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Growth modulation in *Swietenia macrophylla*: Role of salicylic and Jasmonic acids in seedling development

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Abstract

Climate change poses severe challenges to ecosystems, agriculture, and forestry by intensifying extreme weather events like droughts, floods, and heat waves, compromising plant health, productivity, and ecosystem stability. In response to these stresses, plants activate intricate defense mechanisms that mitigate damage and facilitate adaptation to adverse conditions. The defense hormones like Jasmonic Acid (JA) and Salicylic Acid (SA) play a vital role in enhancing plant resilience by regulating the expression of stress-related genes, promoting the production of protective proteins, and initiating physiological adjustments that optimize water-use efficiency and sustain cellular balance. This study investigated the effects of defense hormones, JA and SA, on mahogany seedlings, a species valued for its rapid growth, high-quality wood, workability, and durability. The effects of various concentrations of JA and SA on the growth and development of six-month-old mahogany seedlings were investigated. Seedlings were treated with foliar applications of JA and SA at six different concentrations (0.2 mM, 0.4 mM, 0.6 mM, 0.8 mM, 1 mM and control), with measurements taken every 30 days over a 150-day period. The results indicated that JA at 0.6 mM (T₄) and SA at 0.8 mM (T₅) were the most effective treatments, leading to optimal growth performance. These treatments significantly enhanced overall plant vigor, promoting stability as indicated by the sturdiness quotient and improving seedling quality. The findings demonstrate the potential of JA and SA in enhancing mahogany growth, particularly under stress conditions, highlighting their promising applications in forestry practices.

Keywords: Defense hormones, Jasmonic Acid (JA), Salicylic Acid (SA), Abiotic stress, *Swietenia macrophylla*

1. Introduction

Swietenia macrophylla King, commonly referred to as Indian Mahogany, is one of the most commercially valuable timber tree species in neo-tropical forests, renowned for its rapid growth, fine timber quality, and adaptability to diverse environmental conditions (Lugo *et al.*, 2002). Native to tropical regions of America, Mahogany has been extensively cultivated in India since its introduction in 1795 (Anoop *et al.*, 2014) [2]. Its resilience to varying soil types, including alluvial, volcanic, and lateritic soils, coupled with its high demand in the timber industry, has made it a primary species for afforestation projects in regions like Kerala, Tamil Nadu, and Karnataka (Durai *et al.*, 2017) [12]. Mahogany is often intercropped with agricultural crops, enhancing biodiversity and improving soil fertility through leaf litter decomposition. Its deep-rooting system helps reduce soil erosion, making it an excellent choice for sustainable land management (Reis *et al.*, 2019) [27]. Furthermore, Mahogany plantations contribute to carbon sequestration, aiding in climate change mitigation efforts (Racelis *et al.*, 2019) [24].

Despite its adaptive traits, mahogany growth and productivity are often constrained by abiotic stressors such as drought and salinity, which are becoming increasingly prevalent due to climate change (Rahman *et al.*, 2013) [25]. These stressors disrupt cellular homeostasis, with drought, in particular, leading to cellular dehydration, which triggers secondary stresses, such as osmotic and oxidative stress. These conditions elevate reactive oxygen species (ROS) levels, detrimental to membrane integrity and macromolecular functionality (Ghosh *et al.*, 2014) [16]. Salinity compounds these challenges by restricting water uptake and nutrient availability, further inhibiting the plant's overall growth and yield (Deshmukh *et al.*, 2017) [10].

Plants have evolved sophisticated defense mechanisms to mitigate the adverse effects of abiotic stress. These mechanisms involve the perception and transduction of stress signals, regulating stress-responsive genes, and making metabolic adjustments (Zhang *et al.*, 2022) [38]. According to Chaves *et al.* (2003) [6], plants undergo several phases during stress response, including alarm, acclimation, resistance, and exhaustion, ultimately leading to recovery or death if stress is sustained. The plant hormone Absciscic Acid (ABA) is a critical mediator in drought tolerance, modulating gene expression and stress-responsive pathways. Drought-induced ABA synthesis activates SnRK2 protein kinases, pivotal in regulating the stomatal aperture and conserving water by reducing transpiration (Yoshida *et al.*, 2002; Li *et al.*, 2015) [36]. In addition to ABA, Jasmonic Acid (JA) and Salicylic Acid (SA) play vital roles in modulating plant responses to various abiotic stresses.

JA is synthesized in plastids, peroxisomes, and the cytosol, is essential in stress tolerance (Ahmad *et al.* 2016) [1]. During stress, JA signaling is regulated by the degradation of Jasmonate ZIM-domain (JAZ) proteins, enabling the transcription of genes involved in stress defense (Chini *et al.*, 2007) [7]. The application of exogenous JA has shown promising results in enhancing salt tolerance, as demonstrated by Faghieh *et al.* (2017) [14], where 0.25 mM of Methyl Jasmonate (MeJA) improved the salt tolerance of strawberry seedlings under saline conditions (60 mM NaCl). Similarly, Salicylic Acid is instrumental in drought and salt stress tolerance. Elevated SA levels inhibit stomatal opening, reducing water loss under drought conditions (Sun *et al.*, 2021) [32]. Exogenous application of SA has been shown to enhance plant resilience to salt stress. In mungbean, the application of 0.5 mM SA conferred significant tolerance to 100 mM NaCl, highlighting SA's potential in stress mitigation (Esther *et al.*, 2023) [13]. However, the concentration of SA is crucial, as both excessively low and high levels can increase susceptibility to stress. In contrast, moderate concentrations (0.01 mM to 0.05 mM) offer optimal stress protection (Yuan *et al.*, 2008) [37]. Understanding how these hormones modulate plant growth and stress responses in forestry species like mahogany is critical for developing effective strategies for plantation management under challenging environmental conditions. This study investigates the influence of exogenous applications of Salicylic Acid and Jasmonic Acid on the growth and development of mahogany seedlings, with a focus on key growth parameters such as plant height, biomass allocation, photosynthetic efficiency, and water use. By elucidating the role of these defense hormones in enhancing abiotic stress tolerance, this research aims to contribute to the optimization of forestry practices and the resilience of mahogany plantations amidst changing climatic conditions.

2. Materials and Methods

2.1 Location of the experimental site

This study was conducted at the College of Forestry, Kerala Agricultural University, Vellanikkara, Kerala, India (13° 32'N, 76° 26'E), from July 2023 to September 2024, under the Department of Forest Biology and Tree Improvement. The site experiences a warm, humid climate with an average annual rainfall of 2100–2500 mm, temperatures ranging from 24.4 °C to 42.8 °C, and relative humidity of 80–100%.

2.2. Treatments and Experimental Design

The experiment was conducted using a Completely Randomized Design (CRD) with six treatments comprising different concentrations of Salicylic Acid (SA) and Jasmonic Acid (JA) (Table 1). Each treatment had three replications, with five plants per replication. Six-month-old mahogany seedlings were subjected to foliar applications of the defense hormones, administered twice with a two-day interval, between 9:00 AM and 11:00 AM to maximize absorption and minimize evaporation. A control group was included to establish a baseline for comparison. The study aimed to identify the optimal concentrations of SA and JA that promote enhanced growth and development in mahogany seedlings.

Table 1: Concentrations of defense hormones applied in the study:

Treatments	JA (mM)	SA (mM)
T ₁	Control	Control
T ₂	0.2	0.2
T ₃	0.4	0.4
T ₄	0.6	0.6
T ₅	0.8	0.8
T ₆	1	1

2.2 Observations

2.2.1 Morphological observations

Morphological and physiological parameters were recorded five days after hormone application and subsequently at 30-day intervals for 150 days to evaluate and standardize hormone concentrations based on growth and physiological responses. The morphological parameters measured included seedling height (cm), collar diameter (cm), number of leaves, and root-to-shoot ratio.

2.2.1.1 Volume increase index (cm³)

The volume index of each seedling was calculated for both initial and final observations using the formula:

$$\text{Volume index} = d^2h$$

Where d is the collar diameter (cm) and h is the seedling height (cm).

2.2.1.2 Sturdiness quotient

The sturdiness quotient was determined as the indicator of the strength of the seedlings to adverse climatic conditions (Ritchie, 1984).

$$\text{Sturdiness Quotient} = \frac{\text{Shoot length (cm)}}{\text{Collar diameter (cm)}}$$

2.2.1.3 Seedling quality index

Dickson *et al.*, (1960) [11] gave the formula to calculate seedling quality based on morphological traits and seedling biomass.

$$\text{Seedling Quality Index} = \frac{\text{Total seedling dry weight (g)}}{\left(\frac{\text{Plant height (cm)}}{\text{Collar diameter (cm)}} \right) + \left(\frac{\text{Shoot dry weight (g)}}{\text{Root dry weight (g)}} \right)}$$

2.2.2 Physiological observations

Physiological parameters such as photosynthetic rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and transpiration rate ($\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$) were measured on the third leaf from the tip using a portable IRGA (LI-6400) system. Total chlorophyll content (mg g^{-1})

FW) was estimated using the DMSO method developed by Hiscox and Israelstam (1979) [18], and relative water content (RWC %) was determined following the method described by Barrs (1968) [4].

The morphological and physiological data were analyzed using ANOVA via the General Linear Model (GLM) procedure in R (v4.3.1) to assess treatment significance. Least Square Difference (LSD) tests compared treatment means across growth stages, and Duncan's Multiple Range Test (DMRT) identified significant variations. Hierarchical cluster analysis, performed using Average Linkage with Euclidean Distance, grouped treatments into clusters, with dendrograms and interclass distances visualized via the 'agricolae' package. This integrated approach comprehensively evaluated the effects of JA and SA on seedling growth and physiology.

3. Results and Discussion

Evaluating morphological and physiological parameters in mahogany seedlings over 150 days revealed the impact of JA and SA on growth dynamics. Optimal concentrations of JA and SA significantly enhanced seedling height, collar diameter, photosynthetic efficiency, and chlorophyll content, contributing to improved vigor and stress tolerance. These findings align with studies showing that exogenous application of SA and JA boosts plant growth by enhancing nutrient uptake, optimizing photosynthesis, and activating stress response mechanisms (Rivas-San Vicente & Plasencia, 2011; Monte, 2023) [29, 22].

3.1. Effect of exogenous application of JA and SA on the morphological parameters of the mahogany seedlings

3.1.1. Seedling height (cm)

Exogenous application of JA and SA significantly enhanced seedling height in mahogany. JA at 0.6 mM and SA at 0.8 mM resulted in 158.87% and 139.62% growth after 150 days, respectively (Fig.1). In contrast, the control groups showed lower growth, with JA and SA controls increasing by 74.13% and 69.38%, respectively (Table. 2,3). This growth enhancement is attributed to the role of JA and SA in regulating plant growth through mechanisms such as cell elongation, division, and nutrient allocation (Rohwer & Erwin, 2008) [30]. However, higher concentrations (1.0 mM) inhibited growth, underscoring the importance of precise hormone application to avoid disrupting metabolic processes (Wang *et al.*, 2020) [34]. These findings highlight the effectiveness of optimal hormone concentrations in promoting seedling growth.

3.1.2 Collar diameter (mm)

Defense hormones significantly influenced collar diameter in mahogany seedlings. JA at 0.6 mM (T₅) caused the greatest increase (180.53%, 11.53 mm), while SA at 0.8 mM led to a 146.93% rise (10.63 mm). Controls showed lower growth (75.24% for JA, 74.02% for SA). Higher and lower concentrations inhibited growth, indicating a critical range for optimal development (Table. 2,3). JA enhances vascular development, while SA promotes growth through ROS signaling. However, excessive ROS at high concentrations can inhibit growth, emphasizing the need for precise hormone regulation (Rivas-San Vicente & Plasencia, 2011; Wang *et al.*, 2020; Zhang *et al.*, 2023) [29, 39, 34].



Fig 1: Height increment(cm) under different treatments of defense hormones; A. Height(cm) increase after 45 days of JA treatment, B. Height increase after 150 days of JA treatment, C. Height increase after 150 days of SA treatment.

3.1.3 Number of leaves

JA and SA treatments significantly increased the number of leaves in mahogany seedlings, with optimal concentrations of 0.4 mM JA (221.70%, 39 leaves) and 0.8 mM SA (210.69%, 41 leaves) promoting the highest leaf development (Table. 2, 3). This increase is attributed to the crosstalk between defense hormones and auxin, which stimulates cell division and leaf formation (Pauwels & Goossens, 2011) [23]. Enhanced photosynthetic performance further supports growth by providing energy and resources (Khan *et al.*, 2015) [19].

3.1.4 Biomass accumulation

Biomass accumulation is a critical factor for assessing plant growth and overall health, particularly in terms of fresh and dry weight in Mahogany seedlings. After 150 days, the optimal hormone concentrations for biomass accumulation were observed with specific treatments of Jasmonic Acid (JA) and Salicylic Acid (SA). JA at 0.6 mM (T₄) resulted in the highest fresh weight of 38.71 g and dry weight of 18.32 g, reflecting substantial biomass accumulation (Fig 1). SA at 0.8 mM (T₅) also showed significant growth with a fresh weight of 35.32 g and dry weight of 15.19 g, outperforming both control and other concentrations. However, excessive hormone concentrations, like 1.0 mM of either JA or SA, led to reduced biomass accumulation, highlighting a threshold beyond which hormone application may be counterproductive. This suggests that hormone-induced growth is most effective within an optimal concentration range, promoting cell division and elongation, which is essential for biomass accumulation (Pauwels & Goossens, 2011) [23].

3.2 Seedling quality parameters

Assessing seedling quality is crucial for evaluating their outplanting potential and overall survival. Total seedling height is often considered a key factor among various quality indicators, correlating with the plant's overall vigor. Seedlings with larger shoot mass typically have a higher photosynthetic capacity and better growth potential. However, shoot mass must be balanced with root mass to ensure optimal seedling performance. Larger root masses promote healthier growth and improved survival rates, as roots are crucial for nutrient and water uptake. It is also important to recognize that root mass does not always indicate root fibrosity; a seedling with numerous fine roots may have a similar mass to one with a larger taproot. The

shoot-to-root ratio, which reflects the balance between the transpiring area (shoot) and the water-absorbing area (root),

is an important measure of seedling quality (Haase, 2007; Smith *et al.*, 2012) [17, 31].

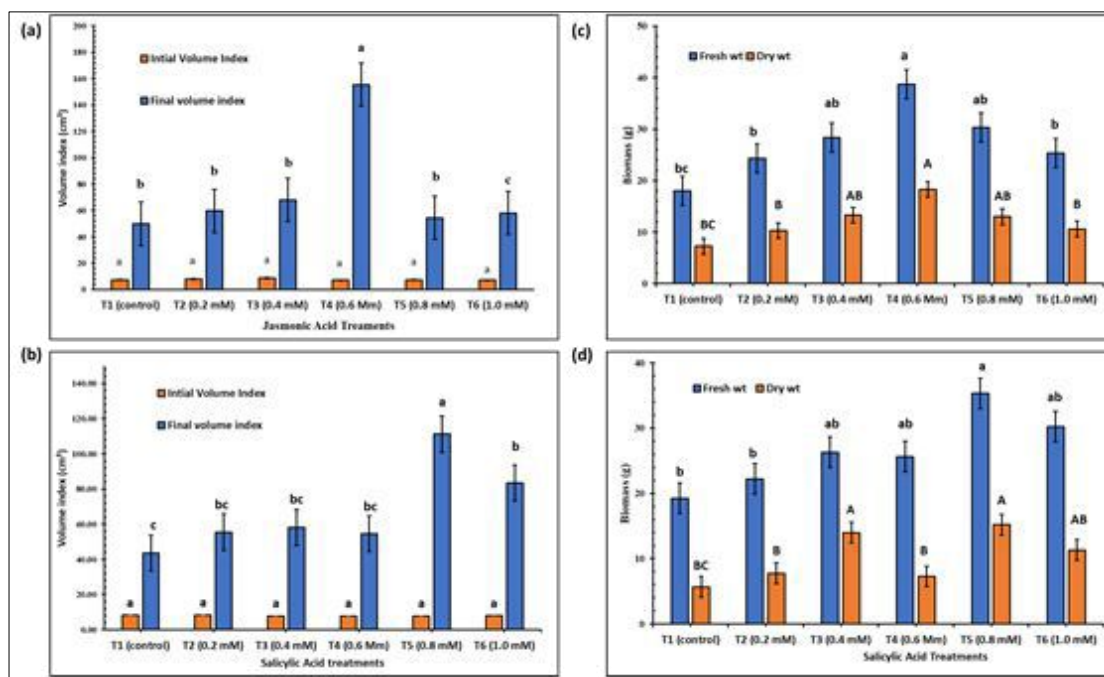


Fig 2: Effect of exogenous application of defense hormones on the volume increment (cm^3) and biomass accretion in Mahogany seedlings a, b). Initial and final volume increment (cm^3) for JA and SA, respectively. c,d). Biomass accumulation in terms of fresh weight and dry weight (g) for JA and SA respectively.

Table 2: Effect of JA on the increment of height (cm), collar diameter (mm), and average number of leaves in mahogany seedlings

Parameter	Treatment/Days	T ₁ (control)	T ₂ (0.2 mM)	T ₃ (0.4 mM)	T ₄ (0.6 mM)	T ₅ (0.8 mM)	T ₆ (1.0 mM)	CD	P-value
Height (cm)	Initial	41.78	42.33	42	41.11	42.89	40.22	NS	>0.05
	30D	47.16 ^c	52.87 ^b	56.13 ^b	69.04 ^a	54.12 ^b	50.91 ^{bc}	5.681	<0.05
	60D	53.11 ^d	62.33 ^{bc}	68.28 ^b	86.15 ^a	64.02 ^{bc}	57.41 ^{cd}	6.987	<0.05
	90D	59.64 ^d	67.00 ^{cd}	77.51 ^b	94.29 ^a	73.08 ^{bc}	64.15 ^{cd}	8.777	<0.05
	120D	67.87 ^d	75.04 ^{bcd}	81.92 ^b	97.07 ^a	78.92 ^{bc}	71.88 ^{cd}	8.648	<0.05
	150D	72.75 ^d	81.71 ^{bc}	86.28 ^b	106.42 ^a	81.43 ^{bc}	77.69 ^{cd}	6.541	<0.05
	Percentage increase	74.13%	93.03%	105.43%	158.87%	89.86%	93.16%		
Collar diameter (mm)	Initial	4.2	4.33	4.39	4.11	4.11	4.13	NS	>0.05
	30D	4.83	4.98	5.05	4.72	4.71	4.75	NS	>0.05
	60D	5.94	6.23	6.32	5.9	5.89	6.04	0.971	<0.05
	90D	6.84 ^b	7.16 ^b	7.27 ^{ab}	8.39 ^a	6.77 ^b	6.95 ^b	1.165	<0.05
	120D	7.04 ^c	8.28 ^b	8.40 ^{ab}	9.69 ^a	7.83 ^b	8.04 ^b	1.347	<0.05
	150D	7.36 ^c	8.40 ^{ab}	9.42 ^b	11.53 ^a	8.04 ^{ab}	8.12 ^{ab}	1.452	<0.05
	Percentage increase	75.24%	94.15%	114.58%	180.53%	95.56%	96.49%		
Number of leaves	Initial	13.67	13.22	12.11	14.33	14.78	14.67	NS	>0.05
	30D	15.53 ^c	16.26 ^{bc}	16.83 ^{bc}	21.36 ^a	20.39 ^{ab}	19.36 ^{abc}	4.139	<0.05
	60D	21.66 ^c	22.69 ^{bc}	23.48 ^{bc}	29.79 ^a	28.45 ^{ab}	27.01 ^{abc}	5.774	<0.05
	90D	25.20 ^c	28.50 ^{bc}	29.50 ^{bc}	37.42 ^a	35.73 ^{ab}	33.92 ^{abc}	7.253	<0.05
	120D	27.24 ^b	32.60 ^b	36.13 ^{ab}	40.13 ^a	34.70 ^{ab}	34.85 ^{ab}	5.535	<0.05
	150D	29.65 ^c	35.62 ^{bc}	38.96 ^{ab}	43.38 ^a	37.28 ^{bc}	38.34 ^{ab}	5.226	<0.05
	Percentage increase	116.96%	169.39%	221.70%	202.65%	152.27%	161.42%		

Significant at 0.05 levels; NS- non significant at 0.05 levels

Values with similar superscripts along the column do not differ significantly

Table 3: Effect of SA on the increment of height (cm), collar diameter (mm) and average number of leaves in mahogany seedlings

Parameters	Treatment/Days	T ₁ (control)	T ₂ (0.2 mM)	T ₃ (0.4 mM)	T ₄ (0.6 mM)	T ₅ (0.8 mM)	T ₆ (1.0 mM)	CD	P-value
Height	Initial	41.77	42.66	46.11	41.11	42	44.55	NS	>0.05
	30D	47.15 ^c	48.33 ^{bc}	52.70 ^b	48.92 ^{bc}	58.17 ^a	57.92 ^a	4.244	<0.05
	60D	53.11 ^c	54.40 ^c	59.02 ^{bc}	54.79 ^{bc}	76.39 ^a	65.59 ^b	5.573	<0.05
	90D	59.64 ^e	61.62 ^{de}	65.66 ^{cd}	68.49 ^c	85.78 ^a	75.74 ^b	5.633	<0.05
	120D	65.47 ^d	67.87 ^{cd}	69.12 ^{cd}	74.65 ^c	93.39 ^a	82.55 ^b	6.952	<0.05
	150D	70.75 ^d	75.28 ^{cd}	79.44 ^{bcd}	83.22 ^{bc}	100.64 ^a	87.42 ^b	8.675	<0.05
	Percentage increase	69.38%	76.47%	72.28%	102.43%	139.62%	96.23%		
Collar diameter	Initial	4.25	4.39	4.26	4.34	4.3	4.2	NS	>0.05
	30D	4.48	4.43	4.59	4.95	5.12	5.13	NS	>0.05
	60D	4.80 ^c	4.99 ^{bc}	5.30 ^{abc}	5.35 ^{abc}	6.01 ^a	5.70 ^{ab}	0.712	<0.05
	90D	5.23 ^c	5.77 ^{abc}	5.85 ^{bc}	6.20 ^{abc}	7.25 ^a	6.60 ^{ab}	0.828	<0.05
	120D	5.65 ^c	6.14 ^{bc}	6.63 ^{bc}	6.89 ^{bc}	8.48 ^a	7.46 ^{ab}	0.854	<0.05
	150D	7.59 ^c	7.89 ^{bc}	8.02 ^b	8.48 ^b	10.63 ^a	9.82 ^{ab}	0.892	<0.05
	Percentage increase	74.02%	79.73%	88.35%	95.18%	146.93%	133.81%		
Number of leaves	Initial	14.33	13.11	13.44	13	13.11	13	NS	>0.05
	30D	17.47 ^{ab}	15.42 ^{ab}	14.96 ^b	17.59 ^{ab}	18.82 ^{ab}	19.15 ^a	3.62	<0.05
	60D	23.76 ^{abc}	20.97 ^{bc}	23.93 ^{abc}	20.34 ^c	25.59 ^{ab}	26.05 ^a	4.921	<0.05
	90D	25.77 ^c	28.51 ^{bc}	29.31 ^{abc}	27.66 ^{bc}	34.80 ^a	32.27 ^{ab}	5.51	<0.05
	120D	28.00 ^b	32.08 ^{ab}	32.10 ^{ab}	31.12 ^{ab}	31.00 ^{ab}	34.35 ^a	5.454	<0.05
	150D	29.68 ^b	32.90 ^b	34.10 ^b	31.92 ^b	40.74 ^a	35.77 ^{ab}	6.168	<0.05
	Percentage increase	107.07%	150.93%	153.61%	145.54%	210.69%	175.15%		

Significant at 0.05 levels; NS- non significant at 0.05 levels

Values with similar superscripts along the column do not differ significantly

3.2.1 Volume index

Height and collar diameter are key indicators of volume increment, crucial for assessing growth and biomass accumulation in mahogany seedlings. After 150 days, optimal growth was observed with specific JA and SA concentrations. JA at 0.6 mM (T₄) resulted in the highest volume at 155.48 cm³, while SA at 0.8 mM (T₅) yielded 111.17 cm³. Control and higher hormone concentrations (1.0 mM) showed minimal growth, indicating that excessive hormone levels may hinder development (Fig 2). JA and SA promote cell division and elongation, especially in the apical meristem and cambium, facilitating vertical growth and collar expansion through enhanced auxin transport (Pauwels & Goossens, 2011) [23].

3.2.2 Sturdiness Quotient

The sturdiness quotient, reflecting seedling stability and stress resilience, is influenced by JA and SA concentrations. JA enhances sturdiness by promoting lignin biosynthesis and cell wall fortification, with the highest quotient at 0.6 mM due to optimal structural reinforcement (Wasternack & Hause, 2013) [35]. Higher concentrations (1.0 mM) overstimulate stress pathways, reducing sturdiness (Fig.3). Similarly, SA strengthens cell wall integrity, with the highest sturdiness at 0.8 mM, balancing growth and defense (Vlot *et al.*, 2009) [33]. Excessive SA (1.0 mM) reduces sturdiness, likely due to toxicity.

3.2.3 Seedling quality index

The seedling quality index, which reflects plant vigor and survival potential, is influenced by JA and SA concentrations. JA enhances seedling quality by improving nutrient uptake and photosynthetic efficiency, with the highest index at 0.6 mM, where growth and stress responses were optimally balanced (Pauwels & Goossens, 2011) [23]. Higher concentrations (1.0 mM) triggered stress responses, reducing quality. SA also improved seedling vigor, with the highest index at 0.8 mM (Khan *et al.*, 2015) [19], while excessive SA (1.0 mM) led to diminished returns due to stress-induced growth inhibition.

3.3. Effect of exogenous application of JA and SA on the physiological parameters of the mahogany seedlings

Exogenous applications of JA and SA significantly enhanced various physiological parameters in mahogany seedlings, promoting growth and metabolic activity. Photosynthesis in mahogany seedlings was significantly enhanced with JA and SA application. JA at 0.6 mM (T₄) achieved peak rates of 3.78 μmol CO₂ m²/s by day 120, while the control group (T₁) declined from 2.55 to 2.14 μmol CO₂ m²/s. SA at 1.0 mM (T₆) reached 4.50 μmol CO₂ m²/s on day 30, with lower concentrations showing moderate improvements. However, a decrease in rates towards the end of the evaluation period was likely due to heat stress and reduced hormone efficacy after 120 days (Table 4.5).

JA and SA significantly enhanced the transpiration rate of mahogany seedlings, which is vital for water balance and gas exchange. JA at 0.6 mM (T₄) peaked at 0.178 mmol H₂O m²/s at 30 days and 0.145 mmol H₂O m²/s at 120 days, while the control group (T₁) decreased from 0.086 to 0.078 mmol H₂O m²/s. SA at 0.8 mM (T₅) reached 0.177 mmol H₂O m²/s at 30 days and 0.142 mmol H₂O m²/s at 120 days.

Both hormones promoted stomatal opening and modulated aquaporin expression, enhancing water transport and improving water regulation, growth, and stress resilience in seedlings (Curticăpean, 2020).

Both hormones also improved Relative Water Content (RWC), with SA at 0.8 mM showing the highest RWC of 86.68% at 30 days, which gradually decreased over time (Wang *et al.*, 2020; Khoshbakht, 2015) [34]. Lastly, total chlorophyll content was significantly higher in JA at 0.6 mM and SA at 0.8 mM, contributing to enhanced photosynthetic efficiency and plant health (Rehman, 2023; Farhangi-Abriz *et al.*, 2018). These findings highlight the potential of JA and SA in improving physiological performance, hydration, and stress resilience in mahogany seedlings.

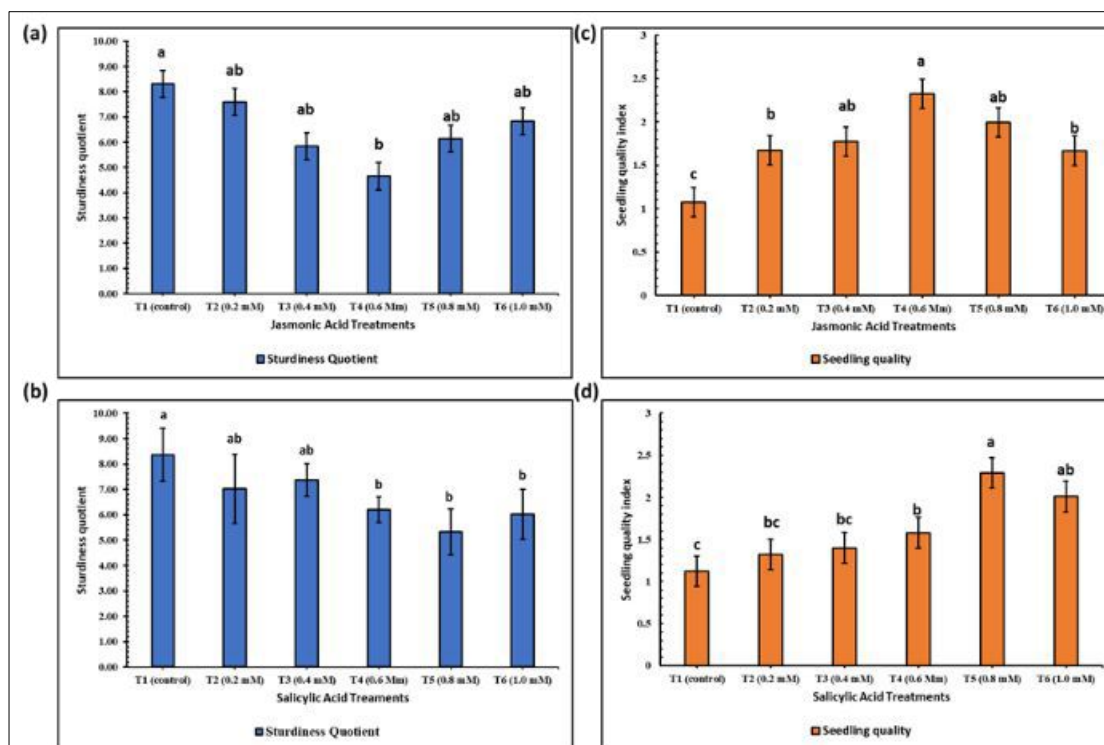


Fig 3: Effect of exogenous application of defense hormones on the seedling characteristics in Mahogany seedlings a, b). Sturdiness quotient for JA and SA, respectively. c, d). Seedling quality index for JA and SA, respectively.

Table 4: Effect of JA on the physiological parameters in mahogany seedlings

Parameter	Treatment/ Days	T ₁ (control)	T ₂ (0.2 mM)	T ₃ (0.4 mM)	T ₄ (0.6 mM)	T ₅ (0.8 mM)	T ₆ (1.0 mM)	CD	P-value
Photosynthetic rate ($\mu\text{mol CO}_2 \text{ m}^{-2}/\text{s}$)	Initial	2.55	2.72	2.69	2.46	2.85	2.74	NS	>0.05
	30D	2.99 ^c	3.30 ^{ab}	3.11 ^{bc}	3.43 ^a	3.29 ^{ab}	3.37 ^{ab}	0.273	<0.05
	60D	2.72 ^c	3.07 ^{ab}	2.76 ^c	3.23 ^a	2.89 ^{bc}	2.96 ^{bc}	0.247	<0.05
	90D	2.78 ^c	3.14 ^b	3.10 ^b	3.67 ^a	2.96 ^{bc}	3.07 ^b	0.262	<0.05
	120D	2.87 ^c	3.24 ^b	3.20 ^b	3.78 ^a	3.06 ^{bc}	3.17 ^b	0.271	<0.05
	150D	2.14 ^{bc}	2.01 ^c	2.24 ^b	2.65 ^a	2.27 ^b	2.22 ^b	0.189	<0.05
Transpiration rate ($\text{mmol H}_2\text{O m}^{-2}/\text{s}$)	Initial	0.086	0.091	0.087	0.094	0.084	0.086	NS	>0.05
	30D	0.122 ^d	0.148 ^{bc}	0.143 ^c	0.178 ^a	0.160 ^b	0.153 ^{bc}	0.012	<0.05
	60D	0.111 ^d	0.135 ^{bc}	0.131 ^c	0.163 ^a	0.146 ^b	0.140 ^{bc}	0.010	<0.05
	90D	0.116 ^d	0.141 ^{bc}	0.136 ^c	0.170 ^a	0.152 ^b	0.146 ^{bc}	0.011	<0.05
	120D	0.099 ^d	0.120 ^{bc}	0.117 ^c	0.145 ^a	0.130 ^b	0.124 ^{bc}	0.009	<0.05
	150D	0.078 ^{ab}	0.073 ^{ab}	0.071 ^b	0.079 ^a	0.077 ^{ab}	0.078 ^{ab}	0.007	<0.05
Relative water content (%)	Initial	54.56	52.89	57.44	58.89	57.11	57	NS	>0.05
	30D	63.96 ^b	74.50 ^a	79.21 ^a	80.62 ^a	73.94 ^a	75.77 ^a	7.401	<0.05
	60D	58.30 ^c	64.52 ^{ab}	66.46 ^a	67.78 ^a	60.23 ^{bc}	66.69 ^a	4.857	<0.05
	90D	62.44 ^b	73.20 ^a	70.23 ^a	73.14 ^a	67.61 ^a	68.22 ^a	5.636	<0.05
	120D	64.77 ^c	69.76 ^{bc}	72.28 ^{ab}	76.74 ^a	72.71 ^{ab}	69.97 ^{bc}	5.726	<0.05
	150D	60.23 ^d	65.25 ^{bcd}	66.85 ^{abc}	72.07 ^a	69.17 ^{ab}	63.65 ^{cd}	4.969	<0.05
Total chlorophyll (mg g^{-1})	Initial	3.121	2.941	2.863	3.191	3.084	3.075	NS	>0.05
	30D	3.434 ^{bcd}	3.294 ^{cd}	3.206 ^d	4.212 ^a	3.855 ^{ab}	3.690 ^{bc}	0.426	<0.05
	60D	2.747 ^c	2.635 ^{cd}	2.565 ^d	3.370 ^a	3.084 ^{ab}	2.952 ^{bc}	0.341	<0.05
	90D	3.478 ^{cd}	3.626 ^{bcd}	3.386 ^d	4.448 ^a	4.070 ^{ab}	3.897 ^{bc}	0.45	<0.05
	120D	3.746	3.529	3.435	3.83	3.7	3.69	NS	>0.05
	150D	2.809	2.647	2.576	2.872	2.775	2.768	NS	>0.05

Significant at 0.05 levels; NS- non significant at 0.05 levels

Values with similar superscripts along the column do not differ significantly

Table 5: Effect of SA on the physiological parameters in mahogany seedlings

Parameter	Treatment/ Days	T ₁ (control)	T ₂ (0.2 mM)	T ₃ (0.4 mM)	T ₄ (0.6 mM)	T ₅ (0.8 mM)	T ₆ (1.0 mM)	CD	P-value
Photosynthetic rate ($\mu\text{mol CO}_2 \text{ m}^{-2}/\text{s}$)	Initial	2.54	2.39	2.44	2.19	2.27	2.42	NS	>0.05
	30D	3.13 ^c	3.41 ^{bc}	3.18 ^c	3.10 ^c	3.84 ^b	4.50 ^a	0.616	<0.05
	60D	2.30 ^c	2.51 ^{bc}	2.83 ^b	2.28 ^c	3.31 ^a	2.34 ^c	0.453	<0.05
	90D	2.50 ^c	2.73 ^{bc}	2.54 ^c	2.48 ^c	3.07 ^b	3.60 ^a	0.492	<0.05
	120D	2.66 ^c	2.90 ^{bc}	2.63 ^c	2.70 ^c	3.27 ^b	3.83 ^a	0.524	<0.05
	150D	2.53 ^c	2.75 ^{bc}	2.50 ^c	2.57 ^c	3.64 ^a	3.10 ^b	0.497	<0.05
Transpiration rate ($\text{mmol H}_2\text{O m}^{-2}/\text{s}$)	Initial	0.091	0.097	0.093	0.091	0.092	0.095	NS	>0.05
	30D	0.113 ^d	0.124 ^{cd}	0.126 ^c	0.123 ^{cd}	0.177 ^a	0.154 ^b	0.012	<0.05
	60D	0.095 ^b	0.096 ^b	0.093 ^b	0.095 ^b	0.122 ^a	0.114 ^a	0.009	<0.05
	90D	0.110 ^c	0.111 ^c	0.115 ^c	0.128 ^b	0.142 ^a	0.132 ^{ab}	0.01	<0.05
	120D	0.119 ^d	0.130 ^c	0.171 ^a	0.133 ^{bc}	0.142 ^b	0.137 ^{bc}	0.011	<0.05
	150D	0.101 ^d	0.110 ^{cd}	0.112 ^c	0.110 ^{cd}	0.158 ^a	0.137 ^b	0.011	<0.05
Relative water content (%)	Initial	62.9	64.18	67	65.21	69.69	69.69	NS	>0.05
	30D	69.38 ^c	72.12 ^{bc}	74.10 ^{bc}	73.23 ^{bc}	86.68 ^a	78.06 ^b	7.502	<0.05
	60D	58.97 ^d	61.30 ^{cd}	67.91 ^{bc}	64.01 ^{bcd}	78.01 ^a	68.84 ^b	6.615	<0.05
	90D	63.51 ^c	64.87 ^c	74.70 ^b	65.67 ^c	83.27 ^a	75.72 ^b	7.175	<0.05
	120D	56.46 ^b	57.67 ^b	66.41 ^a	58.38 ^b	68.28 ^a	67.31 ^a	6.333	<0.05
	150D	56.05	55.36	63.75	54.2	65.55	64.62	NS	>0.05
Total chlorophyll (mg g^{-1})	Initial	2.84	2.676	2.605	2.904	2.806	2.798	NS	>0.05
	30D	3.181 ^{bc}	2.997 ^c	3.152 ^{bc}	3.427 ^{ab}	3.704 ^a	3.414 ^{ab}	0.338	<0.05
	60D	2.668 ^c	2.831 ^{bc}	2.805 ^{bc}	3.050 ^{ab}	3.297 ^a	3.038 ^{ab}	0.3	<0.05
	90D	3.171 ^{bc}	2.988 ^c	3.142 ^{bc}	3.416 ^{ab}	3.692 ^a	3.403 ^{ab}	0.337	<0.05
	120D	3.025	2.85	2.774	3.093	2.988	2.98	0.287	<0.05
	150D	2.556 ^c	2.713 ^{bc}	2.688 ^{bc}	2.923 ^{ab}	3.159 ^a	2.912 ^{ab}	0.288	<0.05

Significant at 0.05 levels; NS- non significant at 0.05 levels

Values with similar superscripts along the column do not differ significantly

3.4 Hierarchical clustering

Hierarchical clustering based on treatment groups revealed distinct patterns of similarity and dissimilarity, with interclass distances indicating the degree of relatedness among treatments. Smaller distances reflected closer relationships, while larger distances signified greater differences. Under JA treatments, three clusters are formed with T₄ (0.6 mM) forming a unique cluster with a significant interclass distance, indicating a markedly distinct response. The control treatment T₁ constituted Cluster 2 with a moderate similarity to other treatments. Cluster 3 included T₂ (0.2 mM), T₃ (0.4 mM), and T₆ (1.0 mM), which

exhibited closely related responses. T₅ (0.8 mM) formed a separate cluster with a notable interclass distance, emphasizing its unique response.

The dendrogram showed T₁ (control) in Cluster 1 for SA treatments, distinctly separate from other treatments. T₅ (0.8 mM) formed Cluster 2, highlighting its unique response. Cluster 3 grouped T₂ (0.2 mM), T₃ (0.4 mM), T₄ (0.6 mM), and T₆ (1.0 mM) with smaller interclass distances, suggesting similar response patterns. Across both analyses, T₁ and T₅ consistently displayed distinct reactions, while other treatments showed closer relationships, underscoring varied response dynamics.

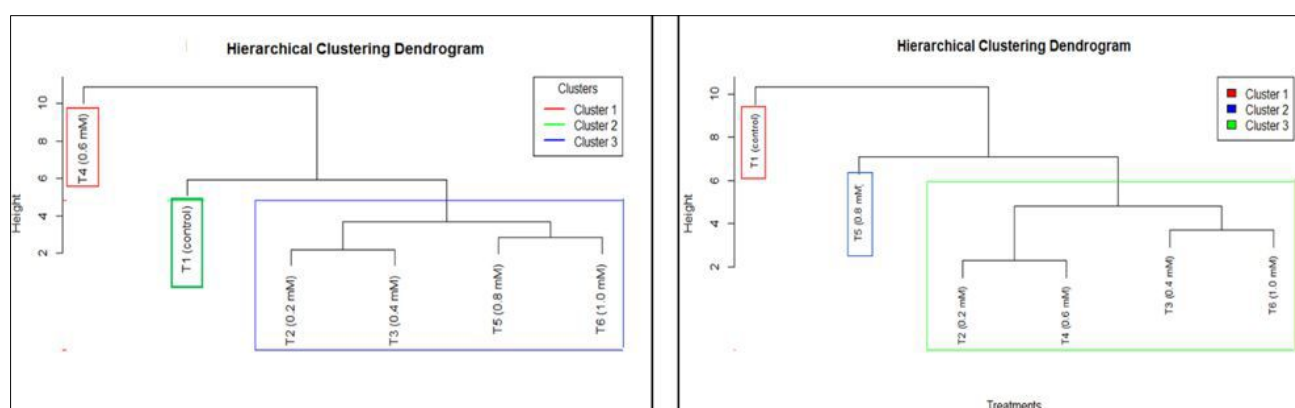


Fig 4: Dendrogram of hierarchical clustering based on morphological and physiological parameters in JA and SA treatment groups

4. Conclusion

The application of JA and SA significantly enhanced the growth of mahogany seedlings, highlighting their potential as effective growth regulators. The study identified optimal concentrations for maximizing growth benefits while minimizing adverse effects. JA performed best at 0.6 mM, while SA exhibited peak effectiveness at 0.8 mM. Both

lower and higher concentrations of these hormones negatively impacted growth parameters, underscoring the importance of precise optimization. Furthermore, these optimal concentrations can be applied to seedlings experiencing abiotic stress to alleviate stress effects and enhance overall growth performance. These findings

provide valuable insights for improving the cultivation and management of forestry species under stress conditions.

5. References

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