
	Stem girth	LAI	Stem girth	LAI	Stem girth	LAI	Stem girth	LAI
T1	$0.29^{c} \pm 0.05$	$0.18^{a} \pm 0.02$	$0.41^{b} \pm 0.05$	$0.68^{ab} \pm 0.06$	$0.98^{b} \pm 0.07$	$3.01^{b} \pm 0.66$	$1.31^{b} \pm 0.05$	$2.20^{a} \pm 0.61$
T2	$0.32^{abc} \pm 0.04$	$0.21^{a} \pm 0.15$	$0.50^{ab} \pm 0.03$	$0.86^{ab} \pm 0.38$	$1.19^{a} \pm 0.08$	$4.42^{ab} \pm 1.01$	$1.53^{ab} \pm 0.20$	$3.45^{a} \pm 1.56$
T3	$0.34^{ab} \pm 0.02$	$0.27^{a} \pm 0.14$	$0.57^{a} \pm 0.03$	$0.78^{ab} \pm 0.32$	$1.14^{a} \pm 0.05$	$4.89^{a} \pm 0.21$	$1.81^{a} \pm 0.19$	$3.04^{a} \pm 1.24$
T4	$0.30^{bc} \pm 0.00$	$0.22^{a} \pm 0.13$	$0.49^{ab} \pm 0.08$	$0.65^{b} \pm 0.24$	$1.23^{a} \pm 0.09$	$4.76^{a} \pm 1.21$	$1.61^{ab} \pm 0.25$	$2.98^{a} \pm 0.99$
T5	$0.32^{abc} \pm 0.02$	$0.23^{a} \pm 0.07$	$0.49^{ab} \pm 0.05$	$0.83^{ab} \pm 0.17$	$1.20^{a} \pm 0.06$	$4.21^{ab} \pm 0.85$	$1.68^{a} \pm 0.28$	$3.51^{a} \pm 0.14$
T6	$0.32^{abc} \pm 0.02$	0.21a ± 0.15	$0.51^{ab} \pm 0.02$	$1.13^{a} \pm 0.32$	$1.20^{a} \pm 0.03$	$4.63^{a} \pm 0.57$	$1.62^{ab} \pm 0.07$	$4.14^{a} \pm 0.38$
T7	$0.31^{abc} \pm 0.02$	$0.20^{a} \pm 0.03$	$0.52^{ab} \pm 0.08$	$0.75^{ab} \pm 0.23$	$1.27^{a} \pm 0.15$	$4.18^{ab} \pm 0.26$	$1.63^{ab} \pm 0.03$	$3.33^{a} \pm 0.74$
T8	$0.36^{a} \pm 0.02$	$0.28^{a} \pm 0.10$	$0.56^{a} \pm 0.07$	$0.76^{ab} \pm 0.14$	$1.18^{a} \pm 0.07$	$4.52^{ab} \pm 0.47$	$1.70^{a} \pm 0.19$	$3.43^{a} \pm 0.31$
T9	$0.36^{a} \pm 0.02$	$0.31^{a} \pm 0.12$	$0.51^{ab} \pm 0.08$	$0.83^{ab} \pm 0.14$	$1.21^{a} \pm 0.08$	$4.74^{ab} \pm 1.11$	$1.61^{ab} \pm 0.12$	$3.72^{a} \pm 0.36$

SD (±) – standard deviation; LSD – least significant difference at 5% level.

chlorophyll content, boron promotes nutrient transport and cell wall stability and cytokinin promotes stomatal activity, vascular development and cell division. When combined, these inputs maximise carbon assimilation, resource allocation and nutrient intake, promoting strong growth, resilience to stress and increased production. In order to optimise crop performance, this synergy emphasises the significance of balanced foliar treatments.

Net assimilation rate (NAR)

The mustard crop's net assimilation rate (NAR) was found to be significantly impacted by the performance of the harvest and the combined applications of secondary nutrients (S), micronutrient (B) and the growth hormone cytokinin, as indicated in Table 4. The NAR is a parameter strongly associated with the photosynthetic processes occurring in the leaf. It quantifies the rate at which the plant's overall dry weight increases with the leaf's area. The findings highlight the notable importance of NAR values throughout various phases of crop development. Significantly, there is a considerable disparity in NAR values observed among the crop subjected to 9 different treatments during the later phases of its growth cycle. The observed variation can be ascribed to the development of siliquae, leading to a distinct distribution of assimilates between vegetative and reproductive growth. During the crop's maturation and the subsequent formation of siliquae, a notable alteration in photosynthetic activity occurs, characterised by a reduction in leaf biomass and a corresponding augmentation in siliquae development. As a result, this study has observed variations in nitrogen use efficiency (NUE) values linked to different yield attributes. During the investigation, a persistent upward trend in NAR values is observed in the latter phases of crop growth. The observed rise can be attributed to an enhanced availability of nutrients to the crop, which is a direct outcome of the presence of boron, sulphur and cytokinin. These essential nutrients facilitate the process of cell elongation and contribute to the growth and development of shoots and roots, thereby increasing the Crop Growth Rate (CGR) and NAR. The experimental results demonstrated a significant increase of 30.31% in Treatment T6, which involved the application of a combination of Boron (1.5%) and cytokinin (15 mg dm^{-3}) to the crop when compared to the control group (T1). Boron plays a crucial role in facilitating the translocation of sugars and photosynthates, thereby enabling the efficient transport of vital nutrients within the plant. Another noteworthy comparison can be made with Treatment T7, in which the simultaneous application of sulphur and cytokinin (sulphur at 0.10% + cytokinin at 35 mg dm^{-3}) resulted in a significant increase of 29.80% in NAR compared to the control group. When Treatment T9, which involved the application of sulphur and cytokinin at their recommended doses, was compared to the control, it resulted in a 12.83% increase in NAR during 30-60 DAS of the crop. During the 60–90 DAS period, a notable rise was observed in Treatment T8. This treatment involved the simultaneous application of sulphur and cytokinin, specifically at a concentration of 0.20% sulphur and 15 mg dm^{-3} cytokinin. This application increased the NAR compared to the control treatment (T1). In addition, Treatment T2, which involved the application of boron at the recommended dosage, exhibited a significant 47.37% increase in net aboveground productivity compared to the control treatment (T1). The order of treatments in terms of percentage increase was as follows: T8, T2, T3, T5, T6, T9, T4, with respective increments of 54.72%, 47.37%, 37.64%, 36.67%, 36.00%, 27.55%, 21.24% and 11.38% compared to the control treatment (T1). During the 90–120 DAS period, Treatment T8 exhibited the highest increase in NAR, with a surge of 54.47%. This increase was observed when the crop was treated with a combination of sulphur at a concentration of 0.20% and cytokines at a dosage of 15 mg dm^{-3}, compared to the control treatment (T1). Furthermore, Treatment T7, which consisted of sulphur at a concentration of 0.10% combined with cytokinin at a concentration of 35 mg dm^{-3}, demonstrated a significant increase of 49.14% in NAR. This was followed by Treatment T5 and T9, which showed increases of 30.25% and 18.61% in NAR, respectively, compared to the control group. The efficacy of utilising a formulation consisting of boron and the plant growth hormone cytokinin to augment crop growth and productivity is a noteworthy observation. The increase significantly influences the augmentation of crop yield production in crop dry matter percentage, contributing to the overall enhancement of the NAR. The correlation above highlights the importance of these factors in attaining enhanced crop growth and productivity (38, 39). The dynamic distribution of assimilates between vegetative and reproductive growth in mustard is reflected in variations in NAR among treatments. While a balanced drop over the reproductive phase suggests a purposeful shift of resources towards pod and seed development, higher NAR during the early phases enhances biomass buildup by promoting vegetative growth. In order to maximise yield and oil content in mustard production, treatments that maintain optimal NAR through effective nutrition usage and hormone management

Table 4. Crop growth rate and net assimilation rate of mustard crop

Treatments	30-60 DAS		60-90 DAS		90-120 DAS	
	CGR	NAR	CGR	NAR	CGR	NAR
T1	$0.0001^{a} \pm 0.00007$	$0.01^{a} \pm 0.01$	$0.0006^{b} \pm 0.00022$	$0.08^{b} \pm 0.03$	$0.0028^{a} \pm 0.0024$	$0.36^{b} \pm 0.31$
T2	$0.0001^{a} \pm 0.00011$	$0.01^{a} \pm 0.01$	$0.0012^{ab} \pm 0.00016$	$0.15^{ab} \pm 0.02$	$0.0025^{a} \pm 0.0006$	$0.32^{b} \pm 0.09$
T3	$0.0001^{a} \pm 0.00004$	$0.01^{a} \pm 0.01$	$0.0010^{ab} \pm 0.00023$	$0.13^{ab} \pm 0.03$	$0.0039^{a} \pm 0.0015$	$0.50^{ab} \pm 0.20$
T4	$0.0001^{a} \pm 0.00007$	$0.01^{a} \pm 0.01$	$0.0007^{b} \pm 0.00016$	$0.09^{b} \pm 0.02$	$0.0034^{a} \pm 0.0009$	$0.43^{ab} \pm 0.13$
T5	$0.0001^{a} \pm 0.00002$	$0.02^{a} \pm 0.01$	$0.0010^{ab} \pm 0.00032$	$0.12^{ab} \pm 0.04$	$0.0040^{a} \pm 0.0025$	$0.51^{ab} \pm 0.33$
T6	$0.0002^{a} \pm 0.00004$	$0.02^{a} \pm 0.01$	$0.0009^{ab} \pm 0.00044$	$0.12^{ab} \pm 0.06$	$0.0033^{a} \pm 0.0019$	0.43ab ± 0.24
T7	$0.0002^{a} \pm 0.00007$	$0.02^{a} \pm 0.01$	$0.0008^{ab} \pm 0.00006$	$0.10^{ab} \pm 0.01$	$0.0055^{a} \pm 0.0015$	$0.71^{ab} \pm 0.20$
T8	$0.0001^{a} \pm 0.00002$	$0.01^{a} \pm 0.00$	$0.0013^{a} \pm 0.00038$	$0.17^{a} \pm 0.05$	$0.0061^{a} \pm 0.0018$	$0.79^{a} \pm 0.24$
T9	$0.0001^{a} \pm 0.00006$	$0.02^{a} \pm 0.01$	$0.0008^{ab} \pm 0.00049$	$0.11^{ab} \pm 0.06$	$0.0034^{a} \pm 0.0005$	$0.44^{ab} \pm 0.06$

SD (±) – standard deviation; LSD – least significant difference at 5% level.

guarantee a strong vegetative framework and successful reproductive outcomes.

Crop growth rate (CGR)

The current investigation aims to comprehensively understand the complex relationship between crop performance and the utilisation of different combinations of secondary nutrients, micronutrients and the growth hormone cytokinin. These factors substantially influence the Crop Growth Rate (CGR) at specific time points, namely 15, 45, 75 and 105 DAS, as presented in Table 4. The Crop Growth Rate (CGR) is a crucial metric for assessing agricultural productivity, as it provides insight into the rate at which dry matter is produced within a given crop. The research has indicated that achieving the optimal canopy growth rate (CGR) depends on having a LAI that is extensive enough to intercept 95% of solar radiation. Increased light interception stimulates canopy growth response (CGR), enhancing LAI. A reciprocal association exists between LAI and light interception, wherein a higher LAI leads to enhanced light interception. This, in turn, augments the canopy growth rate (CGR), ultimately leading to higher crop yields. Significantly, our present findings are on these well-established principles. The potential for mustard production is greatly influenced by the interaction between LAI and Crop Growth Rate (CGR); a larger LAI improves light uptake and photosynthesis, which raises CGR. Healthy leaf development and consistent CGR across growth stages are supported by balanced nutritional treatments, such as applications of boron, sulphur and cytokinin. In the end, this maximises production by guaranteeing effective biomass buildup and assimilate partitioning towards reproductive structures. Achieving high productivity in mustard crops requires optimising LAI and CGR through customised nutrition strategies. In the experiment, a significant increase of 30.1% was observed in Treatment T6, which involved applying a combination of Boron at a higher dose of 1.5% and cytokinin at a lower 15 mg dm⍰^{3} to the crop. This increase was compared to the control treatment (T1). Treatment T3 and T9 exhibited a noticeable augmentation in CGR due to the separate and combined application of sulphur and cytokinin. Furthermore, Treatment T7, which involved the concurrent administration of sulphur and cytokinin (sulphur at 0.10% + cytokinin at 35 mg dm^{-3}), demonstrated a significant 29.80% enhancement compared to the control group. In comparison, Treatment T9 exhibited a 12.83% augmentation in the NAR during the 30-60 DAS period when sulphur and cytokinin were administered at their recommended concentrations. At the 60-90 DAS (interval, Treatment T8 exhibited a noteworthy rise in CGR). This increase was observed when a combination of sulphur and cytokinin (sulphur at 0.20% + cytokinin at 15 mg dm^{-3}) was applied, significantly improving compared to the control treatment (T1). Moreover, Treatment T2, which involved the application of boron at the recommended dosage, exhibited a noteworthy increase of 47.37% compared to the control group. The order of treatments in terms of the percentage increase in treatments is as follows: T8 > T2 > T3 > T5 > T6 > T9 > T4. These treatments exhibit 54.72%, 47.37%, 37.64%, 36.67%, 36.00%, 27.55%, 21.24% and 11.38%, respectively, relative to the control treatment (T1). During the 90–120 DAS period, Treatment T8 exhibited the highest significant increase in crop growth rate (CGR), with a surge of 54.47%. This increase was observed when a higher dose of sulphur (0.20%) and a lower amount of cytokinin (15 mg dm^{-3}) were applied to the crop compared to the control treatment. Another notable comparison can be observed in Treatment T7, which involved using sulphur at a lower dose of 0.10% and cytokinin at a higher amount of 35 mg dm^{-3}. This treatment demonstrated a significant increase of 49.14%. Treatment T5 and T9 exhibited NAR increases of 30.25% and 18.61% respectively, compared to the control group. It is worth mentioning that treatments with higher LAI values exhibit higher CGR values. This can be attributed to the improved interception of light by leaves, which promotes greater photosynthesis and the accumulation of a more significant amount of photosynthates. The concept of CGR is a pivotal measure for evaluating the development of plants during various phases of their life cycle. Using micronutrients and plant growth regulators methodically accelerates plant growth, resulting in enhanced mustard crop yield. Therefore, the crop CGR assessment is a crucial metric for evaluating crops' progress at different growth stages. This highlights the significant importance of accurately administering micronutrients and plant growth hormones to achieve increased yields in quality and quantity (40, 41).

Specific leaf area (SLA)

Plant growth and development are characterised by notable fluctuations in physiological parameters at various stages throughout the crop's growth cycle. One parameter commonly used in plant physiology is Specific Leaf Area (SLA), which quantifies the ratio of a plant's leaf area to its leaf dry weight. This parameter is typically expressed in units of cm^2g^{-1}. Our experiment's results indicate no statistically significant differences in second language acquisition (SLA) observed at different time intervals, precisely at 30, 60, 90 and 120 DAS of the crop. However, the specific leaf area (SLA) values exhibited a decrease in the treated plots in comparison to the control (T1) at 30 and 60 DAS, as shown in Table 5. In contrast, Treatment T4 exhibited a noteworthy increase, demonstrating a statistically significant boost of 30.59% in SLA (Specific Leaf Area). The observed increase in crop growth was attained by applying cytokinin at the recommended dosage, resulting in significant variation compared to the control group (T1). The application of sulphur at its recommended dose resulted in Treatment T3 showing a substantial increase of 6.42% in specific leaf area (SLA) compared to the control group. In addition, Treatment T9, which involved the simultaneous administration of sulphur and cytokinin at their recommended concentrations to the mustard crop at 90 DAS, exhibited a statistically significant increase of 9.28% compared to the control group. In contrast, no statistically significant differences were observed at 120 DAS when comparing specific leaf area (SLA) to the control group. Notably, the influence of Specific Leaf Area (SLA) extends to canopy expansion and overall growth, affecting the total leaf area per plant. Consequently, this impacts the interception of light and the efficacy of light utilisation. Our research findings indicate that the relationship between carbon dioxide (CO_2) and temperature in specific leaf area (SLA) was statistically insignificant within the given context. The findings presented in

Table 5. Specific leaf area and specific leaf weight of mustard crop

Treatments	30 DAS		60 DAS		90 DAS		120 DAS	
	SLA	SLW	SLA	SLW	SLA	SLW	SLA	SLW
T1	204.84^{a} ± 109.72	0.006^{a} ± 0.003	202.07^{a} ± 126.78	0.006^{b} ± 0.004	144.56^{ab} ± 43.88	0.007^{ab} ± 0.002	24.01^{ab} ± 8.15	0.05^{a} ± 0.02
T2	106.83^{a} ± 34.56	0.010^{a} ± 0.003	239.69^{a} ± 81.34	0.005^{ab} ± 0.002	113.56^{b} ± 24.40	0.009^{ab} ± 0.002	29.95^{ab} ± 10.92	0.04^{a} ± 0.01
T3	134.30^{a} ± 71.95	0.010^{a} ± 0.008	190.23^{a} ± 60.22	0.006^{ab} ± 0.002	154.49^{ab} ± 47.80	0.007^{ab} ± 0.002	22.38^{ab} ± 11.98	0.06^{a} ± 0.05
T4	138.07^{a} ± 126.03	0.012^{a} ± 0.009	217.80^{a} ± 131.74	0.006^{ab} ± 0.003	208.29^{a} ± 90.68	0.005^{b} ± 0.002	24.33^{ab} ± 6.61	0.04^{a} ± 0.01
T5	154.56^{a} ± 71.77	0.008^{a} ± 0.004	161.41^{a} ± 27.76	0.006^{ab} ± 0.001	132.46^{ab} ± 50.98	0.009^{ab} ± 0.004	25.80^{ab} ± 10.17	0.04^{a} ± 0.02
T6	105.48^{a} ± 110.98	0.018^{a} ± 0.012	180.66^{a} ± 115.07	0.007^{ab} ± 0.003	140.68^{ab} ± 43.85	0.008^{ab} ± 0.002	33.79^{a} ± 12.03	0.03^{a} ± 0.01
T7	102.52^{a} ± 45.87	0.011^{a} ± 0.004	117.04^{a} ± 43.39	0.010^{a} ± 0.004	141.98^{ab} ± 27.05	0.007^{a} ± 0.001	17.34^{ab} ± 1.63	0.06^{a} ± 0.01
T8	109.52^{a} ± 41.19	0.010^{a} ± 0.004	136.15^{a} ± 18.63	0.007^{ab} ± 0.001	103.18^{a} ± 29.16	0.010^{ab} ± 0.003	15.63^{b} ± 3.50	0.07^{a} ± 0.02
T9	103.89^{a} ± 37.13	0.010^{a} ± 0.003	129.98^{a} ± 38.84	0.008^{ab} ± 0.003	159.36^{ab} ± 35.83	0.007^{ab} ± 0.002	27.65^{ab} ± 2.09	0.04^{a} ± 0.00

SD (±) - standard deviation; LSD - least significant difference at 5% level.

this study demonstrate a clear association between elevated temperatures and increased stomatal conductance in groundnuts. However, it is essential to note that contrasting results have been documented in previous research endeavours (6,42).

Specific leaf weight (SLW)

The metric known as Specific Leaf Weight (SLW) is utilised to quantify the weight of leaves about their respective leaf area, typically expressed in grammes per square centimetre (g cm^{-2}). A higher specific leaf weight (SLW) per unit leaf area indicates increased biomass and this characteristic frequently demonstrates a positive association with anticipated crop yield. In the conducted experiment, it was observed that Treatment T4 showed a significant elevation of 52.39% in SLW (Specific Leaf Weight) upon the application of cytokinin at its recommended dosage in comparison to the control group. In addition, it was observed that Treatment T6 exhibited the most significant augmentation, with a notable rise of 66.45% when a higher dosage of 1.5% boron was administered in conjunction with a lower dosage of 15 mg dm^{-3} cytokinin to the crop. Treatment T7 exhibited a notable 46.21% augmentation in specific leaf weight (SLW) when a lower dosage of 0.10% sulphur was concomitantly administered with a higher dosage of 35 mg dm^{-3} cytokinin, in

Table 6. Correlation matrix

Variables	Plant height 30 DAS	No. of leaves 30 DAS	LAI 30 DAS	NAR 30 DAS	CGR 30 DAS	Pl. ht. 60 DAS	No. of leaves 60 DAS	LAI 60 DAS	NAR 60 DAS	CGR 60 DAS	Pl. ht. 90 DAS	No. of leaves 90 DAS	LAI 90 DAS	NAR 90 DAS	CGR 90 DAS
	Correlation matrix (Pearson (n))														
Plant height30DAS	**1**														
No. of leaves30DAS	-0.037	**1**													
LAI 30 DAS	-0.012	-0.079	**1**												
NAR 30 DAS	-0.301	-0.271	-0.196	**1**											
CGR 30 DAS	-0.275	-0.310	-0.196	**0.995****	**1**										
Pl. ht. 60 DAS	0.364	**-0.703***	0.146	0.221	0.276	**1**									
No. of leaves 60 DAS	0.074	**-0.732***	0.043	**0.739***	**0.764***	**0.771***	**1**								
LAI 60 DAS	0.120	-0.222	-0.292	0.587	0.597	0.385	0.610	**1**							
NAR 60 DAS	0.177	-0.532	0.457	-0.083	-0.091	0.357	0.393	0.028	**1**						
CGR 60 DAS	0.177	-0.532	0.457	-0.083	-0.091	0.357	0.393	0.028	**1.000****	**1**					
Pl. ht. 90 DAS	-0.030	**-0.670***	0.521	0.260	0.287	0.317	0.486	-0.192	0.511	0.511	**1**				
No.of leaves 90	-0.220	-0.114	0.478	-0.284	-0.304	-0.430	-0.282	-0.254	0.375	0.375	0.439	**1**			
LAI 90 DAS	-0.250	-0.208	0.621	-0.245	-0.238	-0.241	-0.166	-0.288	0.419	0.419	0.600	**0.929****	**1**		
NAR 90 DAS	-0.105	-0.012	0.322	0.222	0.222	0.005	0.186	-0.374	0.394	0.394	0.510	-0.025	0.166	**1**	
CGR 90 DAS	-0.105	-0.012	0.322	0.222	0.222	0.005	0.186	-0.374	0.394	0.394	0.510	-0.025	0.166	**1.000****	**1**

Values in bold are different from 0 with a significance level of alpha=0.05 ,*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

comparison to the control treatment (T1). The observed trend in percentage increase among treatments at 30 DAS can be summarised as follows: T6 exhibited the highest growth, followed by T4, T7, T9, T3, T8, T2 and T5, with corresponding increments of 66.45%, 52.39%, 46.21%, 43.29%, 42.82%, 42.28%, 40.89% and 24.60% relative to the control treatment (T1). At the 60-DAS stage, Treatment T7 exhibited the most notable growth enhancement, with a significant increase of 54.69%. This treatment involved the combination of sulphur at a lower dose of 0.10% and cytokines at a higher dose of 35 mg dm^{-3}. Following closely was Treatment T9, which involved the recommended amounts of sulphur and cytokinin applied together. Both treatments demonstrated substantial growth improvements compared to the control treatment (T1). An additional notable augmentation was observed in Treatment T8, exhibiting a 41.95% enhancement, alongside Treatment T6, which demonstrated a 37.51% escalation compared to the control group. At the 90-DAS mark, Treatment T8 exhibited a statistically significant increase of 28.27%. This increase was observed when a combination of sulphur and cytokinin was applied. Moreover, using boron at the recommended dose to the crop resulted in a significant rise of 19.45% in Treatment T2 compared to the control treatment (T1). At 120 DAS, the treatment that exhibited the highest increase was Treatment T8, which recorded a 44.04% increase. This was followed by Treatment T3, which showed a 39.17% increase and Treatment T7, which displayed a 36.03% increase compared to the control treatment (T1). The findings above suggest that the treatments have a notable influence on SLW, which may be associated with the enhancement of crop biomass and the potential increase in yield (31-33).

Correlation matrix and principal component analysis

Correlation is a statistical metric used to evaluate the association and similarities between variables. They are studying the relationship between the number of days and various parameters, which aids in comprehending their respective variations. Correlation measures the degree of association between variables, with the correlation coefficient representing this measure. The correlation coefficient is a numerical value ranging from -1 to +1. A value of +1 signifies a complete positive linear association, whereas -1 signifies an entire negative linear association. In the present context, it is observed that all the parameters demonstrate substantial interrelationships across various stages of growth. The data exhibit a robust correlation among all parameters, suggesting variations in the duration of different growth stages, as shown in Table 6. The Principal Component Analysis (PCA) process entails the computation of the principal components and the subsequent transformation of the data's basis. A selective approach is adopted in certain instances where only the initial principal components are considered, while the remaining components are disregarded. The primary component, also known as the first principal component, can be conceptualised as the vector that optimises the variance of the data when projected onto it. PCA is a fundamental technique for accurate multivariate analysis based on eigenvectors. It exhibits a strong association with factor analysis. Factor analysis involves making assumptions about the underlying structure specific to a particular domain and finding eigenvectors of a slightly modified matrix. In contrast, PCA aims to establish a new orthogonal coordinate system that effectively captures the variance within a single dataset. The present study involved the implementation of a PCA to examine multiple parameters at distinct growth stages. The outcomes of this analysis were subsequently visualised through a Biplot diagram. The graph illustrates the impact of various treatments on specific parameters. For example, the measurements of plant height at 30 DAS, the count of leaves at 30 DAS, the Crop Growth Rate (CGR) and the Net Assimilation Rate (NAR) at both 30 and 60 DAS are subject to the influence of treatments T3 and T8. On the other hand, the plant height observed at 60 DAS is significantly affected by treatments T1 and T7. The number of leaves at 90 DAS, LAI at 60 DAS, NAR at 30 DAS and Crop Growth Rate (CGR) at 30 DAS are affected by treatments T5 and T6. The treatments T2, T4 and T9 significantly influence parameters such as the number of leaves at 60 DAS, LAI at 30 and 90 DAS and plant height at 90 DAS. Using graphical representations offers a distinct advantage in comprehensibility and accessibility compared to the presentation of raw numerical data. The red lines in the Biplot correspond to the active variables, whereas the blue dots represent the operational observations within the PCA (24, 43). Examining the relationship between parameters at various stages of growth facilitates our understanding of the interdependence and significance of variables and statements in terms of their variability. The growth and development of plants are ultimately contingent upon the time necessary for sufficient light interception. Hence, through proficient visualisation and interpretation of the data, users acquire an enhanced comprehension of the data's significance and the observed variations within the study (Fig. 1).

FTIR spectroscopy in combination with principal component analysis

FTIR spectroscopy was employed to analyse leaf samples from treatments T3, T6 and T9, as well as the control group T1, to assess the impact of each treatment, as shown in Fig. 2. FTIR spectroscopy involves the measurement of the infrared spectrum of a sample, facilitating the identification of functional groups within the sample. By comparing the spectra of different treatments with the control, the effects of each treatment can be elucidated. The results revealed notable differences between the treatments and the control. The choice of this specific treatment was driven solely by the observable morphological changes it induced in the plants post-application. These morphological changes were correlated with a substantial increase in plant productivity. Moreover, it is believed that this treatment aids in preventing disease and insect infestations, rendering it the most effective and cost-efficient means of achieving desired outcomes. Fig. 3 displays the observed spectral peak behaviour under various treatments. The results confirm that the treatments influence the spectral peak behaviour, with an increasing trend in the spectral peak as the treatment progresses. It can be concluded that the treatments significantly affect spectral peak behaviour. Furthermore, different types of functional groups were activated and influenced by the treatments, resulting in varying levels of metabolic activity within plant cells. These alterations can induce changes in the physical

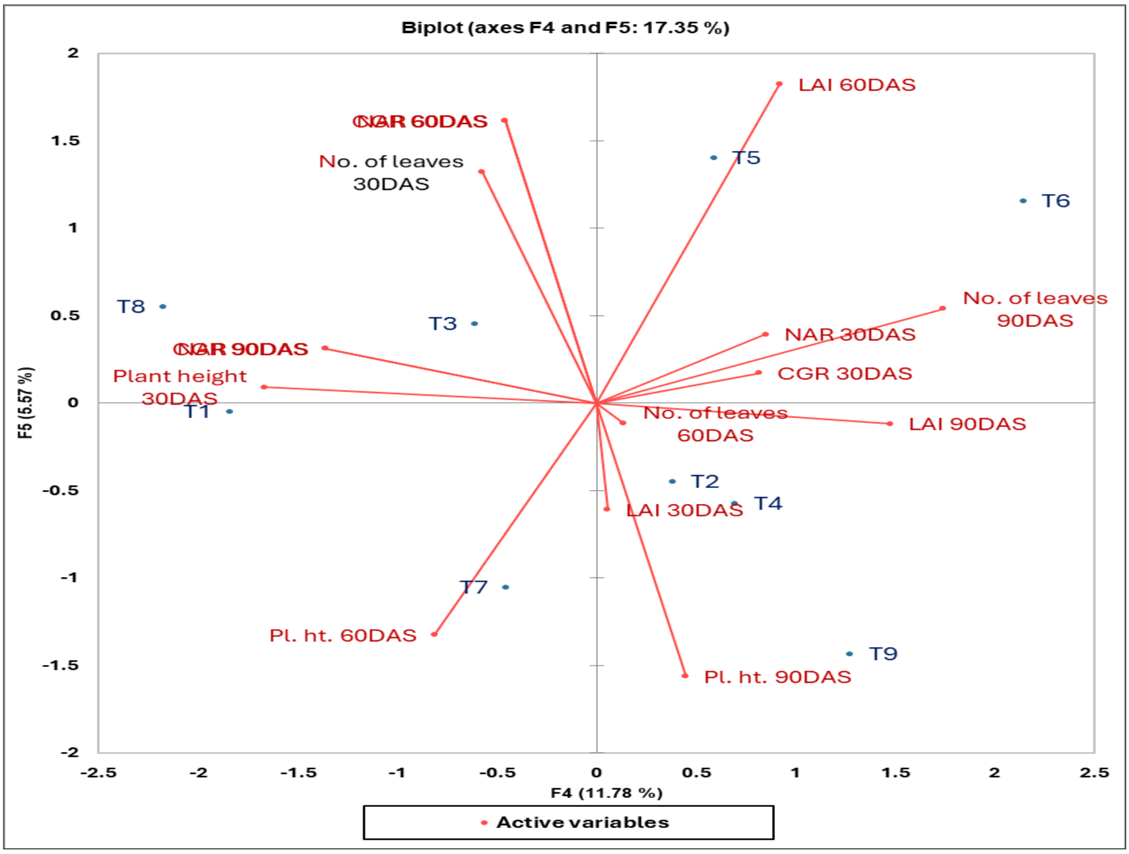


Fig. 1. Biplot diagram for PCA at different days' intervals.

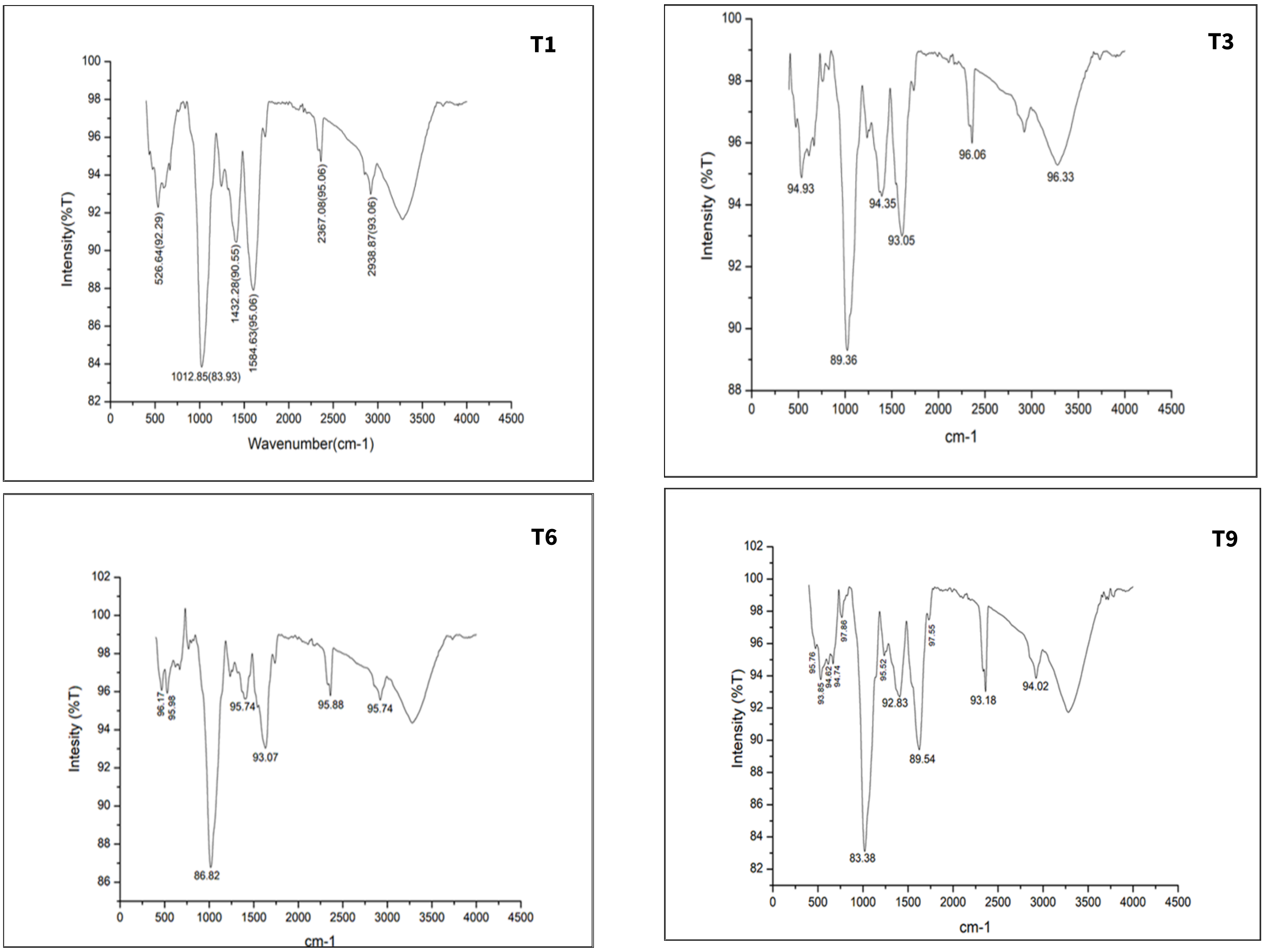
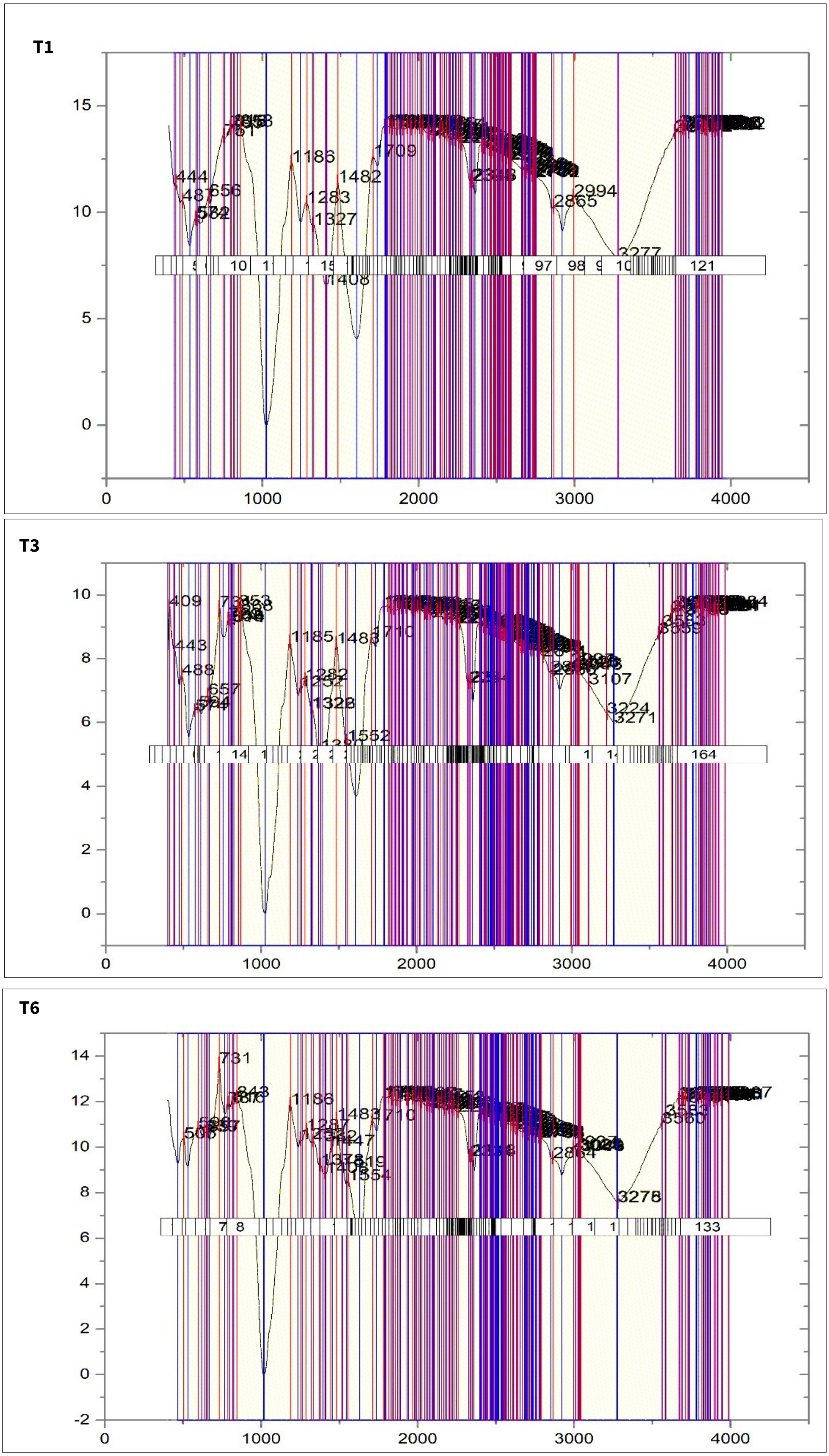


Fig. 2. FTIR spectral patterns of leaf samples treated with various treatments.


T1
444
656
1186
1283
1327
1482
1709
1408
2865
2994
3277
T3
409
443
488
657
1185
1483
1552
3107
3224
3271
T6
731
843
1186
1483
1554
3278

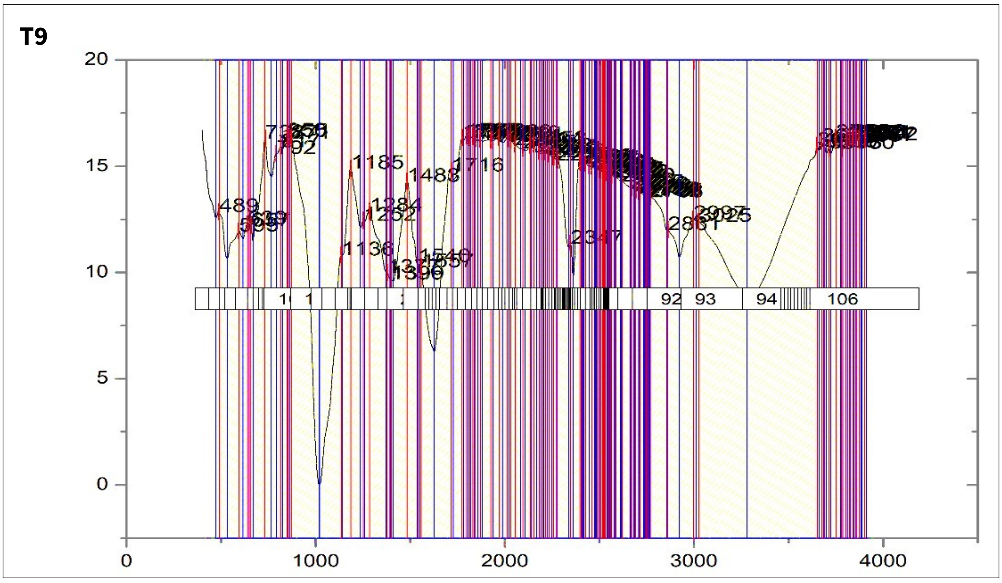


Fig. 3. Peaks obtained during FTIR analysis as a result of different treatments.

and chemical properties of the plants, ultimately impacting their growth and development, thereby affecting yield and produce quality. This indicates that T11 exhibited lower activity than other treatment periods, as evidenced by the lower number of peaks. The variation in peak numbers across different treatment periods can be attributed to differing activity levels within each period. In peak selection, a threshold value for % height was employed, with peaks identified by subtracting this threshold value from the constant value of Y. The peak values were subsequently used to calculate the area under the curve, which, in turn, determined the substance concentration within the sample. PCA was utilised to estimate the factorials and the results demonstrated that PCA effectively captured the underlying structure of the data for T1, T3, T6 and T9. The factorials explained significant data variance, affirming the method's success in data analysis. Fig. 4 presents various analyses, offering valuable data structure and relationship insights. Biplots graphically depict the distribution of PC1 (97.35%) and PC2 (1.87%) for treatments T1, T3, T6 and T9 across different quadrants (Q1, Q2, Q3 and Q4), aiding the identification of the most influential variables impacting the analysis outcomes. The biplot graph suggests a similarity in treatment effects, with treatments clustered in one quadrant, indicating common effects on the data. Eigenvalues were calculated to measure the variance explained by each variable, helping researchers identify the most influential variables affecting the analysis outcome. Fig. 4 illustrates a score plot and a scatter plot based on the analysis of FTIR spectra, revealing distinct outcomes after treatments.

These plots assist in discerning interactions between variables, such as wavelength and identifying those with the most significant impact on the outcome. FTIR spectroscopy reveals variations in spectrum peaks that correspond to morphological characteristics and productivity under various fertilizer treatments, reflecting biochemical changes in mustard plants. Protein, lipid and carbohydrate peaks show increased synthesis and metabolism, promoting energy allocation, oil biosynthesis and vegetative growth. These molecular discoveries demonstrate how metabolic changes brought about by nutrients result in better plant shape and increased yields.

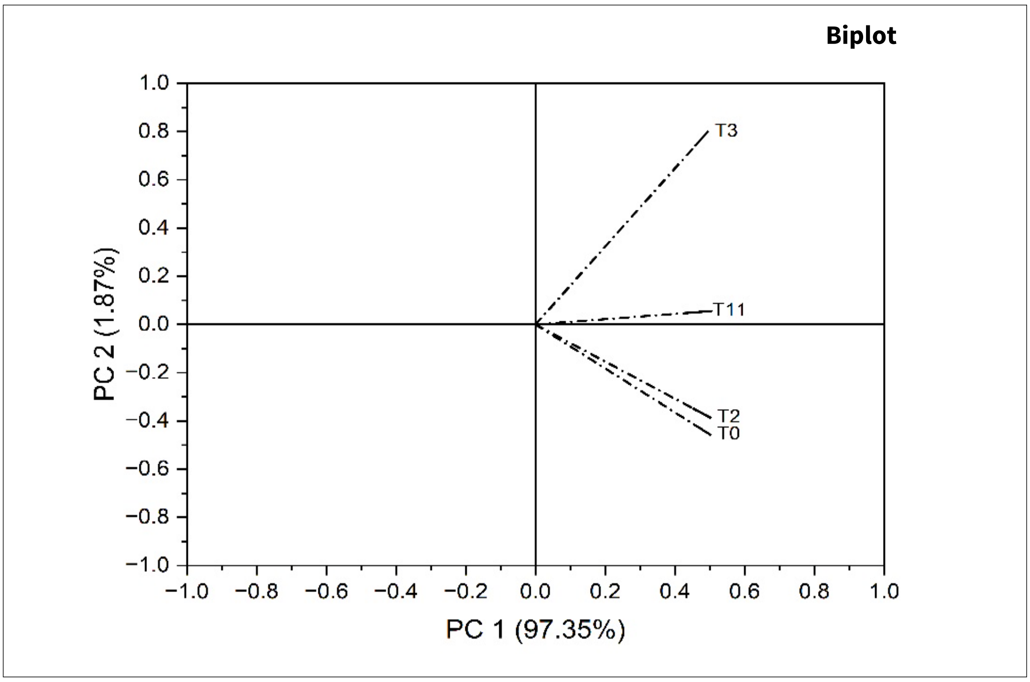
Overall, the FTIR spectral analysis provides valuable insights into how treatments influence the spectral peak behaviour and the subsequent effects on plant metabolism and growth, offering a data-driven approach to decision-making and interpretation (43, 44).

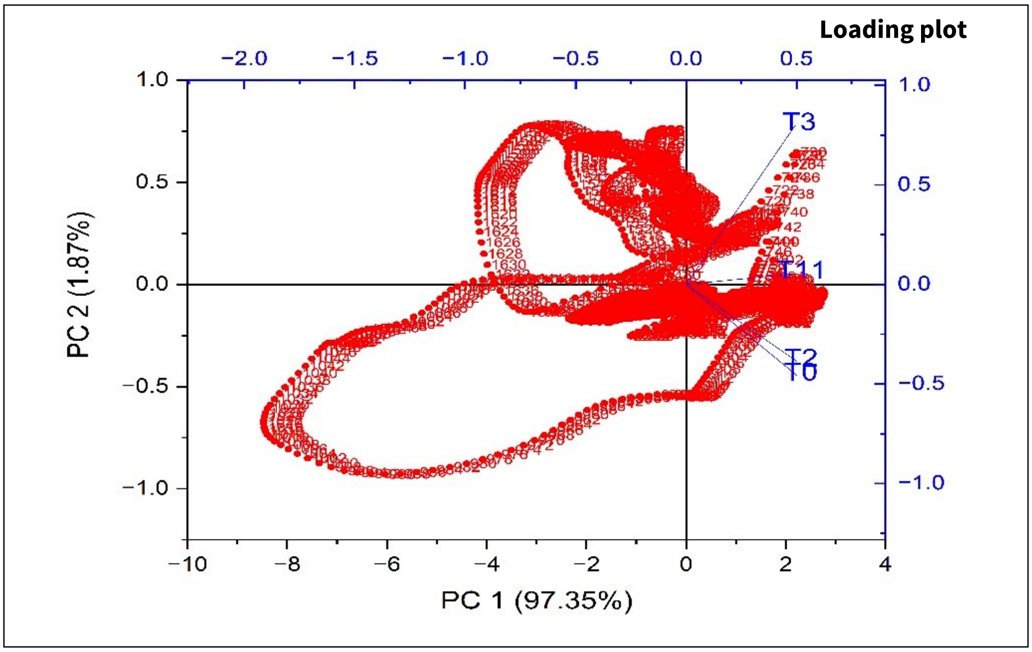
Limitations of the study

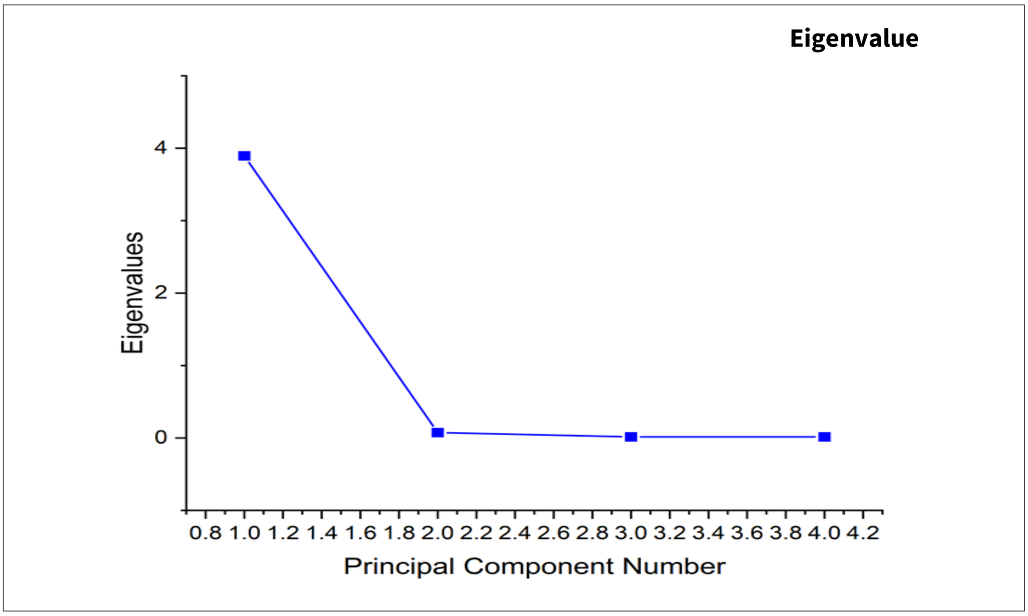
Limited access to advanced tools may have impacted measurement precision, while the focus on specific inputs, such as growth regulators and fertilizers, may underestimate the influence of other agronomic factors. Additionally, the small experimental scale might not fully replicate field-level complexities and the absence of a detailed cost-benefit analysis limits insights into the economic feasibility of the proposed practices.

Conclusion

The study has unequivocally demonstrated the substantial impact of combining secondary nutrients (S), micronutrient (B) and the plant growth hormone cytokinin on the morpho-physiological traits of crops, even when subjected to lower environmental pollution levels while adhering to recommended nitrogenous and phosphatic chemical fertilizer doses across all plots. The utilization of diverse fertilizers and growth hormones has led to remarkable enhancements in the leaf area index, Crop Growth Rate (CGR), Net Assimilation Rate (NAR) and biomass of mustard crop plants. This positive transformation in crop growth rate and net assimilation rate, which represents the gain in weight of a plant community per unit of land and time, reflects the efficient utilization of the applied inputs within specific environmental conditions. Furthermore, the results have shed light on the significant influence of various nutrient and plant growth hormone combinations on the crop's CGR and NAR, ultimately leading to heightened productivity. Notably, the study has pinpointed that the most favourable outcomes were achieved when secondary nutrients (S) and micronutrients (B) were combined with cytokinin. Compared to the control plots, these treated plots demonstrated remarkable increases in growth,


Biplot
PC 2 (1.87%)
PC 1 (97.35%)
T3
T11
T2
T0
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0


Loading plot
PC 2 (1.87%)
PC 1 (97.35%)
T3
T11
T2
T0
−2.0 −1.5 −1.0 −0.5 0.0 0.5
1.0 0.5 0.0 −0.5 −1.0
−10 −8 −6 −4 −2 0 2 4


Eigenvalue
Eigenvalues
Principal Component Number
0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0 4.2
4
2
0

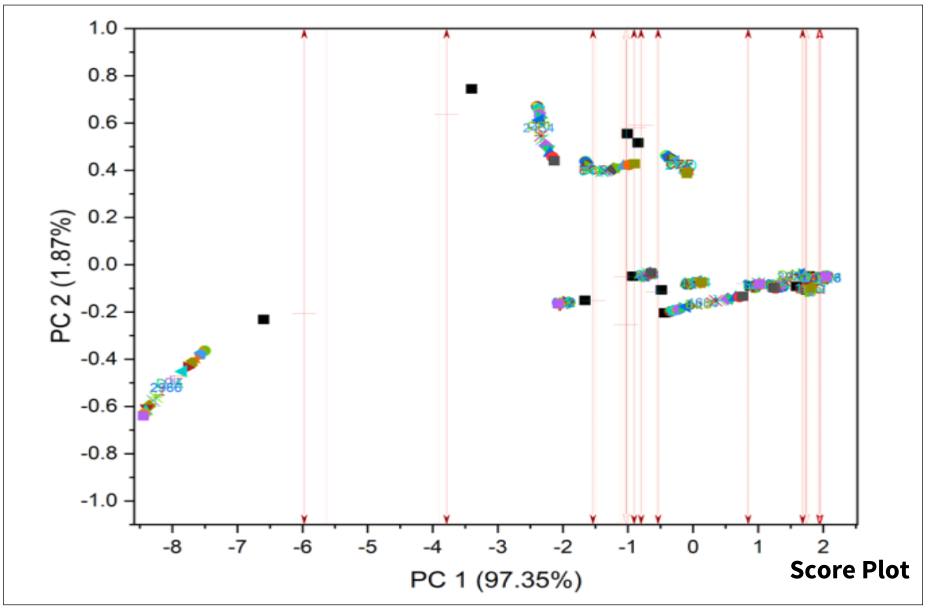


Fig. 4. PCA of FTIR spectra of mustard crops under different treatments.

physiological attributes, biochemical parameters, yield and crop quality. Consequently, it is abundantly clear that integrating plant growth hormones with secondary and micronutrients can substantially enhance the yield and quality of mustard crops. This approach should be considered an integral component of best practices for mustard cultivation, promising increased profitability for farmers. Looking ahead, the effective management of natural resources, an integrated approach to plant-water, nutrient and pest management and the expansion of rapeseed-mustard cultivation into new areas within diverse cropping systems will play pivotal roles in further elevating and stabilizing productivity and production levels. The long-term impacts of various nutrient combinations on soil health, microbial activity and general sustainability require more research. Developing environmentally friendly methods will require an understanding of how repeated applications affect the structure and nutrient balance of the soil. Furthermore, testing these therapies in various cropping systems and environmental circumstances can reveal information about their efficacy and adaptability, allowing for optimisation for various agricultural contexts. Long-term soil health and ecological resilience preservation, as well as consistent agricultural productivity, will be guaranteed by such a study.

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Authors' contributions

PK carried out the experimental design. MS and SRD carried out the data collection and data analysis. MS wrote the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors state that they have no interest in conflicts.

Ethical issues: None

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