Enhancing Rapeseed Yield and Quality via Growth Regulators and Microelement Optimization: Implications for Food Production and Security

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Abstract

During the Rabi season of 2022 - 23, we conducted a field experiment at Lovely Professional University’s Agronomy Farm in Phagwara to assess the impact of a combined application of growth regulators, namely indole acetic acid (IAA) and salicylic acid (SA), and micronutrients zinc (Zn) and iron (Fe), on the growth parameters of toria. Our results revealed that the application of IAA at a concentration of 0.1 g/l, in conjunction with SA at 0.15 g/l, along with Zn (0.05 g/l) and Fe (0.015 g/l), led to a substantial improvement in growth parameters. Remarkably, these outcomes were on par with those obtained from the application of IAA at 0.2 g/l and SA at 0.3 g/l, combined with ZnSO₄ (0.05 g/l) and FeSO₄ (0.015 g/l), surpassing the results of individually applied IAA and SA. Conversely, the control treatment exhibited the least favorable growth parameters. Overall, the adoption of such practices not only enhances rapeseed productivity but also contributes to sustainable food production systems, bolstering food security efforts on a global scale.

Keywords
Indole acetic acid, Salicylic acid, Zinc, Iron, Plant height, Primary branches, Number of leaves, Leaf area index, Chlorophyll content (SPAD units)

Introduction

Rapeseed and mustard are the third most vital edible oilseed crops in India, following groundnut and soybean. India boasts a substantial expanse of land designated for oilseed cultivation, encompassing roughly 12 - 15% of the total global land [1, 2]. Despite this vast acreage, India’s oilseed production constitutes only a modest 6 - 7% of the world’s total output, even as it strives to provide sustenance for a massive population of 1.34 billion. To put this into perspective, during the 2020 - 21 period, the world collectively cultivated 36.12 million hectares (mha) of rapeseed mustard, yielding a staggering 72.29 million metric tons (mt). On average, each hectare yields 2000 kg of rapeseed mustard. Despite India’s expansive land dedicated to oilseed cultivation, it struggles to match the global production levels required to sustain its growing population. Globally, India ranks second in oilseed cultivation and fourth in oilseed production [3, 4]. Uttar Pradesh leads the country in oil-seed cultivation, covering approximately 0.69 mha. However, it secures the fourth position in production, contributing around 0.89 mt of oilseeds. Uttar Pradesh averages a yield of approximately 1290 kg per hectare (kg/ha) as of 2020. Rajasthan holds the title of the leading oilseed producer within India, boasting an impressive production of 3.5 mt of mustard. States like Haryana and Madhya Pradesh closely follow Rajasthan’s oilseed production. Projections suggest that India’s population will reach 1.42 billion by 2025 and is expected to
rise further to 1.48 billion by 2030. Concurrently, the demand for edible oil in the country is projected to grow at around 3.54% from 2011 to 2030. To provide context, India’s current per capita edible oil consumption is 16.38 kg per year, and this log is estimated to increase significantly to 23.1 kg per year by 2030. These projections consider population growth and improving living standards in India [5, 6]. As living standards improve, per capita edible oil consumption is expected to rise. Rapseed and mustard, contributing to about 8% of India’s edible oil production, offer a promising opportunity for the nation to achieve self-sufficiency in oilseed production. However, India’s crop productivity in this sector remains notably low, with an average yield of 1040 kg/ha. India’s average oilseed crop yield of 1040 kg/ha falls significantly short of the global average of 2000 kg/ha. In contrast, countries like Chile achieve a remarkable crop productivity of 3810 kg/ha, and the European Union records 3150 kg/ha in the cultivation of rapseed and mustard. Cultivating oilseed crops, particularly rapseed and mustard, on marginal lands with limited resources presents a substantial challenge in India. Farmers with limited resources often struggle to adopt advanced agricultural technologies, especially in effectively managing crop nutrients. This challenge hinders the realization of the total yield potential of oilseed crops like mustard, making cultivation less financially rewarding for these farmers [7-9]. Consequently, a significant gap persists between the demand for oilseeds and their actual production in India. In regions where rapseed and mustard are cultivated, the deterioration of soil fertility has emerged as a significant issue, resulting in subpar crop yields. Indian mustard, in particular, demands relatively high nutrient levels, and inadequate nutrient supply can lead to inefficient utilization. This situation highlights the urgency of implementing strategies to address nutrient management challenges and improve the productivity and profitability of mustard farming in India. Plant growth regulators are crucial in modifying crop development by influencing how plants respond to internal and external factors that regulate different growth stages. This impact stretches from the initial germination and vegetative growth stages to the reproductive phase, maturation, ageing (senescence), and even the post-harvest preservation of crops. Using chemical plant growth regulators has seen a notable rise in efforts to boost crop yields. Phytohormones, natural chemical messengers present in plants, play a crucial role. Even in minute quantities, they initiate signals that regulate numerous aspects of plant growth and their capacity to withstand various forms of stress. Applying external phytohormones during different stressful conditions can efficiently trigger a plant’s defense mechanisms in a coordinated manner, aiding the plant in effectively managing stress. IAA is a significant plant hormone categorized as an auxin [10-12]. It is pivotal in plant development, encompassing cell division, elongation, differentiation, root growth, apical dominance, and shoot elongation. The use of supplemental exogenous IAA has proven to be a valuable strategy for addressing various challenges arising from environmental and biological factors. This approach significantly enhances growth, germination, and overall crop yield, improving agricultural results. In addition to IAA, SA plays vital roles in plant physiology, encompassing plant growth, thermogenesis, flower induction, nutrient absorption, ethylene production, stomatal regulation, photosynthesis, and enzyme functions. SA is recognized for its defensive function in plants at suitable concentrations. However, the applications of exogenous SA are pretty diverse in safeguarding plants against various biotic and abiotic stress factors, such as salt, heavy metals, drought, and temperature [13, 14]. Therefore, this study aims to explore the impact of applying IAA, SA, Zn, and Fe on the growth of Brassica juncea. Strategic growth regulators and microelement optimization can boost rapseed yield and quality. This method boosts agricultural productivity and addresses food security and production. The world’s food supply relies on rapseed, a versatile crop that provides edible oil and protein-rich meals for humans and livestock. Optimizing crop yield and quality is crucial to feed a growing population and ensure food security in a world with many environmental and socioeconomic challenges. Farmers can mitigate ecological stressors like drought, salinity, and nutrient deficiencies, which reduce crop productivity. You can overcome these issues by using growth regulators and microelement optimization in rapseed cultivation. Auxins, cytokinins, and gibberellins regulate plant growth, development, and stress. These regulators strengthen rapseed plants against environmental stress. Microelements like boron, Zn, and manganese are cofactors in many enzymatic processes that help plants absorb nutrients, photosynthesis, and overall health. Maximizing growth regulator use and microelement availability in rapseed cultivation can boost biomass accumulation, flower and pod formation, and seed yield. Rapseed oil’s content, fatty acid composition, and nutritional value increase, making it a valuable commodity in the food and feed industries. These innovative farming methods boost food production and farm sustainability. Farmers can build robust systems that meet current and future food needs by using resources efficiently and reducing environmental impact. Growth regulators and microelement optimization in rapseed cultivation are strategies and responsibilities we share to achieve food security goals and promote sustainable food production worldwide.

Materials and Method

The experiment occurred during the 2022 - 2023 rabi season at the Research Farm of Agronomy, Lovely Professional University, Phagwara, India. Tria variety TL-17, developed by Punjab Agricultural University (PAU), Ludhiana, served as the experimental material. The study employed a Randomized Block Design (RBD) with eleven treatments and three replications. Crop cultivation involved flatbed planting using a line sowing method of 30 × 10 cm spacing. All cultural practices adhered to the guidelines of PAU, Ludhiana. The experimental soil was loamy sand with a pH of 7.9. A recommended dose of fertilizer (40 kg N and 20 kg P₂O₅ per hectare) was applied during land preparation using urea and SSP. The foliar application of plant growth regulators and microelements followed the prescribed treatments, with applications 30 and 60 days after sowing. Observations were made on plant height, primary branches, number of leaves, and chlorophyll content (measured in SPAD units) with the help of standard protocol. Five random plants within each net plot were selected and tagged for these observations. The height of five plants was measured in
centimeters from their bases to the fully opened youngest leaf, and the average height of the plants at harvest was calculated. The total number of fully opened green leaves produced by five plants was counted, and their average was determined as the number of leaves per plant. The chlorophyll content of five tagged plants was meticulously recorded from the third fully opened leaf using the SPAD meter (Model-Minolta-SPAD 502), and the average value was calculated and expressed in SPAD units. Additionally, the primary branches of five randomly tagged plants per plot were recorded, the mean value was computed, and the number of primary branches per plant was expressed accordingly.

**Results and Discussion**

**Plant height (cm)**

Taller plants were consistently observed among the treatments, with T₄ (comprising IAA at 0.1 g/l, SA at 0.15 g/l, ZnSO₄ at 0.05 g/l, and FeSO₄ at 0.015 g/l) exhibiting the tallest average height of 171.91 cm. This was followed closely by T₆ (comprising IAA at 0.2 g/l, SA at 0.3 g/l, ZnSO₄ at 0.05 g/l, and FeSO₄ at 0.015 g/l) and T₉ (comprising IAA at 0.1 g/l, SA at 0.075 g/l, ZnSO₄ at 0.05 g/l, and FeSO₄ at 0.015 g/l), both of which also demonstrated enhanced plant height when compared to the plants treated with individual applications of IAA and SA. In contrast, the control treatment resulted in shorter plants, with an average height of 160.48 cm. This variation in plant height among treatments underscores the significance of the combined application of growth regulators and micronutrients, particularly the synergistic effects of IAA, SA, ZnSO₄, and FeSO₄, in promoting plant growth compared to the use of individual growth regulators alone [15, 16]. This might be due to enhanced cell division, cell differentiation, and shoot elongation of IAA, SA, and micronutrients (Table 1 and figure 1). The findings presented here demonstrate a significant favourable influence of specific treatment combinations on plant height. Treatment T₄, containing a combination of IAA, SA, ZnSO₄, and FeSO₄, resulted in the tallest plants with an average height of 171.91 cm. This is particularly noteworthy compared to the heights observed in plants treated with individual applications of IAA and SA. The most likely explanation for the enhanced growth in T₄ is a synergistic effect between the applied compounds. IAA is a well-known plant growth regulator promoting cell elongation and division. At low concentrations, SA can also positively influence growth processes. Adding ZnSO₄ and FeSO₄, essential micronutrients, might enhance these effects by providing necessary cofactors for enzymatic cell division and elongation processes. While T₄ exhibited the most significant impact, T₄ with different IAA and SA concentrations, also showed increased height compared to individual applications. This suggests a potential concentration-dependent response and the possibility of further optimizing the hormonal balance within the treatment regime for maximizing plant height. Future studies should investigate the underlying physiological mechanisms by which this treatment combination promotes growth. Gene expression analysis could reveal if the observed synergy is associated with the coordinated upregulation of genes involved in cell wall synthesis or cell cycle progression [17, 18]. This study highlights the potential for manipulating plant growth through strategic combinations of plant growth regulators and micronutrients. Understanding the specific interactions between these compounds and their influence on physiological processes will be crucial for developing optimized protocols.

![Figure 1: Growth and its alteration under different treatments.](image)

**Table 1: Growth parameters of toria as influenced by treatments.**

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Plant height (cm)</th>
<th>Number of primary branches</th>
<th>Number of leaves (SPAD units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₄ - Control</td>
<td>160.48</td>
<td>4.97</td>
<td>14.20</td>
</tr>
<tr>
<td>T₄ - SA (0.15 g/l)</td>
<td>164.15</td>
<td>5.75</td>
<td>15.47</td>
</tr>
<tr>
<td>T₄ - IAA (0.1 g/l)</td>
<td>168.82</td>
<td>6.10</td>
<td>15.43</td>
</tr>
<tr>
<td>T₄ - IAA (0.1 g/l) + SA (0.15 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>171.91</td>
<td>7.05</td>
<td>17.00</td>
</tr>
<tr>
<td>T₄ - IAA (0.15 g/l) + SA (0.15 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>168.71</td>
<td>6.30</td>
<td>16.37</td>
</tr>
<tr>
<td>T₄ - IAA (0.25 g/l) + SA (0.0225 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>170.16</td>
<td>6.07</td>
<td>16.13</td>
</tr>
<tr>
<td>T₄ - IAA (0.05 g/l) + SA (0.15 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>168.44</td>
<td>6.59</td>
<td>16.03</td>
</tr>
<tr>
<td>T₄ - IAA (0.1 g/l) + SA (0.075 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>170.08</td>
<td>6.62</td>
<td>16.30</td>
</tr>
<tr>
<td>T₄ - IAA (0.05 g/l) + SA (0.3 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>169.28</td>
<td>6.66</td>
<td>16.53</td>
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<td>T₄ - IAA (0.25 g/l) + SA (0.075 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>168.26</td>
<td>6.71</td>
<td>15.50</td>
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<td>T₄ - IAA (0.2 g/l) + SA (0.3 g/l) + ZnSO₄ (0.05 g/l) + FeSO₄ (0.015 g/l)</td>
<td>170.92</td>
<td>6.95</td>
<td>16.60</td>
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<td>S.E.M.</td>
<td>1.677</td>
<td>0.335</td>
<td>0.457</td>
</tr>
<tr>
<td>C.D</td>
<td>4.947</td>
<td>0.988</td>
<td>1.349</td>
</tr>
</tbody>
</table>

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for maximizing plant height in agricultural and horticultural applications. While the current study demonstrates a positive effect on plant height, it’s essential to investigate if this treatment combination is specific to the studied plant species or growth stage. Testing this approach on different plant types and developmental stages will broaden the applicability of these findings. Increasing concentrations beyond the optimal range observed in T₄ might lead to detrimental effects. Future studies should employ a broader range of concentrations to establish a dose-response curve and identify potential thresholds beyond which growth is inhibited. The current research likely experimented with controlled environmental conditions. Investigating how this treatment combination interacts with environmental factors like light intensity, temperature, and water availability will provide a more comprehensive understanding of its effectiveness in real-world scenarios. Considering the potential for increased yield through enhanced plant height, further research should evaluate the impact of this treatment on other economically important traits, such as biomass production, fruit or seed yield, and overall crop productivity. Economic analysis would also be valuable in assessing the cost-effectiveness of implementing this approach in agricultural settings. We can better understand the observed synergy and its potential for practical applications in plant growth manipulation by addressing these considerations and pursuing further research [19, 20]. This study presents compelling evidence for the effectiveness of a specific combination of plant growth regulators (IAA and SA) and micronutrients (ZnSO₄ and FeSO₄) in promoting plant height. The observed synergy suggests a complex interplay between hormonal regulation and nutrient availability, potentially influencing cellular processes like cell division and elongation. By delving deeper into these aspects, we can unlock the full potential of this approach for targeted plant growth manipulation and potentially enhance agricultural productivity.

**Number of primary branches**

A higher number of primary branches, precisely 7.05, were observed in toria plants treated with T₄ (comprising IAA at 0.1 g/l, SA at 0.15 g/l, ZnSO₄ at 0.05 g/l, and FeSO₄ at 0.015 g/l). Interestingly, this result was on par with the number of primary branches observed in toria plants treated with T₄ (comprising IAA at 0.2 g/l, SA at 0.3 g/l, ZnSO₄ at 0.05 g/l, and FeSO₄ at 0.015 g/l) and T₁₀ (comprising IAA at 0.2 g/l, SA at 0.075 g/l, ZnSO₄ at 0.05 g/l, and FeSO₄ at 0.015 g/l). In contrast, the control group exhibited the minimum number of primary branches. This notable difference in the number of primary branches among the treatments suggests that the combined application of IAA, SA, ZnSO₄, and FeSO₄ is more effective in promoting branching in toria plants compared to the use of individual growth regulators alone. The observed increase in branching is likely due to the influence of IAA and SA, which are known to stimulate branching in plants, enhancing the overall branching pattern in toria plants (Table 1, figure 1 and figure 2). The results regarding the number of main branches in toria plants subjected to different combinations offer fascinating observations and justify an additional investigation [21-23]. Treatment T₄, which involved the utilization of a mixture comprising IAA, SA, ZnSO₄, and FeSO₄, exhibited the highest mean count of primary branches (7.05), which was found to be similar to the values observed in treatments T₈ and T₁₀. These findings require a more thorough examination of the possible mechanisms involved. The auxin IAA plays a multifaceted role in the process of branching. When present in low concentrations, it can stimulate the growth of axillary buds (reference auxin and bud branching), resulting in an augmentation of primary branches. Nevertheless, IAA can impede branching at elevated concentrations by promoting apical dominance, as indicated by the reference to apical dominance and auxin. The response observed in T₄ may indicate an ideal concentration of indole-3-acetic acid (IAA) that can effectively stimulate bud outgrowth while avoiding suppression of the main stem. The understanding of the role of SA in branching is relatively limited, as certain studies propose that its effects on branching can vary depending on the concentration and plant species (reference SA and branching). The concurrent administration of SA and IAA in T₄, T₁₀, and T₁₁ may establish a hormonal equilibrium that facilitates bud growth without excessive stimulation. According to the reference on micronutrients and auxin metabolism, it is suggested that ZnSO₄ and FeSO₄ considered essential micronutrients, may indirectly impact branching by facilitating auxin biosynthesis and signaling pathways. The observed increase in primary branches may be attributed to the presence of these entities in the T₄, T₁₀, and T₁₁ combinations. In a manner akin to measuring plant height, examining whether this phenomenon is exclusive to toria plants is imperative [24-26]. Conducting experiments on different species could uncover wider applicability or responses that are specific to each species. Although T₄, T₁₀, and T₁₁ exhibited comparable outcomes, a more thorough comprehension necessitates the establishment of a dose-response curve for each constituent. This analysis would determine whether there are specific concentration ranges that will maximize branching and identify any potential thresholds beyond which branching may be inhibited. To
gain a comprehensive understanding of the molecular mechanisms involved, it is necessary to investigate the impact of this treatment combination on auxin metabolism, signaling pathways, and bud development. This can be achieved through the analysis of gene expression and targeted protein studies. Examining the interplay between light intensity, temperature, and water availability about the impact of the treatment on branching is crucial for comprehending its efficacy in practical contexts. The desirability of increased branching may vary. Subsequent research should assess the influence on additional agronomically significant characteristics, such as fruit or seed yield, to evaluate the overall advantage for crop production.

A more comprehensive comprehension of the impact of observed treatments on branching in toria plants can be achieved by examining these factors and pursuing additional research. This knowledge can be utilized to optimize methodologies for crop management and enhance the branching patterns, thereby leading to improved yield or the desired plant architecture. Nevertheless, the inclination at which these branches arise from the primary stem also substantially impacts the absorption of light, utilization of nutrients, and plant structure. The potential augmentation in primary branches could impact the growth and maturation of secondary and tertiary branches. A more comprehensive understanding of the plant’s architectural response can be obtained by evaluating the comprehensive branching hierarchy and its reaction to the treatments. Integrating IAA, SA, micronutrients, and environmental factors on branching in computational models holds significant potential as a valuable tool. These models can forecast the most effective treatment plans for achieving specific branching patterns in various plant species under different growth conditions. Examining the interaction between this treatment approach and other management practices, such as pruning or light manipulation techniques, can facilitate the development of more comprehensive strategies to optimize plant architecture and crop productivity. By integrating these supplementary factors into forthcoming investigations, we can enhance our comprehension of the impact of these interventions on branching in toria plants. Enhancing light interception and improving overall plant growth and yield can be achieved by implementing strategies that promote a more open canopy with optimal branch angles. Modifying the arrangement of branches can enhance air circulation within the canopy, potentially mitigating the susceptibility to fungal diseases [27, 28]. Comprehending the fundamental mechanisms could provide valuable insights for breeding programs to create cultivars with specific branching traits suitable for particular cropping systems. The results regarding the number of main branches in toria plants subjected to combinations of growth regulators and micronutrients emphasize the possibility of deliberately altering branching patterns. Through a comprehensive examination of the fundamental mechanisms and an investigation into the interplay with various factors, it is possible to uncover novel approaches for optimizing plant architecture and augmenting agricultural productivity using inventive management strategies.

**Number of leaves**

A significantly higher number of leaves per toria plant, totaling 17.00, were observed in the group treated with $T_{19}$, which consisted of IAA at 0.1 g/l, SA at 0.15 g/l, ZnSO$_4$ at 0.05 g/l, and FeSO$_4$ at 0.015 g/l. This result was remarkably consistent with the number of leaves recorded in toria plants treated with $T_{17}$ (comprising IAA at 0.2 g/l, SA at 0.3 g/l, ZnSO$_4$ at 0.05 g/l, and FeSO$_4$ at 0.015 g/l) and $T_{18}$ (comprising IAA at 0.05 g/l, SA at 0.3 g/l, ZnSO$_4$ at 0.05 g/l, and FeSO$_4$ at 0.015 g/l). These outcomes contrast the results of applying IAA and SA individually, which produced comparable results. The similarity in leaf numbers between these treatments may be attributed to the combined application of IAA and SA. These growth regulators are known to influence leaf senescence, a process that involves the ageing and eventual death of leaves. The combined application of these regulators likely delayed the onset of leaf senescence, resulting in the retention of a more significant number of leaves on the toria plants. This, in turn, led to a substantial increase in the number of leaves observed in these treatments, ultimately contributing to enhanced plant vitality and productivity (Table 1, figure 1 and figure 2). The observed increase in leaf count (17.00) in toria plants subjected to $T_{42}$ treatment (IAA 0.1 g/l, SA 0.15 g/l, ZnSO$_4$ 0.05 g/l, FeSO$_4$ 0.015 g/l) is an intriguing result that justifies further investigation at the molecular and physiological levels. The potential for targeted manipulation of leaf production through specific combinations of plant growth regulators and micronutrients is further emphasized by the consistency observed in $T_{17}$ (IAA 0.2 g/l, SA 0.3 g/l) and $T_{18}$ (IAA 0.05 g/l, SA 0.3 g/l). Auxin, specifically indole-3-acetic acid (IAA), assumes a crucial function in the process of leaf initiation at the shoot apical meristem (SAM) (auxin and leaf initiation). $T_{19}$ may offer an ideal concentration of IAA to stimulate the production of cytokines in the SAM, resulting in enhanced formation of leaf primordia and subsequent maturation into fully developed leaves. Although the exact function of SA in leaf initiation is not fully understood, certain studies indicate that it may be able to regulate auxin signaling pathways. The potential synergistic effect of SA at specific concentrations in $T_{19}$, $T_{20}$, and $T_{21}$, in conjunction with IAA, may enhance its impact on leaf initiation while maintaining apical dominance. The presence of ZnSO$_4$ and FeSO$_4$ is of utmost importance in the synthesis of chlorophyll and in numerous enzymatic processes that are vital for the development of leaves [29–31]. Their inclusion in these treatments may indirectly enhance leaf count by facilitating the physiological mechanisms essential for robust leaf development. Examining gene expression patterns about leaf initiation, specifically the KNOX and AUX/IAA families, and the applied treatments can yield significant insights. The enhanced leaf primordia formation hypothesis would be supported by the up regulation of genes related to cytokinin biosynthesis and auxin signaling within the SAM. Gaining insight into the interplay among crucial regulatory proteins within auxin signaling pathways, which SA may modulate, has the potential to provide a more comprehensive understanding of the molecular mechanisms underlying the regulation of leaf initiation by these treatments. Consistent with prior findings, it is imperative to conduct experiments on alternative plant species to ascertain whether the observed effect is exclusive to toria or applicable to various genotypes. To gain a more thorough understanding, it is necessary to create dose–response curves for each component (IAA, SA, micronutrients) to determine the
ideal concentration range for maximizing leaf number while minimizing the risk of adverse effects at higher doses [32-34]. Integrating IAA, SA, micronutrients, and environmental factors into computational models for leaf initiation holds significant potential as a valuable tool for predicting optimal treatment regimens to achieve desired leaf numbers across various cultivars and growing conditions. Gaining insight into the underlying mechanisms responsible for the augmentation of leaf count can inform breeding initiatives aimed at cultivars exhibiting enhanced photosynthetic capabilities, potentially enhancing agricultural productivity. The optimization of canopy structure for enhanced light interception and improved overall plant growth could be achieved by integrating this approach with other agronomic practices, such as light manipulation or nutrient management strategies. A more comprehensive comprehension of the impact of distinct amalgamations of growth regulators and micronutrients on leaf production in toria plants can be attained by utilizing sophisticated research methodologies and investigating prospective avenues. This knowledge can be utilized to create innovative approaches for manipulating leaf quantities in crop plants, substantially improving crop productivity and photosynthetic effectiveness.

**Chlorophyll index (SPAD unit)**

Chlorophyll content, measured in SPAD units. The data reveals that T4, consisting of IAA at 0.1 g/l, SA at 0.15 g/l, ZnSO4 at 0.05 g/l, and FeSO4 at 0.015 g/l, displayed a significantly higher chlorophyll content of 72.5 SPAD units. Following closely was T11, where a combination of IAA (0.2 g/l), SA (0.3 g/l), ZnSO4 (0.05 g/l), and FeSO4 (0.015 g/l) yielded a chlorophyll content of 71.40 SPAD units. In contrast, the control treatment exhibited the lowest chlorophyll content at 62.69 SPAD units. Chlorophyll content is a crucial indicator of a plant's photosynthetic capacity and overall health. The significant increase in chlorophyll content in treatments T1 and T4 can be attributed to the combined effects of the growth regulators and micronutrients. These substances likely enhanced the plant's photosynthetic processes, producing more excellent chlorophyll. The improved chlorophyll content in these treatments indicates healthier and more vigorous plants, essential for achieving higher crop yields and overall productivity (Table 1, figure 1 and figure 2). The potential impact of IAA and SA in T4 on chlorophyll production may be attributed to their involvement in regulating plant growth. Promoting cell division and expansion by IAA can potentially increase the number of chloroplasts and, as a result, a higher chlorophyll content. On the other hand, SA can elicit defense mechanisms that augment photosynthetic activity and chlorophyll production as a secondary outcome [35-39]. Adding ZnSO4 and FeSO4 to T4 can supply crucial micronutrients necessary for the metabolic processes of chlorophyll. Zn is an essential constituent of chlorophyll molecules, while Fe assumes a pivotal function in the enzymatic processes involved in chlorophyll biosynthesis. The coexistence of these elements may potentially enhance the process of chlorophyll synthesis through a synergistic effect. Notably, treatment T11, characterized by elevated concentrations of IAA and SA compared to T4, demonstrated a marginally reduced chlorophyll content. This observation implies that the impact of these growth regulators on chlorophyll biosynthesis may vary depending on their concentration. An optimal range for IAA and SA may exist for stimulating chlorophyll production, beyond which their influence may become inhibitory. To clarify the precise mechanisms at play, gene expression analysis could be conducted to examine how the applied compounds in T4 control the expression of genes involved in chlorophyll biosynthesis. Enzyme activity assays about crucial enzymes involved in chlorophyll biosynthesis may also provide valuable insights. Additional investigation involving a broader spectrum of IAA and SA concentrations and ZnSO4 and FeSO4 may contribute to establishing a more accurate concentration range that maximizes chlorophyll stimulation. Understanding how these treatments augment chlorophyll content is paramount [40-45]. There exists a direct correlation between chlorophyll concentration and photosynthetic capacity. Gas exchange measurements can be utilized to evaluate the influence of T4 on plant photosynthetic rates and overall growth. The data presented in this study demonstrate the potential of certain plant growth regulators and combinations of micronutrients to augment the content of chlorophyll. The response to the treatments may exhibit specificity concerning the plant species employed in the experimental study. Plant species demonstrate diverse levels of sensitivity towards growth regulators and micronutrients. Further research should investigate how these findings can be applied to various plant species [46-55]. Environmental variables such as light intensity, temperature, and nutrient availability significantly influence plant growth and chlorophyll biosynthesis. Future research should consider implementing controlled experimental conditions or the statistical consideration of environmental factors to isolate the specific effects of the applied treatments. The data indicates a momentary representation of chlorophyll concentration at a particular juncture. Further research is required to assess the enduring impact of these interventions on chlorophyll concentrations and the overall well-being of plants. Furthermore, it is imperative to conduct additional research on the potential adverse effects, such as phytotoxicity, that may arise from elevated concentrations of growth regulators. Considering the practicality of implementing these treatments in agricultural environments is necessary. Practical considerations should be considered when evaluating the cost of the applied compounds and the ease of implementation [53-59]. The preliminary results about the stimulatory impact of particular interventions on chlorophyll levels exhibit promising outcomes. Additional investigation into the constraints and examination of possible uses will be essential to convert these results into tangible remedies for enhancing plant well-being and agricultural output.

**Conclusion**

The results of this study underscore the significant impact of growth regulators and micronutrients on various growth parameters in rapeseed (Brassica juncea). These treatments had a notable positive effect on essential growth indicators, including plant height, the number of leaves per plant, leaf area index, the number of primary branches, and chlorophyll content measured in SPAD units. These improvements ultimately enhance the crop’s growth potential. This research emphasizes
the critical role of carefully selected growth regulators and microelements in the cultivation of rapeseed, providing valuable insights for farmers and researchers seeking to maximize the growth of this oilseed crop. Further research is encouraged to delve into the specific mechanisms responsible for these effects and their potential ecological implications, which could lead to the refinement of rapeseed cultivation practices.

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Conflict of Interest

None.

References


