

Impact of Foliar Spraying of 5-Aminolevulinic Acid and Nano-Zinc Oxide on Leaf Chemical Composition and Pigment Content of Dwarf Bougainvillea 'Jewel Pink'

Bushra Alawi Hussain Khalaf¹ and Zeyad Mohammed Abdulrazzaq^{2*} 

^{1,2} Department of Horticulture and Landscaping, College of Agriculture, University of Anbar, Iraq

*Corresponding author email: zeyadmohammed@uoanbar.edu.iq

Abstract

The study was carried out in the greenhouse of the Horticulture Department/University of Anbar from October 2025 to April 2026 to identify the effect of foliar application of the growth regulator 5-ALA and Nano-ZnO on increasing the chemical content of the leaves and flower clusters of *Bougainvillea* spp. Jewel pink plants. The study included spraying the foliage in the early morning with 5-ALA [control treatment: (0, 25, 50 and 100 mg L⁻¹) and Nano-ZnO (0, 50 and 100 mg L⁻¹). The experiment was designed according to RCBD with three seedlings and three replicates. Spraying dwarf Bougainvillea seedlings with the growth regulator 5-ALA at a concentration of 50 mg L⁻¹ (A₃) resulted in a significant improvement in chemical growth characteristics. This treatment exhibited the highest levels of beta-carotene content in inflorescences (2.93 mg g⁻¹ FW) and higher levels of total chlorophyll (2.17 mg g⁻¹ FW), nitrogen (2.25%), phosphorus (0.49%), potassium (2.09%), carbohydrates (27.24%), and zinc (66.36 mg kg⁻¹) in the leaves. In contrast, the control treatment A₁ (0 mg L⁻¹) showed the lowest significant improvements in these growth characteristics. Furthermore, spraying the foliage with Nano-ZnO (ZnO-NPs) at a concentration of 75 mg L⁻¹ (Z₂) also demonstrated a significant improvement in the same chemical characteristics, with values of 2.66 mg g⁻¹ and 2.06 mg g⁻¹ FW, as well as 2.08, 0.46, 2.00, 26.03%, and 61.98 mg kg⁻¹, respectively. While the rates were reduced to the lowest possible level when treated with distilled water (the control treatment), the spray treatments of 50 mg L⁻¹ of 5-ALA and 75 mg L⁻¹ of Nano-ZnO (A₃Z₂) excelled in chemical growth characteristics, except for leaf phosphorus and carbohydrate content. In comparison, A₁Z₁ (0 mg L⁻¹) resulted in the least significant differences in these same characteristics.

Keywords: *Bougainvillea* Dwarf, 5-ALA, Nano-ZnO, chemical growth

1. Introduction

Dwarf *Bougainvillea* spp. is a perennial climbing plant. The leaves are simple, rounded, whole, and arranged alternately on the stem. They possess diminutive true flowers lacking aesthetic appeal, yet their decorative value is evident in gardens, streets, and the formation of plant hedges, attributed to the allure of their floral inflorescences and vibrant bracts, which exhibit color variation depending on species and varieties. They belong to the *Nyctaginaceae* family and are distinguished by robust growth and resilience to drought, as well as extreme temperatures. They are distinguished by the presence of robust, colored bracts arranged in spike-like inflorescences [9, 20, 22, 33].

Previous studies have demonstrated that foliar application of growth regulators and micronutrients is crucial for plant growth and development, since it directly and indirectly initiates certain vital physiological processes within the plant. Foliar feeding is regarded as a significant and effective scientific technique for addressing nutrient deficiencies and enhancing plant resilience to various stresses, particularly concerning micronutrients that are commonly deficient in most soils [6, 11, 31].

5-aminolevulinic acid (5-ALA) serves as the precursor for the growth regulator involved in the synthesis of tetrapyrrole molecules, including phytochrome, chlorophyll, and vitamin B12 in plants. Recent evidence indicates a significant positive impact on enhancing growth traits and augmenting plant

resistance to diverse stimuli, alongside a function analogous to cytokinin and auxins in promoting lateral bud formation and elevating plant hormone synthesis. In tissue culture, it facilitates the division of plant cells, stimulates the emergence and proliferation of callus, and enhances the concentration of active chemical compounds in the plant, especially in the leaves and inflorescences [28, 41, 42, 44].

Zinc is a vital micronutrient necessary for the stimulation and activation of several enzymes and nucleic acids. Engages in oxidation-reduction reactions and regulates the biosynthesis of auxin (IAA) and chlorophyll. It enhances glucose concentration in plant leaves and energy production, which is critical for maximizing respiration and photosynthesis efficiency [17, 30, 34]. This study was conducted to evaluate the individual and combined effects of foliar-applied 5-ALA and ZnO nanoparticles on the chemical attributes of dwarf Bougainvillea 'Jewel Pink'.

2. Materials and Methods

The experiment was conducted in a greenhouse at Anbar University from September 2025 to March 2026 to evaluate the effects of foliar application of the growth regulators 5-ALA and Nano-ZnO on the chemical growth parameters of dwarf *Bougainvillea* (Jewel Pink). Seedlings, which were two years old, they were placed in plastic pots filled with 20 kg of sandy loam soil. The study employed a two-factor (4 x 3) factorial design within a Randomized Complete Block Design, incorporating three replicates and three seedlings per experimental unit, with 108 seedlings, in accordance with the Least Significant Difference (LSD) method at a probability threshold of 0.05 [32].

A total of 108 seedlings exhibiting the most uniform growth were selected for the application of the two agents. The first agent involved the application of four concentrations of 5-ALA: 0 mg L⁻¹, 25 mg L⁻¹, 50 mg L⁻¹, and 100 mg L⁻¹, with the control being the application with distilled water. The second factor comprised the application of three doses of Nano-ZnO: 0 mg L⁻¹, 75 mg L⁻¹, and 150

mg L⁻¹. The first factor (5-ALA) was applied to the foliage of seedlings on November 1, 2025, December 1, 2025, January 1, 2026, and February 1, 2026. The second factor was applied two days after each application of the first factor.

5-Aminolevulinic acid is 99% pure, requiring the calculation of the necessary weights for the experiment based on the equation provided, as noted by [15].

Each weight was dissolved in distilled water, and the volume was adjusted to 1 litre to obtain the requisite concentrations, following the methodology outlined by [29].

Second factor: Application of zinc oxide nanoparticles at three concentrations: Z₁: Spray, 0 mg L⁻¹ (distilled water) - Application of zinc oxide nanoparticles at a concentration of 75 mg L⁻¹, designated as Z₂. The application of zinc oxide nanoparticles at a concentration of 150 mg L⁻¹, referred to as Z₃, was conducted using the same methodology employed for the preparation of the growth regulator, 5-Aminolevulinic acid, noting that the substance is 99% pure, contrary to the 100% purity claimed by [15].

3. Results

3.1 Total Chlorophyll Concentration in Seedling Foliage (mg g⁻¹ FW)

Table 1 indicates that the application of the growth regulator 5-ALA at a concentration of 50 mg L⁻¹ (A₃) led to a notable enhancement in total leaf chlorophyll content (2.17 mg g⁻¹ FW), whereas the control treatment A₁ (spraying with distilled water) exhibited a reduction, attaining 1.51 mg g⁻¹ FW. Application of ZnO-NPs on seedlings at a concentration of 75 mg L⁻¹ (Z₂) yielded the highest total leaf chlorophyll content, measuring 2.06 mg g⁻¹ FW, whereas the control treatment Z₁ (spraying with distilled water) exhibited a reduced total leaf chlorophyll content of 1.58 mg g⁻¹ FW. The results indicated significant disparities among the interaction treatments; the A₃Z₂ treatment yielded the highest total leaf chlorophyll content at 2.69 mg g⁻¹ FW, whereas the A₁Z₁

treatment recorded the lowest at 1.45 mg g^{-1} FW.

Table 1: Impact of foliar spraying of 5-ALA and ZnO-NPs on Total Chlorophyll in Dwarf Bougainvillea (mg g^{-1} FW)

Treatments	Z ₁ ZnO-NPs (0)	Z ₂ ZnO-NPs (75)	Z ₃ ZnO-NPs (150)	Average A
A ₁ 5-ALA (0)	1.45	1.54	1.55	1.51
A ₂ 5-ALA (25)	1.53	1.87	1.74	1.72
A ₃ 5-ALA (50)	1.71	2.69	2.10	2.17
A ₄ 5-ALA (100)	1.62	2.14	1.85	1.87
Average Z	1.58	2.06	1.81	
LSD _A		0.18		
LSD _Z		0.15		
LSD _{A*Z}		0.31		

3.2 Percentage of Nitrogen in Seedling Foliage

Table 2 indicates that spray treatment A₃ exhibited a marked superiority over the other treatments, attaining the highest nitrogen content in the leaves of dwarf Bougainvillea seedlings at 2.25%, in contrast to the distilled water spray treatment (control treatment) A₁, which produced a nitrogen content of 1.27%.

The Z₂ spray treatment showed superiority by attaining the maximum nitrogen content in the leaves at 2.08%, whereas the control treatment Z₁ exhibited the lowest at 1.65%. The results in the same table validate the superiority of the interaction treatment A₃Z₂, which attained the highest significant difference in leaf nitrogen content at 2.67%. In contrast, the control treatment A₁Z₁ recorded the lowest at 1.05%.

Table 2: Impact of foliar spraying of 5-ALA and ZnO-NPs on The nitrogen content (%) in Dwarf Bougainvillea

Treatments	Z ₁ ZnO-NPs (0)	Z ₂ ZnO-NPs (75)	Z ₃ ZnO-NPs (150)	Average A
A ₁ 5-ALA (0)	1.05	1.29	1.48	1.27
A ₂ 5-ALA (25)	1.82	2.15	1.81	1.93
A ₃ 5-ALA (50)	1.88	2.67	2.20	2.25
A ₄ 5-ALA (100)	1.86	2.22	2.04	2.04
Average Z	1.65	2.08	1.88	
LSD _A		0.15		
LSD _Z		0.13		
LSD _{A*Z}		0.25		

3.3 Phosphorus Content in Leaves (%)

Table 3 illustrates notable disparities between the two experimental regimens. The 5-ALA growth regulator spray treatment at a dose of 50 mg L⁻¹ produced a considerable increase in leaf phosphorus content, achieving 0.49%, compared to the control treatment at 0 mg L⁻¹, which yielded 0.35%. The ZnO-PNs spray treatment at a concentration of 75 mg L⁻¹

yielded the highest leaf phosphorus content at 0.46%, whereas the treatment at 0 mg L⁻¹ produced the lowest content at 0.38%, which was not significantly different from the 150 mg L⁻¹ treatment, which recorded 0.41% phosphorus content. The table likewise indicates no substantial variations in the interaction coefficients between the two experimental treatments.

Table 3: Impact of foliar spraying of 5-ALA and ZnO-NPs on The phosphorus (%) in Dwarf Bougainvillea

Treatments	Z ₁ ZnO-NPs (0)	Z ₂ ZnO-NPs (75)	Z ₃ ZnO-NPs (150)	Average A
A ₁ 5-ALA (0)	0.32	0.36	0.36	0.35
A ₂ 5-ALA (25)	0.35	0.44	0.39	0.39
A ₃ 5-ALA (50)	0.46	0.52	0.50	0.49
A ₄ 5-ALA (100)	0.41	0.50	0.41	0.44
Average Z	0.38	0.46	0.41	
LSD _A		0.03		
LSD _Z		0.03		
LSD _{A*Z}		N.S		

3.4 Percentage of potassium in seedling leaves

Table 4 indicates that treatment A₃ exhibited the highest potassium concentration in the leaves, measuring 2.09%, whereas the control treatment A₁ recorded the lowest at 1.62%. Treatment Z₂ significantly surpassed the control treatment Z₁, which exhibited the lowest potassium content in the leaves of dwarf *Bougainvillea* seedlings at 1.66%, compared to Z₂'s 2.00% potassium content.

The results in the same table indicated substantial disparities in the interaction coefficients between the two experimental variables. Treatment A₃Z₂ had the highest potassium concentration in the leaves, measuring 2.30%. Treatment A₄Z₁ (5-ALA spray at 100 mg L⁻¹ and ZnO-NPs at 0 mg L⁻¹) yielded the lowest potassium concentration in the leaves of dwarf *Bougainvillea* seedlings, measuring 1.57%.

Table 4: Impact of foliar spraying of 5-ALA and ZnO-NPs on The potassium (%) in Dwarf Bougainvillea

Treatments	Z ₁ ZnO-NPs ₍₀₎	Z ₂ ZnO-NPs ₍₇₅₎	Z ₃ ZnO-NPs ₍₁₅₀₎	Average A
A ₁ 5-ALA ₍₀₎	1.59	1.67	1.59	1.62
A ₂ 5-ALA ₍₂₅₎	1.72	1.88	1.73	1.78
A ₃ 5-ALA ₍₅₀₎	1.77	2.30	2.21	2.09
A ₄ 5-ALA ₍₁₀₀₎	1.57	2.17	1.78	1.84
Average Z	1.66	2.00	1.83	
LSD _A		0.10		
LSD _Z		0.09		
LSD _{A*Z}		0.17		

3.5 Percentage of Carbohydrate Content in Seedling Leaves

The data presented in Table 5 indicate that treatment A₃ was the most effective, demonstrating a significant increase in carbohydrate content of dwarf Bougainvillea leaves sourced from seedlings, with a measured value of 27.24%. In contrast, the control treatment A₁ yielded the lowest carbohydrate content at 22.29%. Treatment Z₂

also showed a marked increase in leaf carbohydrate content, reaching 26.03%. Conversely, the control treatment Z₁ recorded the least carbohydrate content at 23.38%. The findings in the same table suggest that there were no significant differences in the interaction coefficients between the two experimental factors: the application of the growth regulator 5-ALA and zinc oxide nanoparticles (ZnO-NPs).

Table 5: Impact of foliar spraying of 5-ALA and ZnO-NPs on The carbohydrate (%) in Dwarf Bougainvillea

Treatments	Z ₁ ZnO-NPs ₍₀₎	Z ₂ ZnO-NPs ₍₇₅₎	Z ₃ ZnO-NPs ₍₁₅₀₎	Average A
A ₁ 5-ALA ₍₀₎	20.86	22.58	23.42	22.29
A ₂ 5-ALA ₍₂₅₎	22.59	25.81	24.29	24.23
A ₃ 5-ALA ₍₅₀₎	25.32	29.88	26.53	27.24
A ₄ 5-ALA ₍₁₀₀₎	24.75	25.84	24.94	25.18
Average Z	23.38	26.03	24.80	
LSD _A		1.14		
LSD _Z		0.99		
LSD _{A*Z}		N.S		

3.6 Zinc concentration in seedling foliage (mg kg⁻¹)

The findings in Table 6 indicated that the 5-ALA spray treatment (A₃) markedly outperformed the other treatments in the experiment, attaining the highest average zinc concentration in the leaves of *Bougainvillea* dwarf seedlings at 66.36 mg kg⁻¹, whereas the distilled water spray treatment (A₁) recorded the lowest average at 34.89 mg kg⁻¹. The ZnO-NPs spray treatment (Z₂) showed a marked superiority, attaining the greatest average zinc concentration in the leaves at 61.98 mg kg⁻¹, in contrast to the control treatment (Z₁), which

exhibited the lowest significant zinc concentration at 43.58 mg kg⁻¹. The table indicated that the A₃Z₂ interaction treatment (application of 5-ALA and ZnO-NPs) was markedly more effective, resulting in the maximum zinc concentration in dwarf *Bougainvillea* leaves at 75.23 mg kg⁻¹. The A₃Z₃ interaction treatment yielded a level of 72.54 mg kg⁻¹, which was not markedly different, but the A₁Z₁ interaction treatment, involving the application of distilled water, resulted in the lowest amount of 29.65 mg kg⁻¹.

Table 6: Impact of foliar spraying of 5-ALA and ZnO-NPs on the zinc concentration (mg kg⁻¹) in Dwarf *Bougainvillea*

Treatments	Z ₁ ZnO-NPs (0)	Z ₂ ZnO-NPs (75)	Z ₃ ZnO-NPs (150)	Average A
A ₁ 5-ALA (0)	29.65	38.66	36.35	34.89
A ₂ 5-ALA (25)	43.17	65.44	48.71	52.44
A ₃ 5-ALA (50)	51.30	75.23	72.54	66.36
A ₄ 5-ALA (100)	50.21	68.58	66.83	61.87
Average Z	43.58	61.98	56.11	
LSD _A		2.98		
LSD _Z		2.58		
LSD _{A*Z}		5.17		

3.7 Beta-carotene concentration in seedling inflorescences (mg g⁻¹ FW)

Table 7 indicates that the application of the growth regulator 5-Aminolevulinic acid at a concentration of 50 mg L⁻¹ (A₃) on dwarf *Bougainvillea* seedlings enhanced the beta-carotene content of the inflorescences to 2.93 mg g⁻¹ FW, whereas the control treatment, sprayed with distilled water (A₁), yielded the lowest concentration at 2.10 mg g⁻¹ FW. Upon application of nano-zinc oxide to the seedlings, the maximum concentration of

beta-carotene in the flower buds was recorded in treatment Z₂ (75 mg L⁻¹), yielding 2.66 mg g⁻¹ FW, whereas treatment Z₁ (0 mg L⁻¹) resulted in the minimal concentration of 2.31 mg g⁻¹ FW. The chart also reveals substantial disparities among the interaction treatments. Treatment A₃Z₂ yielded the highest beta-carotene content in flower buds (3.23 mg g⁻¹ FW), whereas treatment A₁Z₁ (the control) produced the lowest concentration (1.92 mg g⁻¹ FW).

Impact of foliar spraying of 5-ALA and ZnO-NPs on beta-carotene concentration (mg g⁻¹ FW) in Dwarf Bougainvillea

Treatments	Z ₁ ZnO-NPs ₍₀₎	Z ₂ ZnO-NPs ₍₇₅₎	Z ₃ ZnO-NPs ₍₁₅₀₎	Average A
A ₁ 5-ALA ₍₀₎	1.92	2.14	2.25	2.10
A ₂ 5-ALA ₍₂₅₎	2.19	2.43	2.31	2.31
A ₃ 5-ALA ₍₅₀₎	2.99	3.23	2.57	2.93
A ₄ 5-ALA ₍₁₀₀₎	2.14	2.81	2.75	2.57
Average Z	2.31	2.66	2.47	
LSD _A		0.10		
LSD _Z		0.08		
LSD _{A*Z}		0.17		

4. Discussion

4.1 Impact of 5-ALA Application on the Chemical Composition Attributes of Dwarf Bougainvillea Seedlings

5-ALA is a fundamental precursor in chlorophyll biosynthesis. By forming tetrapyrrole compounds, it enhances chlorophyll stability and elevates intermediate levels-specifically protoporphyrin IX (PPIX), magnesium protoporphyrin IX (Mg-PPIX), and protochlorophyllide (Pchlde)-ultimately increasing chlorophyll *a* and *b* concentrations. Furthermore, 5-ALA significantly improves electron transport activity within the photosystem II center, upregulates photosynthesis-related genes, and enhances overall photochemical efficiency. It also contributes to the synthesis of vitamin B12 and phytochromes, as supported by the data in Table 1. These results align with previous findings established by [21, 40, 44].

Leaf nitrogen levels in dwarf Bougainvillea seedlings increased significantly following 5-ALA application (Table 2). This accumulation is attributed to the enhanced activity of key nitrogen-assimilating enzymes, including nitrate reductase (NR), glutamine synthetase (GS), and glutamate synthase (GOGAT), which

collectively augment the average nitrate reduction capacity. Additionally, 5-ALA treatment improves the seedlings' capacity to uptake and assimilate mineral nutrients and nitrates directly from the soil [40, 41].

The application of 5-ALA enhances phosphorus (P) absorption and its subsequent translocation to the leaves by upregulating root phosphate transport genes, expanding root surface area, and increasing mycorrhizal colonization [7, 41]. This process facilitates the source-to-sink delivery of photoassimilates by actively loading phosphorus into the phloem, thereby significantly increasing leaf P concentrations (Table 3).

Application of 5-ALA promotes potassium (K⁺) uptake and maintains cell membrane integrity by activating (K⁺) transport channels and optimizing ionic equilibrium. Furthermore, it upregulates H⁺ - ATPase enzyme activity, facilitating the active transport of potassium across root cell membranes for distribution to leaf tissues, as corroborated by the data in Table 4 [41, 44].

Table 5 demonstrates that the application of 5-ALA on dwarf Bougainvillea seedlings enhances chlorophyll content, photosystem II (PSII) efficiency, and carbon fixation during photosynthesis. Moreover, it

promotes the overexpression of Calvin cycle enzymes, including FBPase, TPI, and RuBisCO, which jointly augment the synthesis of ingested substances and the accumulation and control of carbohydrates in leaf tissues [10, 43].

Zinc serves as a cofactor in the activation of several enzymes, such as Carbonic Anhydrase (CA) and Superoxide Dismutase (SOD). It also aids in the transmembrane transport and absorption of zinc ions (Zn^{2+}) through ZIP carriers and enhances their incorporation into the xylem tissue for distribution to aerial structures such as leaves (Table 6) by improving root functions. Application of 5-ALA to seedlings enhances leaf mineral content due to improved root uptake efficiency, alongside an increase in leaf size, thickness, and mineral composition [44, 45]. The rationale for the augmentation of leaf nitrogen, phosphorus, potassium, and zinc content aligns with the findings of [44].

Beyond chlorophyll synthesis, 5-ALA boosts the gene expression of phytoene synthase (PSY) and other carotenogenesis genes while activating the methylerythritol phosphate (MEP) pathway. This stimulates beta-carotene flux within the chromoplasts of *Bougainvillea* bracts, enhancing color intensity and ornamental value. These findings demonstrate that 5-ALA markedly elevates carotenoid accumulation by upregulating critical biosynthetic enzymes, including geranylgeranyl pyrophosphate synthase (GGPPS), phytoene synthase 1 (PSY1), phytoene desaturase (PDS), and lycopene beta-cyclase (LCYB) (Table 7), consistent with previous reports [8, 13, 37, 40].

4.2 Impact of ZnO-NP Application on the Chemical Growth Attributes of Dwarf *Bougainvillea* Seedlings

Zinc serves as a crucial cofactor for the Delta-ALA Dehydratase (ALAD) enzyme, which facilitates the initial step in the chlorophyll biosynthesis pathway, stabilises the thylakoid membrane structure, and enhances the efficacy of the second

photosynthesis system, thereby safeguarding and augmenting the chlorophyll reserves in the leaves (as evidenced by the findings in Table 1). Additionally, ZnO-NPs effectively deliver zinc to the plant by infiltrating the cells, permeating the plant cell membranes, and integrating into metabolic processes. Research indicates that chlorophyll content in leaves elevates following the addition of zinc, which serves as a crucial element for synthesising plant pigments by acting as a cofactor for enzymes and proteins, in addition to stimulating numerous physiological processes within plant cells. It can enhance the chlorophyll content of leaves when plants encounter various environmental challenges, including salinity [14, 16, 23]. This aligns with the findings established by [2, 4].

ZnO-NPs enhance nitrogen absorption by stimulating the nitrate reduction enzyme cascade ($NR \rightarrow GS \rightarrow GOGAT$), so facilitating the transformation of nitrate into ammonium and the subsequent synthesis of amino acids. Zinc ions (Zn^{2+}) serve as cofactors for primary enzymes, enhance root architecture, and augment the capacity to absorb greater quantities of nitrogen and transport it to the leaves, thus elevating their nitrogen content (Table 2). They enhance the capacity of roots to assimilate phosphorus, potassium, and zinc, as elucidated by [23, 27], and corroborate the findings of [12].

ZnO-NPs enhance phosphorus availability (Table 3) and augment its absorption by stimulating the activity of phosphatase produced by the roots, facilitating the mobilisation of organic phosphorus in the root zone. Zinc serves as a cofactor for phosphate transport proteins and is crucial for enhancing root development and augmenting the surface area for absorption. [25] cited this study, and [14] corroborated it.

[25] and [26] indicated that zinc oxide nanoparticles enhance potassium equilibrium by activating H^+ -ATPase pumps in root membranes, thereby stimulating potassium channel activity. They also maintain cell membrane integrity by minimising potassium

efflux from cells. Furthermore, the enhancement of photosynthesis and the sequestration of the resultant carbon generate additional energy that facilitates the transfer of active potassium, thus increasing its concentration in leaves. The results presented in Table 4 support this and are consistent with the findings of [36].

[39] noted that the significant increase in zinc levels in the leaves (Table 5) following the application of ZnO-NPs can be attributed to the rapid ion release (Zn^{2+}) from nano-zinc, which modulates various physiological, biochemical, and molecular processes that promote the orderly and beneficial growth of the plant. When directly sprayed onto seedlings, the nanoparticles are readily absorbed, leading to enhanced availability and accumulation proportional to the concentration used during application. This interpretation is consistent with the assertions made by [14].

Prior research has demonstrated that zinc oxide nanoparticles can enhance carbohydrate accumulation in leaves (see Table 6) by improving photosynthesis, thereby increasing levels of fixed carbon. The Zn^{2+} ion acts as a cofactor for the enzyme Carbonic Anhydrase (CA), which catalyses the conversion of CO_2 and H_2O into HCO_3^- and H^+ . This process aids in providing carbon to the RuBisCO enzyme, which is crucial for initiating carbon fixation. Additionally, zinc oxide nanoparticles improve the regulation of carbon-assimilation enzymes within the Calvin cycle and facilitate sugar transport by activating the enzyme Sucrose synthase (SuSy). These effects significantly augment carbohydrate accumulation in plant leaves and contribute to increased seedling biomass [19, 35].

The augmentation of beta-carotene pigment in plant flowers (Table 7) following the application of zinc nanoparticles may be attributed to its function in activating enzymes that synthesise secondary metabolites, resulting in the production of diverse substances including phenols, chlorophyll, and carotenoids [5]. [16] and [24] established that

zinc is a crucial cofactor in the Methylerythritol phosphate route (MEP pathway), supplying the necessary substances for carotenoid production. ZnO-NPs augment the activity of the Phytoene synthase (PSY) enzyme, which initiates carotenoid production. It aids in preserving plastids and establishing more stable circumstances for the plant to accumulate beta-carotene in bract tissues. The elevated concentration of beta-carotene intensifies the hue of the bracts and augments their visual appeal. The findings aligned with the conclusions drawn by [1].

5. Conclusions

The simultaneous application of 5-ALA (50 mg L^{-1}) and ZnO-NPs (75 mg L^{-1}) (A_3Z_2) led to improved vegetative, root, floral, and chemical growth and development of dwarf *Bougainvillea* seedlings. This superiority results from the synergistic interaction between the two agents, which augmented plant physiological activity, improved nutrient uptake and transport, and facilitated the synthesis of key chemicals and compounds involved in plant tissue growth, hence boosting plant dry weight. Moreover, it enhanced floral and chemical attributes, facilitated the activation and control of physiological and biochemical processes along with their corresponding enzymes pertinent to plant growth and development, and augmented stress tolerance. The application of distilled water to dwarf *Bougainvillea* seedlings yielded the least significant variations in all chemical growth variables when compared to treatments utilising either or both chemicals.

6. References

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