Vol. 15, No. 2 (2026): 720 - 731
http://dx.doi.org/10.23960/jtepl.v15i2.720-731

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Enhancing Morphological and Physiological Sugarcane Growth through Natural Plant Growth Regulators Made of Banana Weevil

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Article History:

Received : 30 November 2025
Revised : 02 December 2025
Accepted : 19 February 2026

Keywords:

Auxin,
Cytokinin,
Natural Plant Growth Regulators,
Plant Morphological,
Plant Physiological,
Sugarcane Nurseries.

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ABSTRACT

Natural plant growth regulators (NPGR) have a significant impact on plant growth, particularly on plant morphological and physiological characteristics. The aim of this study was to examine the effects of immersion duration with banana weevil NPGR on the physiological and morphological traits of bud chips of sugarcane clone PS 862. The experiment was arranged in a randomized completed block design with a single factor of immersion duration. Five immersion treatments included T0 (control), T1 (1.5 h), T2 (3 h), T3 (4.5 h), and T4 (6 h), were performed with 5 samples and 3 blocks of replications, resulting in a total of 75 plant samples. Results revealed that immersion of 1.5 h was optimal for NPGR absorption in sugarcane seedlings with better plant growth. Immersion for 1.5 h resulted in the significantly highest stem diameter (6.03 mm), the longest root length (43.73 cm), and the highest stomatal density (127.04 stomata/mm²). These indicated the improved physiological performance of sugarcane seedlings under moderate NPGR exposure. Significant effect was not observed on the total amount of chlorophyll; most likely due to the small number of leaves generated during the seedling phase. The study concluded that using NPGR, especially with a 1.5 h immersion time, could improve the growth and morphological characteristics of BC variety PS 862.

1. INTRODUCTION

Plant growth regulators (PGR) have a significant impact on plant growth, particularly on morphological and physiological characteristics. This influence extends to various plants, including sugarcane nurseries. PGRs can be categorized into different types based on their primary functions, which include auxin, cytokinin, gibberellin, ethylene, and abscisic acid (Orozco-Mosqueda *et al.*, 2023). The use of gibberellins not only affects plant growth but also influences fruit development (Kumari *et al.*, 2022). Auxin functions as a regulator of morphological growth by promoting cell division and elongation through the signaling of auxin formation, profoundly impacting meristematic development in plants (Lin *et al.*, 2023). Commonly used auxins as PGRs include indole acetic acid 4 (IAA), indole butyric acid (IBA), and phenylacetic acid (PAA) (Chen *et al.*, 2023). Cytokinin encompass two main types, namely adenine and phenylurea (Kativat *et al.*, 2022). Examples of adenine-based cytokinin include zeatin, kinetin, and benzyl adenine (BA), while phenylurea-based cytokinin include compounds like thidiazuron (TDZ), which cannot be naturally synthesized by plants (Ranganatha *et al.*, 2023). Besides serving in the process of fruit ripening, ethylene also plays a role in accelerating epinasty and stimulating abscission in leaves (Liao *et al.*, 2023). Additionally, it can inhibit stem elongation and impede auxin transport both basipetally and laterally. Abscisic acid (ABA) is classified as an inhibitory compound, working in opposition to auxin and gibberellin (Ma *et al.*, 2023). ABA also serves to regulate and prevent metabolic processes from overwhelming plants (Hmmam *et al.*, 2023). While ABA is naturally produced by plants, synthetic ABA examples include daminozide and pyrabactin.

Exogenous PGRs can be either synthetic or natural in origin. This study focuses on a Natural Plant Growth Regulator (NPGR) derived from the banana weevil. Indonesia ranks as the third largest banana-producing country globally, following India and China (Waghmare*et al.*, 2021). During the banana harvest, the plants preserved for the next cycle are the saplings (suckers), while the banana weevils are typically left unused, making them available for use as exogenous NPGR (Prameswari *et al.*, 2022). NPGR extracted from banana weevils contains important plant growth hormones, including auxin, cytokinin, and gibberellins (Mangais *et al.*, 2022), which can be administered as exogenous PGRs for sugarcane seeds.

This NPGR also contains several vital amino acids, such as tryptophan, threonine, lysine, and leucine, as well as non-essential amino acids like serine, tyrosine, and glycine. Tryptophan serves as the raw material for producing auxins, while serine is a raw material for cytokinin production One method of administering NPGR is by sugarcane bud chips (BC) immersion. The application of auxin through immersion can expedite root formation at the BC node, thus enhancing the basipetal transport of auxin (Wu *et al.*, 2022). This condition triggers the production of cytokinin for bud formation (Cao *et al.*, 2023) at the BC node. The duration of NPGR immersion influences the extent of basipetal transport of growth-regulating compounds in plant tissues (Bruno *et al.*, 2021), which affects the initiation of root and shoot development in bud chips (BC). Longer immersion allows greater absorption of bioactive compounds such as auxins and cytokinins, enhancing early physiological responses, whereas excessive duration may cause hormonal imbalance and inhibit growth. Therefore, determining the appropriate immersion duration is essential to optimize BC growth. This study aimed to evaluate the effect of different NPGR immersion durations from banana weevil on the morphological and physiological characteristics of BC of sugarcane variety PS 862.

2. MATERIALS AND METHODS

2.1. Time and Place

The experimental was conducted from January to June 2022, spanning the transition period from the rainy to the dry season. The work took place at two specific sites in Sleman, Yogyakarta, Indonesia (7°44'3.63"S, 110°26'33.22"E) and in the LPP Polytechnic Integrated Experimental Field and the Wedomartani Practice Farm. The latter location is utilized as a specialized platform for agricultural research and practical training. Seasonal variations in environmental factors, such as temperature, rainfall, and humidity, were considered, as they could significantly influence plant growth and nutrient availability

2.2. Plant Material and Equipment

The materials used consisted of Sugarcane Bud Chip (BC) seeds of the PS 862 variety, water, planting media (sandy regosol soil, manure/compost, husk charcoal), kepok banana weevil, coconut water, brown sugar, and EM-4 solution. The study utilized sandy regosol soil as the primary medium, which is abundant at the site. Important equipment utilized in this study included polybags size of 30×30 cm, buckets, hoes, soil sieves, analytical scales, glassware, and digital camera, water hoses, plastic buckets, tape meters, rulers, 1000 ml measuring cups, and analytical scales.

2.3. Experimental Design

The experimental was arranged in a non-factorial randomized complete block design (RCBD) with a single factor of immersion duration. Five treatments, each with 5 samples and 3 blocks as replications were used, resulting in a total of 75 plant samples. The treatments included T0 (control), T1 (1.5 h), T2 (3 h), T3 (4.5 h), and T4 (6 h).

2.4. Experimental Procedure

The research implementation began with the preparation of the planting media, which involved mixing topsoil from Mediterranean soil with shrimp fertilizer and husk charcoal in a 1:1:1 ratio. This was followed by watering the planting media, planting BC PS 862 seeds, preparing NPGR from banana weevil (consisting of 1 kg kepok banana weevil, 2,500 ml coconut water, 100 grams of brown sugar, and 1 bottle cap of EM-4 microbes, followed by anaerobic fermentation for 21 days), BC immersion, BC planting, and BC maintenance on the growing media, which included activities such as watering and selection.

Observations were made starting in the second week after planting, with weekly observations for a total of 12 data collection points. The observation variables included plant height (cm), number of leaves, and stem diameter (mm). After the completion of the study, additional data were collected for variables such as the longest root length (cm), fresh weight (g), and dry weight (g). Physiological observations focused on variables such as the number of stomata, stomata density, and chlorophyll content.

2.5. Statistical Analysis

Data analysis was performed using the Statistical Product and Service Solutions (SPSS) software, version 16.0 with ANOVA test, for testing the comparison of treatment means. If the results showed a significant effect, further testing was conducted using Duncan's Multiple Range Test (DMRT) at α = 5% level to determine the difference in means between treatments.

3. RESULTS AND DISCUSSION

The analysis of the results indicated that NPGR application significantly affected all morphological variables of BC seedlings of sugarcane variety PS 862. As shown in Table 1, treatment T1 (1.5 h) produced significantly higher growth compared to the control (T0) and longer immersion durations (T2–T4) based on DMRT at 5%. Plant height under T1 reached 83.31 cm, exceeding T0 by 11.83 cm and T4 by 17.98 cm. Stem diameter was also highest in T1 (6.03 mm), which was 1.81 mm larger than T4, indicating better development of vascular tissues (xylem and phloem) that support efficient transport of water and nutrients. Root length followed a similar pattern, with T1 producing the longest roots (43.73 cm), significantly greater than the control (32.77 cm).

Table 1. Effect of immersion durations on the plant growth (height, number of leaves, stem diameter, and longest root length) of sugarcane seedling

Treatment	Plant height (cm)	Number of leaves (strand)	Stem diameter (mm)	Longest root length (cm)
T_0 (control)	71.48 b	5.90 a	5.33 b	32.77 a
T_1 (1.5 h)	83.31 c	6.30 b	6.03 c	43.73 b
T_2 (3 h)	74.93 b	6.03 ab	4.85 ab	37.83 a
T_3 (4.5 h)	72.82 b	6.03 ab	4.81 ab	34.77 a
T_4 (6 h)	65.33 a	5.76 a	4.22 a	33.63 a

Note: Means in the same column followed by the same letters show no significant difference based on DMRT at 5%.

Table 2. Effects of NPGR treatments on the physiological characteristics of sugarcane seedlings

Treatment	Stomatal density	Stomatal openings	Amount of chlorophyll
T_0 (control)	115.96b	3.13b	29.10a
T_1 (1,5 hours)	127.04c	3.02ab	28.37a
T_2 (3 hours)	99.33a	2.81a	28.25a
T_3 (4.5 hours)	116.74b	2.87a	30.66a
T_4 (6 hours)	102.00ab	3.02ab	28.45a

Note: Means in the same column followed by the same letters show no significant difference based on DMRT at 5%.

Physiological responses presented in Table 2 support these morphological trends. Stomatal density was highest in T1 (127.04), significantly higher than T2 (99.33) and T0 (115.96), suggesting improved gas exchange capacity under optimal NPGR exposure. In contrast, chlorophyll content did not differ significantly among treatments, indicating that immersion duration mainly influenced structural growth and gas exchange-related traits rather than chlorophyll synthesis at the early growth stage. Overall, these results indicate that moderate NPGR immersion duration (1.5 hours) optimizes growth responses, while prolonged exposure may reduce effectiveness due to possible hormonal imbalance or physiological stress.

3.1. Plant Height

Immersion for a duration of 1.5 hours appears to be the optimum period for proper NPGR absorption by BC, thereby enhancing the roles of auxins in meristem cell division and cytokinin in cell differentiation. The elongation of stems is a result of the processes involving cell division, elongation, and the enlargement of new cells within the apical meristem and stem segments, ultimately leading to an increase in plant height (Jiang *et al.*, 2020). The combined presence of auxins and cytokinin enhances both cell division and differentiation (Farman *et al.*, 2019), and these processes can be influenced by light conditions (Tian *et al.*, 2022). Auxins have the capacity to affect meristem cell division, consequently promoting root growth, with higher auxin levels leading to increased distribution to meristematic plant parts (Zhang *et al.*, 2022). At specific concentrations, auxins can encourage changes in the ratio of cytokinin formation within plants (Kurepa & Smalle, 2022). NPGR, being an exogenous hormone, is believed to stimulate cell elongation in the roots, as protein synthesis occurs to activate enzymes that participate in the synthesis of endogenous hormones. This condition leads to an increased plasticity in the cell wall, making it more flexible and allowing water to enter the cells through osmosis, resulting in cell expansion and elongation (Yadav *et al.*, 2022). Plant height, in addition to the influence of NPGR, is also thought to be influenced by light conditions. The screenhouse employed in this study has a shading level of 70%, which implies that only 30% of the incoming light intensity is available. At this reduced level, auxins may optimally collaborate with cytokinin to promote cell division and elongation (Li *et al.*, 2022). The optimal light intensity affect the expression of proteinase inhibitor (PIN) genes, which play a crucial role in auxin transport within plants (Aoki-Shioi *et al.*, 2023). Auxins contribute to the activation of the cell division cycle 2 (Cdc2) gene expression, while endogenous cytokinin activate cyclin-dependent kinase (CDKs) genes encoded by the Cdc2 gene. Therefore, auxins and cytokinin indirectly contribute to the increase in plant height.

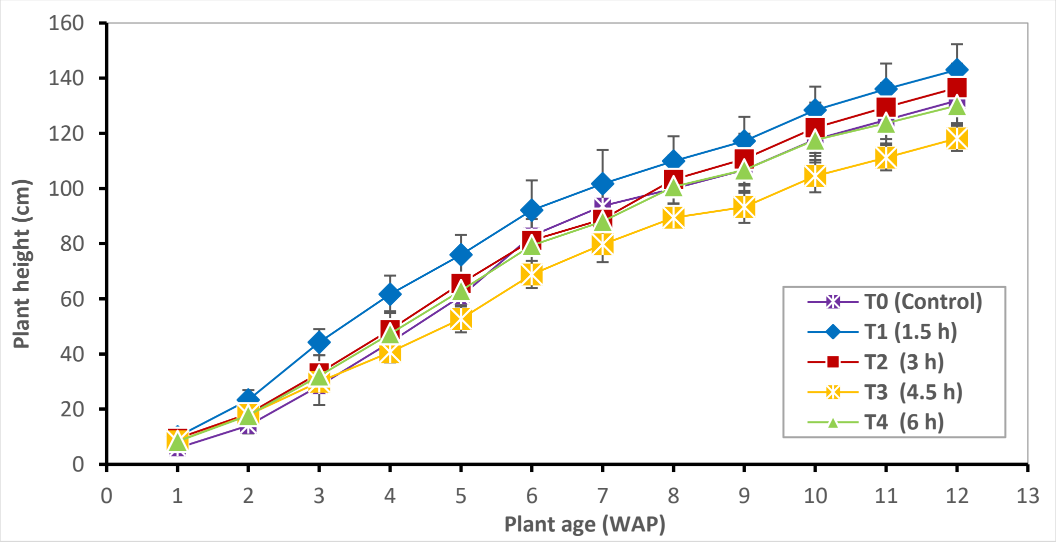

Figure 1. Effects of NPGR on the development of plant height of sugarcane seedlings during 12 WAP

3.2. Number of Leaves

The immersion of NPGR did not have a significant effect on the number of leaves, although the analysis revealed that an immersion duration of 1.5 h produced the highest value for the number of leaves, as indicated in Figure 2. One of the key roles of auxin in leaf growth is to facilitate the development of prospective leaf meristem tissue (Traas, 2019). The number of leaves in seedlings is influenced by the interplay of hormones (auxins and cytokinin) (Wu *et al.*, 2021) as well as the composition of the growing medium, which includes microorganisms and nutrients (Xiong *et al.*, 2022). Excessive levels of auxin may hinder the functioning of cytokinin, potentially impacting leaf formation and expansion (Sosnowski *et al.*, 2019). When the root system has fully developed, auxin transport increases, leading to a decrease in the expression of the isopentenyl transferase (IPT) gene, which acts as a catalyst for cytokinin (Li *et al.*, 2022). An increase in auxin concentration can lead to a dominance of cell division, resulting in a greater number of meristematic areas. While this can lead to increased root formation and plant height, it may simultaneously slow down leaf growth (Godoy *et al.*, 2021). Given the non-significant results attributed to the NPGR treatment, it is important to consider the consistent contribution of the growing medium, it is suspected that the microorganisms in the seedling medium thrive, thereby optimizing the ammonization process (Yin *et al.*, 2019). Ammonization is a biological process conducted by soil organisms where complex nitrogen (N) compounds in the growing medium are utilized by these organisms and subsequently excreted in the form of simpler N compounds, such as ammonium (Zhang *et al.*, 2023). The absorption of N in the growing medium (ammonium) prevents leaves from undergoing autolysis, thus ensuring that leaf growth and the increase in the number of leaves remain uninterrupted. Furthermore, the presence of organic potassium (K) in the growing medium, derived from manure, allows plants to absorb it in the form of K+ ions. K+ ions play a crucial role in regulating osmotic potential and cell enlargement within leaf vacuoles (Zahoor *et al.*, 2017). They also influence the entry of H+ ions into the thylakoid membrane (Chen *et al.*, 2016), optimizing the pH for the synthesis of adenosine triphosphate (ATP) as a source of energy in plant cells. The increased accumulation of K+ in vacuoles elevates their osmotic potential (Hajihashemi *et al.*, 2020), promoting cell enlargement, and consequently, enhancing leaf growth. These conditions are presumed to be present in the growing medium in this research study.

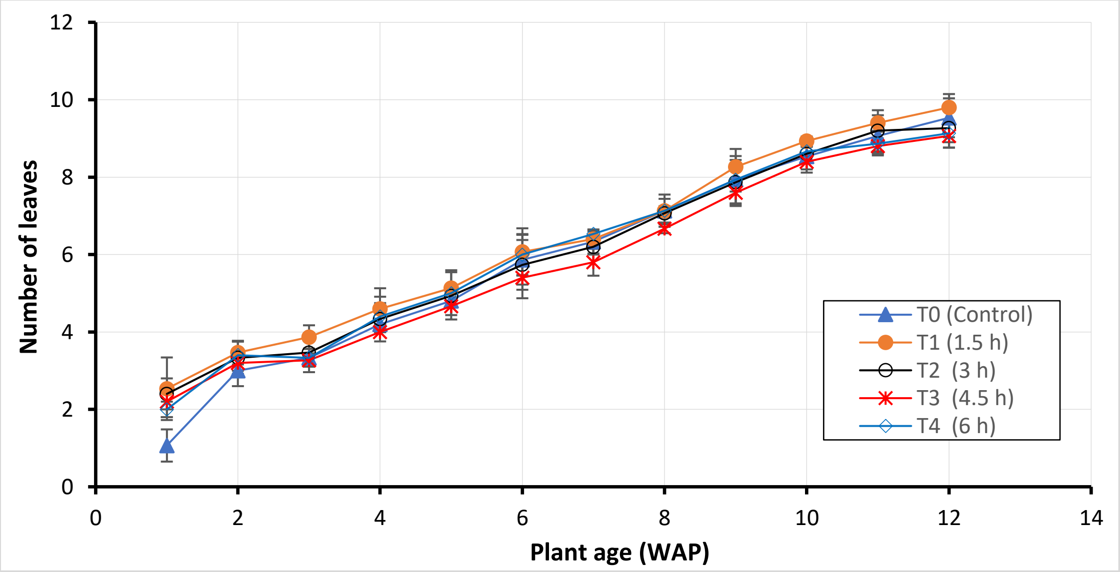

Figure 2. Effect of NPGR treatments on the development of number of leaves of sugarcane seedlings

3.3. Stem Diameter

Treatment T1 (1.5 h) represents the optimal duration for NPGR absorption by the Bud Chips (BC), enabling effective auxin entry into plant cells (Figure 3). This absorption process takes place across the entire surface of the stem, leading to an increase in turgor pressure within the cells, subsequently resulting in cell enlargement (Hoermayer *et al.*, 2020). This enhancement is reflected in the observation that growth in sugarcane stem diameter is closely linked to an increase in heigh (Hamza & Hadi, 2020). This connection can be attributed to the process of nutrient transport from the soil to the leaves, which occurs through the stem via xylem tissue (Luostarinen *et al.*, 2017). Endogenous auxins are synthesized in the plant's meristematic regions and subsequently transported basipetally to the lateral buds, initiating endogenous cytokinin synthesis (Yang *et al.*, 2022). The appropriate of auxin can stimulate the expression of the IPT gene, which acts as an enzyme catalyzing the formation of cytokinin, leading to lateral bud sprouting and cell differentiation (Li *et al.*, 2022). In cases where exogenous auxins in the BC are used more extensively to promote root initiation and increase plant height, the quantity of cytokinin in the lateral shoots can increase. Increasing cytokinin levels results in the differentiation of vascular transport in lateral shoots (Bloch *et al.*, 2019). The intricate interplay between auxin and cytokinin in plant growth and development underscores the importance of timing and balance in optimizing these processes.

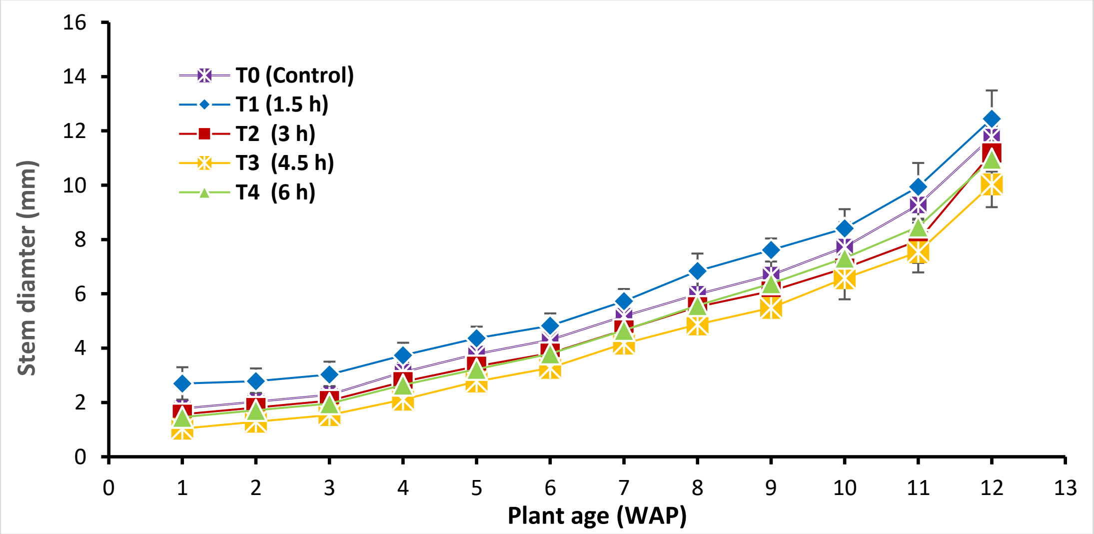

Figure 3. Effect of NPGR treatments on the development of stem diameter of sugarcane seedlings

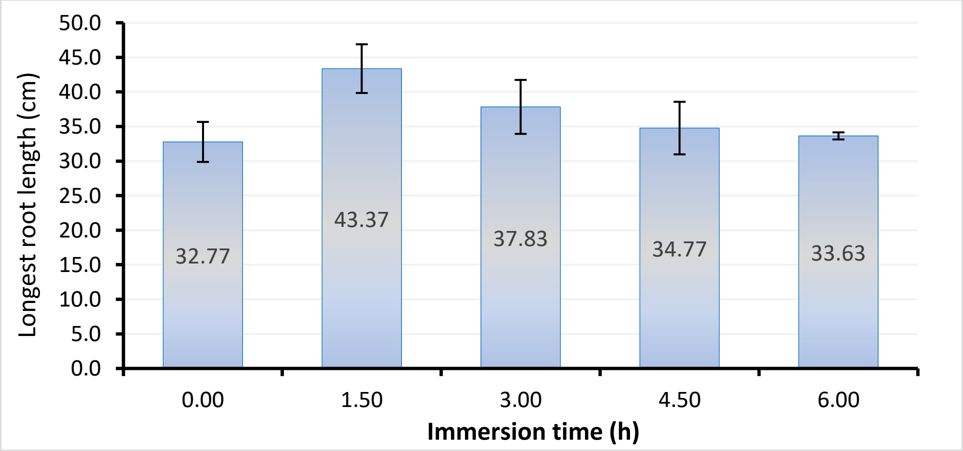

Figure 4. Effect of immersion time in NPGR on the longest root length of sugarcane seedlings

3.4. Longest Root Length

The T1 treatment, as depicted in Figure 4, appears to represent the optimal duration for NPGR absorption by the sugarcane bud chip (BC). Higher concentration in auxin compared to cytokinin leads to differentiation, particularly in the context of root growth. The influence of auxins manifests in the flexing of the cell wall, resulting in the elongation of plant cells due to the influx of water through osmosis (Barbez *et al.*, 2017). However, an excess of NPGR is suspected to disrupt enzymatic reactions within cells, potentially hindering cell elongation through a reduction in cellular mechanisms. This excess accumulation of hormones can pose a hindrance to overall plant growth as it may impede the functioning of other hormones, subsequently inhibiting growth. The application of NPGR induces root meristem division, facilitating continued growth and an increased rate of nutrient uptake (Mroue *et al.*, 2018), including essential elements like nitrogen (N), phosphorus (P), and potassium (K). This, in turn, contributes to heightened plant height and stem diameter (Egamberdieva *et al.*, 2022). The intricate balance of these growth-regulating hormones underscores the complexity of plant development and growth dynamics.

3.5. Number of Stomata

The optimal concentration of NPGR, as observed in the T1 treatment in Figure 5, underscores the significance of maintaining a well-balanced phytohormone profile to promote the growth and development of sugarcane seedlings. This balance is believed to stimulate the synthesis of endogenous cytokinin. Stomatal density is closely linked to the appropriate concentration of cytokinin (Górski *et al.*, 2021). An optimal cytokinin concentration is thought to promote the division of epidermal cells, potentially through the suspected expression of the D-type cyclin (CycD3) gene (Randall *et al.*, 2015). The CycD3 gene is instrumental in controlling the cell division cycle and contributes to stomatal development by regulating the mitotic cycle within cells (Weimer *et al.*, 2018). Stomatal density is also influenced by the expression of CDKA and CDKB genes, with CDKB specifically contributing to the development of stomata on leaves (Yang *et al.*, 2019). Conversely the lower stomatal density observed may be attributed to suboptimal cytokinin levels and potentially excessive transpiration due to insufficient water availability. In response to such conditions, plants may activate specific genes, such as TaNAC48 (for instance in Arabidopsis), leading to an increase in abscisic acid (ABA) levels (Chen *et al.*, 2021a). ABA plays a pivotal role in regulating transpiration by influencing the opening and closing of stomata, especially under conditions of limited water supply (Sussmilch *et al.*, 2019). These intricate interplays between hormones and genes underscore the complexity of plant physiological responses to environmental and hormonal cues.

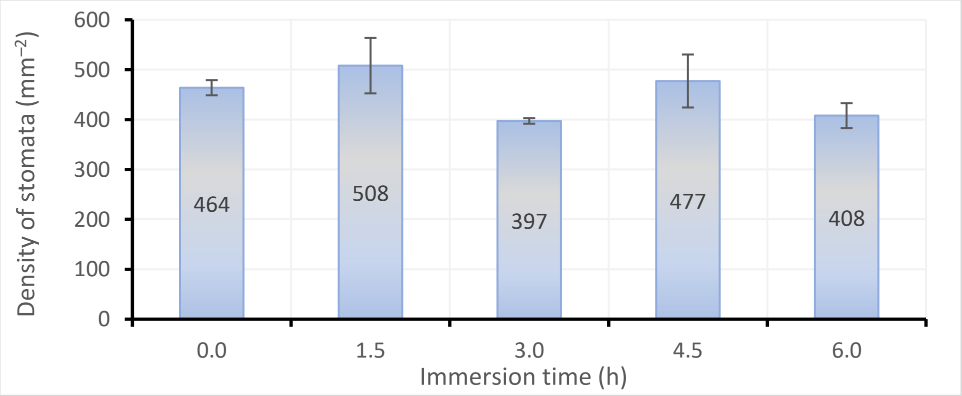

Figure 5. Test Results for the Effects of NPGR on the Stomatal Density of Sugarcane Seedlings

3.6. Stomatal Opening

In Figure 6, the effects of NPGR on the number of stomatal opening in sugarcane seedlings is depicted. As the primary phytohormones governing plant growth and development, cytokinin and auxin play significant roles in regulating stomatal opening. In this study, stomatal openings appeared to be relatively normal. Regarding stomata, there is a complex interplay between auxin, cytokinin, and ethylene in their effects on the inhibition of abscisic acid (ABA) signaling, thereby preventing stomatal closure (Gao *et al.*, 2022). Auxin has been found to effectively suppress stomatal closure, particularly under dark conditions. The application of NPGR (auxin) to the vegetative BC tissue is believed to induce ethylene biosynthesis (Chen *et al.*, 2021b). The presence of ethylene activity is likely to impede ABA signaling, thereby mitigating stomatal closure based on these findings, it is suggested that the effects of auxins and cytokinin on the inhibition of stomatal closure may be modulated through ethylene biosynthesis in epidermal leaf tissue. Other factors that could typically lead to stomatal closure, such as water deficiency, may not have been present in this study. As a result, the expression of the TaNAC gene, which typically increases ABA levels to regulate transpiration during stomatal closure, might not have occurred (Abd El-Moneim *et al.*, 2020); this gene often plays a critical role in responding to conditions such as salinity and drought stress (Llanes *et al.*, 2021).

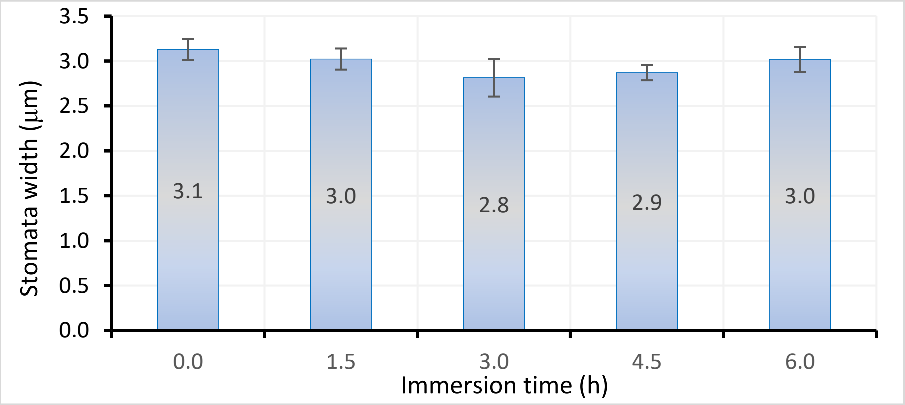

Figure 6. Effects of NPGR on the number of stomata opening in sugarcane seedlings

3.7. Amount of Chlorophyll

The analysis results (Figures 7 and 8) showed no significant effect on the total chlorophyll amount. This lack of effect can be attributed to the limited number of leaves formed during the seedling phase. The NPGR is also believed to induce DNA methylation, which leads to the remodeling and rearrangement of cells in differentiated leaf organs, ultimately affecting the amount of chlorophyll present. The production of phytohormones requires ATP energy and active ATPases, with most of the energy primarily directed toward vegetative growth. The induction of auxin through NPGR can stimulate cell division by affecting the cell wall. This, in turn, activates the proton pump located on the

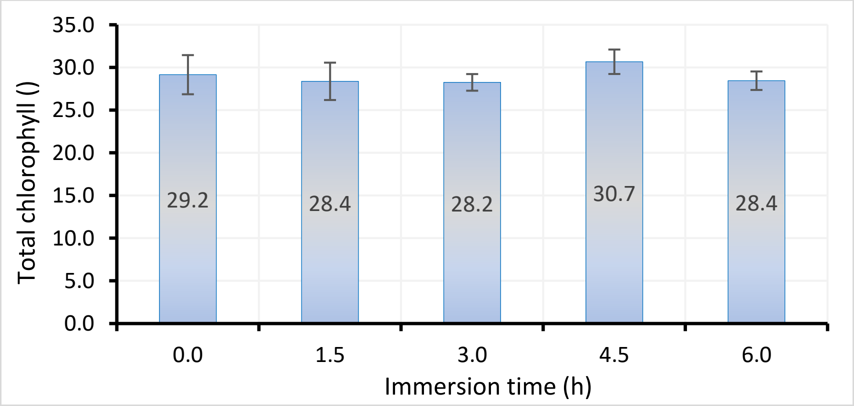

Figure 7. Effects of NPGR treatment on the amount of total chlorophyll in sugarcane seedlings

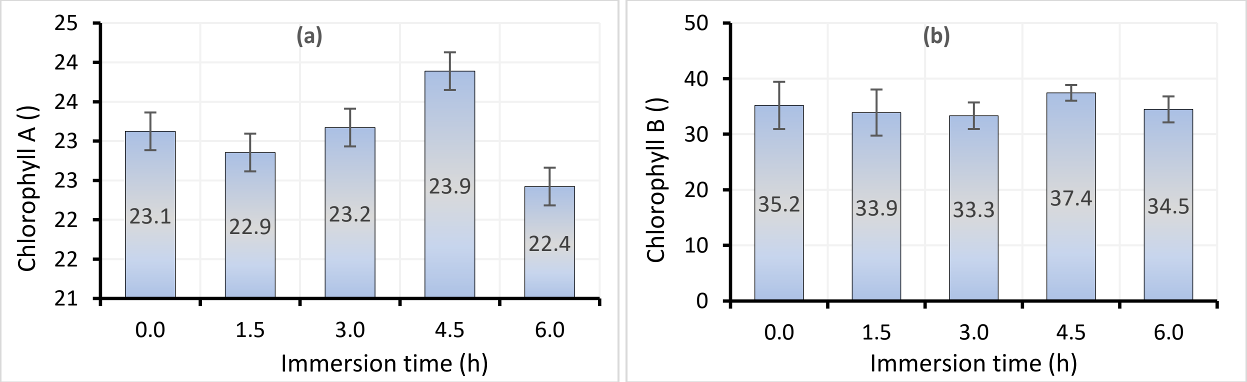

Figure 8. Effects of NPGR treatment on the amount of chlorophyll in sugarcane seedlings: (a) A Chlorophyll, (b) B Chlorophyll

plasma membrane, disrupting the hydrogen bonds between cellulose fibbers of the cell wall. This enhanced flexibility results in reduced cell wall pressure and increased expansion.

These flexible cells promote enhanced nitrogen metabolism within the cell, facilitating chlorophyll formation. Another factor that may have an impact is the intensity of light. The light received by the seeds in this study is thought to be suboptimal for the active functioning of the enzyme protochlorophyllide oxidoreductase (POR), which plays a crucial role in chlorophyll biosynthesis. However, excessive light intensity can potentially lead to photooxidation and the destruction of chlorophyll. In the results of the analysis, it is evident that there is no significant effect on the total amount of chlorophyll. This is likely because, during the seedling phase, the number of leaves formed is still limited.

The production of phytohormones requires ATP energy and active ATPases, while most of the energy is still primarily focused on vegetative growth (Apine *et al.*, 2021). Induction of auxin through NPGR can promote cell division by influencing the cell wall. This, in turn, activates the proton pump located on the plasma membrane (Kanayama, 2017). The activation of the proton pump can disrupt the hydrogen bonds between cellulose fibbers of the cell wall, making the cell wall more flexible. This increased flexibility results in decreased cell wall pressure and expansion (Kabała & Janicka, 2023). These flexible cells lead to enhanced nitrogen metabolism within the cell, facilitating the formation of chlorophyll (Zhou *et al.*, 2021). Another factor that may have an impact is the intensity of light. The light received by the seeds in this study is thought to be suboptimal for the active functioning of the enzyme protochlorophyllide oxidoreductase (POR), which plays a vital role in chlorophyll biosynthesis (Johannissen *et al.*, 2022). However, excessive light intensity can potentially lead to photooxidation and the destruction of chlorophyll.

4. CONCLUSIONS

This study successfully determined that the optimal immersion period for sugarcane Bud Chips (BC) in the Natural Plant Growth Regulator (NPGR) extract is 1.5 h (T1), yielding the greatest improvements in key morphological traits, including plant height, stem diameter, and root length. This optimal duration promotes a favorable hormonal balance (auxin and cytokinin) crucial for cell division and expansion, while higher doses (T2–T4) may hinder growth by disrupting enzymatic activities. Physiologically, the optimal NPGR dose supports desirable stomatal density and openness by modulating ABA signaling, although the study found no significant treatment effect on total chlorophyll content, likely due to limited leaf area and energy prioritization toward vegetative growth. Consequently, the application of NPGR at the precise 1.5 h immersion time is critical for harnessing its potential to enhance the early growth and morphological development of sugarcane seedlings (variety PS 862) in agricultural practice.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
SSTP	✓	✓		✓	✓	✓		✓	✓	✓			✓	✓
KRY		✓	✓		✓	✓	✓	✓	✓	✓				✓
FNS		✓				✓		✓		✓	✓			
YP			✓	✓	✓	✓		✓	✓		✓		✓	
FFH				✓	✓			✓		✓	✓			
MS				✓	✓		✓			✓		✓	✓	
SK							✓			✓		✓		

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

REFERENCES

Abd El-Moneim, D., Alqahtani, M.M., Abdein, M.A., & Germoush, M.O. (2020). Drought and salinity stress response in wheat: Physiological and TaNAC gene expression analysis in contrasting Egyptian wheat genotypes. *Journal of Plant Biotechnology*, ***47***(1), 1–14. https://doi.org/10.5010/JPB.2020.47.1.001

Aoki-Shioi, N., Nagai, Y., Deshimaru, M., & Terada, S. (2023). Precursor genes of Bowman-Birk-type serine proteinase inhibitors comprise multiple inhibitory domains to promote diversity. *Biochimica et Biophysica Acta (BBA) - General Subjects*, ***1867***(1), 130248. https://doi.org/10.1016/j.bbagen.2022.130248

Apine, I., Megre, D., Dokane, K., Kondratovics, U., & Tomsone, S. (2021). Effect of exogenous auxin application on starch concentration during adventitious root formation of deciduous azalea 'Madame Debene' cuttings. *Acta Horticulturae*, ***1331***. https://doi.org/10.17660/ActaHortic.2021.1331.15

Barbez, E., Dünser, K., Gaidora, A., & Busch, W. (2017). Auxin steers root cell expansion via apoplastic pH regulation in *Arabidopsis thaliana*. *Proceedings of the National Academy of Sciences*, ***114***(24), E4884–E4893. https://doi.org/10.1073/pnas.1613499114

Bloch, D., Puli, M.R., Mosquna, A., & Yalovsky, S. (2019). Abiotic stress modulates root patterning via ABA-regulated microRNA expression in the endodermis initials. *Development*, ***146***(17), dev177097. https://doi.org/10.1242/dev.177097

Bruno, L., Talarico, E., Cabeiras-Freijanes, L., Madeo, M.L., Muto, A., Minervino, M., Lucini, L., Miras-Moreno, B., Sofo, A., & Araniti, F. (2021). Coumarin interferes with polar auxin transport altering microtubule cortical array organization in *Arabidopsis thaliana* (L.) Heynh. root apical meristem. *International Journal of Molecular Sciences*, ***22***(14), 7305. https://doi.org/10.3390/ijms22147305

Cao, D., Chabikwa, T., Barbier, F., Dun, E.A., Fichtner, F., Dong, L., Kerr, S.C., & Beveridge, C.A. (2023). Auxin-independent effects of apical dominance induce changes in phytohormones correlated with bud outgrowth. *Plant Physiology*, *192*(2), 1420–1434. https://doi.org/10.1093/plphys/kiad034

Chen, J., Gong, Y., Gao, Y., Zhou, Y., Chen, M., Xu, Z., Guo, C., & Ma, Y. (2021a). TaNAC48 positively regulates drought tolerance and ABA responses in wheat (*Triticum aestivum* L.). *The Crop Journal*, *9*(4), 785–793. https://doi.org/10.1016/j.cj.2020.09.010

Chen, Q., Bai, L., Wang, W., Shi, H., Botella, J.R., Zhan, Q., Liu, K., Yang, H.-Q., & Song, C.-P. (2021b). COP1 promotes ABA-induced stomatal closure by modulating the abundance of ABI/HAB and AHG3 phosphatases. *New Phytologist*, *229*(4), 2035–2049. https://doi.org/10.1111/nph.17001

Chen, S., Zhong, K., Li, Y., Bai, C., Xue, Z., & Wu, Y. (2023). Evolutionary analysis of the melon (*Cucumis melo* L.) GH3 gene family and identification of GH3 genes related to fruit growth and development. *Plants*, ***12***(6), 1382. https://doi.org/10.3390/plants12061382

Chen, Z.-H., Wang, Y., Wang, J.-W., Babla, M., Zhao, C., García-Mata, C., Sani, E., Differ, C., Mak, M., Hills, A., Amtmann, A., & Blatt, M.R. (2016). Nitrate reductase mutation alters potassium nutrition as well as nitric oxide-mediated control of guard cell ion channels in *Arabidopsis*. *New Phytologist*, ***209***(4), 1456–1469. https://doi.org/10.1111/nph.13714

Egamberdieva, D., Ma, H., Reckling, M., Omari, R.A., Wirth, S., & Bellingrath-Kimura, S.D. (2022). Interactive effects of biochar, nitrogen, and phosphorous on the symbiotic performance, growth, and nutrient uptake of soybean (*Glycine max* L.). *Agronomy*, ***12***(1), 27. https://doi.org/10.3390/agronomy12010027

Farman, S., Mushtaq, A., & Azeem, M.W. (2019). Plant growth regulators (PGRs) and their applications: A review. *International Journal of Chemical and Biochemical Sciences*, ***15***, 94–103.

Forgione, I., Wołoszyńska, M., Pacenza, M., Chiappetta, A., Greco, M., Araniti, F., Abenavoli, M.R., Van Lijsebettens, M., Bitonti, M.B., & Bruno, L. (2019). Hypomethylated drm1 drm2 cmt3 mutant phenotype of *Arabidopsis thaliana* is related to auxin pathway impairment. *Plant Science*, ***280***, 383–396. https://doi.org/10.1016/j.plantsci.2018.12.029

Gao, H., Yu, W., Yang, X., Liang, J., Sun, X., Sun, M., Xiao, Y., & Peng, F. (2022). Silicon enhances the drought resistance of peach seedlings by regulating hormone, amino acid, and sugar metabolism. *BMC Plant Biology*, ***22***, 422. https://doi.org/10.1186/s12870-022-03785-5

Godoy, F., Kühn, N., Muñoz, M., Marchandon, G., Gouthu, S., Deluc, L., Delrot, S., Lauvergeat, V., & Arce-Johnson, P. (2021). The role of auxin during early berry development in grapevine as revealed by transcript profiling from pollination to fruit set. *Horticulture Research*, ***8***, 140. https://doi.org/10.1038/s41438-021-00568-1

Górski, F., Gerotti, G.M., & Magalhães, H.M. (2021). Relationship between auxins and cytokinins in the growth and organogenesis of *Ocimum basilicum* L. 'Grecco a Palla'. *Canadian Journal of Plant Science*, ***101***(5), 698–713. https://doi.org/10.1139/cjps-2020-0067

Hajihashemi, S., Brestic, M., Landi, M., & Skalicky, M. (2020). Resistance of *Fritillaria imperialis* to freezing stress through gene expression, osmotic adjustment and antioxidants. *Scientific Reports*, ***10***, 10427. https://doi.org/10.1038/s41598-020-67399-6

Hamza, M.H., & Hadi, A.A.-K. (2020). Study of the effect of foliar spray with nano fertilizer and biological fertilization in some characteristics of vegetative and root growth of orange seedlings. *Plant Archives*, ***20***(Suppl. 2), 2839–2844.

Hmmam, I., Raza, A., Djalovic, I., Khedr, N., & Abdellatif, A. (2023). An in vitro approach to investigate the role of abscisic acid in alleviating the negative effects of chilling stress on banana shoots. *Phyton-International Journal of Experimental Botany,* ***92***(6), 1695–1711. https://doi.org/10.32604/phyton.2023.028317

Hoermayer, L., Montesinos, J.C., Marhava, P., Benková, E., Yoshida, S., & Friml, J. (2020). Wounding-induced changes in cellular pressure and localized auxin signalling spatially coordinate restorative divisions in roots. *Proceedings of the National Academy of Sciences, 117*(26), 15322–15331. https://doi.org/10.1073/pnas.2003346117

Jiang, Z.-f., Liu, D.-d., Wang, T.-q., Liang, X.-l., Cui, Y.-h., Liu, Z.-h., & Li, W.-b. (2020). Concentration difference of auxin involved in stem development in soybean. *Journal of Integrative Agriculture,* ***19***(4), 953–964. https://doi.org/10.1016/S2095-3119(19)62676-6

Johannissen, L.O., Taylor, A., Hardman, S.J.O., Heyes, D.J., Scrutton, N.S., & Hay, S. (2022). How photoactivation triggers protochlorophyllide reduction: Computational evidence of a stepwise hydride transfer during chlorophyll biosynthesis. *ACS Catalysis,* ***12***(7), 4141–4148. https://doi.org/10.1021/acscatal.2c00866

Kabała, K., & Janicka, M. (2023). Structural and functional diversity of two ATP-driven plant proton pumps. *International Journal of Molecular Sciences, 24*(5), 4512. https://doi.org/10.3390/ijms24054512

Kanayama, Y. (2017). Sugar metabolism and fruit development in the tomato. *The Horticulture Journal,* ***86***(4), 417–425. https://doi.org/10.2503/hortj.OKD-IR01

Kativat, C., Chueakhunthod, W., & Tantasawat, P.A. (2022). The effects of cytokinin and plating density on protoplast culture of sunflower. *Journal of Plant Biotechnology,* ***49***(4), 331–338. https://doi.org/10.5010/JPB.2022.49.4.331

Kumari, P., Topno, S.E., & Bahadur, V. (2022). Effect of plant growth regulators on plant growth, yield and fruit quality of brinjal. *International Journal of Environment and Climate Change,* ***12***(11), 2736–2743. https://doi.org/10.9734/ijecc/2022/v12i1131262

Kurepa, J., & Smalle, J.A. (2022). Auxin/cytokinin antagonistic control of the shoot/root growth ratio and its relevance for adaptation to drought and nutrient deficiency stresses. *International Journal of Molecular Sciences,* ***23***(4), 1933. https://doi.org/10.3390/ijms23041933

Li, K., Tian, H., Mao, J., Khan, A., Tahir, M. M., Li, S., Chen, S., Shao, Y., & Zhang, D. (2022). Effect of darkness treatment on the morphology, hormone status and gene expression of developing adventitious root in apple rootstock. *Plant Cell, Tissue and Organ Culture,* ***148***, 331–346. https://doi.org/10.1007/s11240-021-02192-2

Li, Y.-Y., Hao, Z.-G., Miao, S., Zhang, X., Li, J.-Q., Guo, S.-X., & Lee, Y.-I. (2022). Profiles of cytokinins metabolic genes and endogenous cytokinins dynamics during shoot multiplication in vitro of *Phalaenopsis*. *International Journal of Molecular Sciences,* ***23***(7), 3755. https://doi.org/10.3390/ijms23073755

Liao, B., Li, F., Yi, F., Du, M., Tian, X., & Li, Z. (2023). Comparative physiological and transcriptomic mechanisms of defoliation in cotton in response to thidiazuron versus ethephon. *International Journal of Molecular Sciences,* ***24***(8), 7590. https://doi.org/10.3390/ijms24087590

Lin, Q., Gong, J., Zhang, Z., Meng, Z., Wang, J., Wang, S., Sun, J., Gu, X., Jin, Y., Wu, T., Nuo, Y., Wang, Y., Kai, L., Jiang, J., & Qi, S. (2023). The *Arabidopsis thaliana* trehalose-6-phosphate phosphatase gene AtTPPI regulates primary root growth and lateral root elongation. *Frontiers in Plant Science,* ***13***, 1088278. https://doi.org/10.3389/fpls.2022.1088278

Llanes, A., Palchetti, M. V., Vilo, C., & Ibañez, C. (2021). Molecular control to salt tolerance mechanisms of woody plants: Recent achievements and perspectives. *Annals of Forest Science,* ***78***, 96. https://doi.org/10.1007/s13595-021-01107-7

Luostarinen, K., Hakkarainen, K., & Kaksonen, H. (2017). Wood anatomy of seed and basal bud originated downy birches (*Betula pubescens* Ehrh.) grown at four different sites. *Silva Fennica, 51*(1), 1694. https://doi.org/10.14214/sf.1694

Ma, L., Zhao, Y., Chen, M., Li, Y., Shen, Z., Cao, Y., Wu, D., Yu, M., Grierson, D., & Shi, Y. (2023). The microRNA ppe-miR393 mediates auxin-induced peach fruit softening by promoting ethylene production. *Plant Physiology,* ***192***(2), 1638–1655. https://doi.org/10.1093/plphys/kiad182

Mangais, R., Rampe, H. L., & Siahaan, P. (2022). Vegetative growth response of soybean (*Glycine max* L. Merril) after applicated several plant growth regulators (PGRs). *Akta Agrosia,* ***25***(1), 11–16. https://doi.org/10.31186/aa.25.1.11-16

Mroue, S., Simeunovic, A., & Robert, H.S. (2018). Auxin production as an integrator of environmental cues for developmental growth regulation. *Journal of Experimental Botany,* ***69***(2), 201–212. https://doi.org/10.1093/jxb/erx259

Orozco-Mosqueda, M.del C., Santoyo, G., & Glick, B.R. (2023). Recent advances in the bacterial phytohormone modulation of plant growth. *Plants,* ***12***(3), 606. https://doi.org/10.3390/plants12030606

Prameswari, W., Anandyawati, A., Prasetyo, P., Salamah, U., Oktavia, D., & Setyowati, N. (2022). Natural plant growth regulator effect on the vegetative growth of Long Pepper (*Piper retrofractum* Vahl.). *International Journal of Agricultural Technology,*

18(3), 1167–1178. https://li04.tci-thaijo.org/index.php/IJAT/article/view/7306

Randall, R. S., Miyashima, S., Blomster, T., Zhang, J., Elo, A., Karlberg, A., Immanen, J., Nieminen, K., Lee, J.-Y., Kakimoto, T., Blajecka, K., Melnyk, C. W., Alcasabas, A., Forzani, C., Matsumoto-Kitano, M., Mähönen, A. P., Bhalerao, R., Dewitte, W., Helariutta, Y., & Murray, J. A. H. (2015). AINTEGUMENTA and the D-type cyclin CYCD3;1 regulate root secondary growth and respond to cytokinins. *Biology Open, **4***(10), 1229–1236. https://doi.org/10.1242/bio.013128

Ranganatha, M., Rao, N.N., Giridhar, P., & Sharma, A. (2023). Micropropagation and in vitro flowering in *Basella alba*. *Plant Cell, Tissue and Organ Culture, **154***, 111–119. https://doi.org/10.1007/s11240-023-02515-5

Sosnowski, J., Malinowska, E., Jankowski, K., Król, J., & Redzik, P. (2019). An estimation of the effects of synthetic auxin and cytokinin and the time of their application on some morphological and physiological characteristics of *Medicago* × *varia* T. Martyn. *Saudi Journal of Biological Sciences, **26***(1), 66–73. https://doi.org/10.1016/j.sjbs.2016.12.023

Sussmilch, F.C., Schultz, J., Hedrich, R., & Roelfsema, M.R.G. (2019). Acquiring control: The evolution of stomatal signalling pathways. *Trends in Plant Science, **24***(4), 342–351. https://doi.org/10.1016/j.tplants.2019.01.002

Tian, C., Zhang, J., Gu, J., Li, W., & Cao, Y. (2022). Light controlled biomaterials for regulating cell migration and differentiation. *Smart Materials in Medicine, **3***, 209–216. https://doi.org/10.1016/j.smaim.2022.01.005

Traas, J. (2019). Organogenesis at the shoot apical meristem. *Plants, **8***(1), 6. https://doi.org/10.3390/plants8010006

Waghmare, S.S., Adat, S.R., Mohite, V.K., Waghule, A.A., & Patale, S.S. (2021). Study of Bunchy Top of Banana Virus (BBTV) and its control by integrated disease management (IDM). *International Journal of Current Microbiology and Applied Sciences, **10***(11), 416–429. https://doi.org/10.20546/ijcmas.2021.1011.047

Weimer, A.K., Matos, J.L., Sharma, N., Patell, F., Murray, J.A.H., Dewitte, W., & Bergmann, D.C. (2018). Lineage- and stage-specific expressed CYCD7;1 coordinates the single symmetric division that creates stomatal guard cells. *Development, **145***(6), dev160671. https://doi.org/10.1242/dev.160671

Wu, W., Du, K., Kang, X., & Wei, H. (2021). The diverse roles of cytokinins in regulating leaf development. *Horticulture Research, **8***, 118. https://doi.org/10.1038/s41438-021-00558-3

Wu, Y., Chang, Y., Luo, L., Tian, W., Gong, Q., & Liu, X. (2022). Abscisic acid employs NRP-dependent PIN2 vacuolar degradation to suppress auxin-mediated primary root elongation in *Arabidopsis*. *New Phytologist, **233***(1), 297–312. https://doi.org/10.1111/nph.17783

Xiong, Z., Xiong, D., Yang, D., Cui, K., Peng, S., & Huang, J. (2022). Effects of contrasting N supplies on leaf photosynthetic induction under fluctuating light in rice (*Oryza sativa* L.). *Physiologia Plantarum, **174***(2), e13636. https://doi.org/10.1111/ppl.13636

Yadav, S., Yugandhar, P., Alavilli, H., Raliya, R., Singh, A., Sahi, S.V., Sarkar, A.K., & Jain, A. (2022). Potassium chloroaurate-mediated in vitro synthesis of gold nanoparticles improved root growth by crosstalk with sucrose and nutrient-dependent auxin homeostasis in *Arabidopsis thaliana*. *Nanomaterials, **12***(12), 2099. https://doi.org/10.3390/nano12122099

Yang, K., Zhu, L., Wang, H., Le, J., *et al.* (2019). A conserved but plant-specific CDK-mediated regulation of DNA replication protein A2 in the precise control of stomatal terminal division. *Proceedings of the National Academy of Sciences of the United States of America, **116***(36), 18126–18131. https://doi.org/10.1073/pnas.1819345116

Yang, L., Sun, J., Yan, C., Wu, J., Wang, Y., Ren, Q., Wang, S., Ma, X., Zhao, L., & Sun, J. (2022). Regeneration of duckweed (*Lemna turonifera*) involves genetic molecular regulation and cyclohexane release. *PLoS ONE, **17***(1), e0254265. https://doi.org/10.1371/journal.pone.025426

Yin, S., Bai, J., Wen, X., Zhang, G., Han, L., & Hu, X. (2019). Effects of polycyclic aromatic hydrocarbon (phenanthrene) addition on soil nitrogen mineralization processes in rural and urban river wetlands of the Pearl River Estuary, China. *Journal of Agro-Environment Science, **38***(3), 600–608. https://doi.org/10.11654/jaes.2018-1543

Zahoor, R., Zhao, W., Abid, M., Dong, H., & Zhou, Z. (2017). Potassium application regulates nitrogen metabolism and osmotic adjustment in cotton (*Gossypium hirsutum* L.) functional leaf under drought stress. *Journal of Plant Physiology, **215***, 30–38. https://doi.org/10.1016/j.jplph.2017.05.001

Zhang, Z., Gao, L., Ke, M., Gao, Z., Tu, T., Huang, L., Chen, J., Guan, Y., Huang, X., & Chen, X. (2022). GmPIN1-mediated auxin asymmetry regulates leaf petiole angle and plant architecture in soybean. *Journal of Integrative Plant Biology, **64***(7), 1325–1338. https://doi.org/10.1111/jipb.13269

Zhou, Z., Zhang, K., Wang, L., Su, Y., Wang, J., Song, T., Yang, X., Tang, J., & Lin, S. (2021). Nitrogen availability improves the physiological resilience of coral endosymbiont *Cladocopium goreaui* to high temperature. *Journal of Phycology, **57***(4), 1187–1198. https://doi.org/10.1111/jpy.13156