Germination sensitivity and seedling quality of mahogany (*Swietenia macrophylla*) in response to saline irrigation

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Salinity is a major abiotic constraint to seed germination and early seedling establishment in forest tree species, especially in arid and semi-arid regions where freshwater scarcity necessitates the use of saline irrigation. The present study assessed the effect of varying salinity (4.0–8.0 dS m^{-1}) on seed germination and seedling quality of *Swietenia macrophylla* (mahogany) under nursery conditions at the Indian Council of Agricultural Research–Central Soil Salinity Research Institute, Karnal. Germination parameters, final germination percentage (FGP), germination index (GI), coefficient of velocity of germination (CVG), and seedling quality indices declined significantly with increasing salinity. The FGP decreased from 28% in the control to 7% at 8.0 dS m^{-1}. Higher salinity prolonged the mean germination time and significantly reduced growth and Dickson quality index values. The present study highlights the salinity sensitivity of mahogany during germination and underscores the need to screen and select tolerant genotypes for sustainable afforestation in saline-prone areas.

Keywords: Biomass allocation, Dickson quality index, germination, mahogany, salinity, *Swietenia macrophylla*

FORESTS restoration programmes, along with sustainable agroforestry activities, are placing more stress on the integration of multipurpose tree species into production systems. Effective development of such systems largely depends on the generation of healthy and vigorous seedlings. Seed germination is a critical phase that, in most instances, defines the success of the plantation and its future survival. Germination in many forest tree species is inhibited by seed dormancy, protective or hard seed coats, and environmental stress (temperature, light, water supply)[1–4]. Water deficits and salinity, among others, are the most harmful of these stresses; they slow down germination, decrease germination percentage, and diminish seedling quality[5–7]. The germination characteristics of economically and ecologically useful species are therefore of high significance, not only in conservation, but also in large-scale plantations. However, the effect of subtle environmental variation on germination requirements is common within species[8,9], and indicates that genetic and environmental factors interact[10]. Drought or water stress[4,7,11,12], salinity[6,7,13–15], and temperature[1,3,16–18] are all abiotic stresses that control seed germination. In addition, provenance effects are typically pronounced, whereby seeds collected from different localities show substantial disparities in optimal germination responses[3,8,9].

One of the most economically and ecologically valuable multipurpose tree species is *Swietenia macrophylla* King (big leaf mahogany) of the family *Meliaceae*, which has been known to possess fine grain, durability and resistance to decay. Introduced outside Central and South America, the species is now naturalised in several sub-tropical countries, including India, where it was first introduced in 1865. Its timber is highly sought after for furniture, shipbuilding, and decorative veneers, being among the most important timber species in the world[11,19,20]. In addition to timber value, species have diverse uses in the production of bioenergy, hydrocarbons, and phytochemicals[19]. Illegal logging and trade have put mahogany under extreme pressure, leading to its inclusion in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)[21], requiring a new approach for sustainable propagation and plantation strategies.

The growing shortage of freshwater resources in arid and semi-arid areas has encouraged the necessity to use alternative sources such as saline groundwater, drainage water and treated wastewater to irrigate forest plantations[22]. These activities not only alleviate water shortages but also contribute to biomass production, ecological restoration, and green-belt development in the region. Nevertheless, salinity in soil is a significant environmental stressor that adversely affects the growth of plants, germination of seeds, and overall productivity of forest tree species[15,22,23]. Halophytes, on the other hand, respond positively to salinity, with intermediate salt levels improving reproductive ability in the form of seed production, flower counts and pollen viability[24]. They are resilient due to a combination of morphological, anatomical and physiological adaptations that allow them to survive in severe conditions[15,25].

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Conversely, some forest tree species have anatomical and leaf structure adaptations at the initial stages of growth, which are vital in establishing the saplings[26]. As the juvenile stage has played a crucial role in determining survival and productivity, anatomical and hydraulic characters prove helpful in selecting productive and drought-resilient tree species, thus ensuring better establishment over time[26,27].

Most research conducted in the past has focused on crops, with very few studies having been conducted on multipurpose forestry tree species. Therefore, there is a lack of empirical evidence of the impact of saline irrigation on the germination and initial growth of tree species, especially mahogany. This information gap is a major obstacle towards the use of mahogany in restorative and agroforestry systems within saline-prone landscapes. Considering the economic value of *S. macrophylla*, and the increasing necessity to use the low-quality water to manage nursery and plantation, it is essential to assess the influence of salinity on seed germination and the initial growth of the seedling. The present study was then conducted to determine the impacts of varying degrees of saline irrigation on germination behaviour, early growth performance, and seedling quality of mahogany under nursery conditions. The study, in particular, investigated cumulative germination patterns, important germination indices and seedling quality parameters under varying salinity levels. The present article aims to fill a knowledge gap in an important area of need and to inform nursery management, afforestation programmes and sustainable forestry practices in areas where the use of saline water is becoming a significant issue.

Methodology

Experimental site and materials

The present study was conducted from August to November 2024 to assess the effects of saline irrigation on seed germination and seedling quality of *Swietenia macrophylla* (mahogany). The experiment was conducted at the nursery of the Indian Council of Agricultural Research - Central Soil Salinity Research Institute (ICAR–CSSRI), Karnal, India (29°43'N, 76°58'E; 244 m above mean sea level). The regional climate is semi-arid, with winters extending from November to March and summers from April to October. The area receives an average annual rainfall of 650–700 mm, the majority of which occurs during July to September. A completely randomised design (CRD) was followed, whereby four irrigation treatments: control (tap water) and three salinity levels (EC_{iw} ≈4.0, 6.0, and 8.0 dS m^{-1}) were used. Each treatment was replicated four times. Saline water was sourced from groundwater at Nain Farm, Panipat, and applied directly according to the treatment schedule. Irrigation was carried out twice a week, and the salinity of the growth medium was periodically monitored.

The seeds of the mahogany were procured from the Kerala Forest Research Institute (KFRI), Thrissur, India. Before sowing, the sand substrate was sterilised with hot water and chlorine, thoroughly washed, and placed in plastic trays. The 25 seeds were spaced 10 cm apart in each tray. The seeds were subjected to a salt stress by providing the different concentrations of saline irrigation water (EC_{iw} ∼4.0, 6.0, and 8.0 dS m^{-1}).

Seed germination assessment

The effects of salt stress were assessed through seed germination indices in the nursery. Seed germination was recorded every alternate day from the date of sowing and continued for 35 days after sowing (DAS) till the last germination. Emergence was defined as a visible protrusion of the hypocotyl or cotyledon (≥0.5 cm above the substrate). Both daily and cumulative germination counts were recorded to calculate germination parameters, such as final germination percentage (FGP), mean germination time (MGT), germination index (GI), and coefficient of velocity of germination (CVG). The germination phase dynamics were taken into account using the imbibition period. The first day of germination (FDG, days) was recorded as the day on which the first visible germination occurred within the seed lot. The last day of germination (LDG, days) was noted as the day on which the final germination event was observed. The time spread of germination (TSG, days) was calculated as the interval between the first and last germination events, thereby indicating the duration of the germination period within each treatment. Mathematically, TSG was expressed as: TSG = (LDG – FDG). The calculated germination indices were as follows:

Final germination percentages (FGP):

$$\mathrm{FGP} = \frac{\text{Number of germinated seeds}}{\text{Total seeds sown}} \times 100 \qquad (1)$$

Mean germination time (MGT, days)[3,28] :

$$\mathrm{MGT} = \frac{\sum(n_i * d_i)}{\sum n_i} \qquad (2)$$

where, n_i is the number of seeds germinated on day i; and d_i is the number of days from sowing.

Germination index (GI)[29] :

$$GI = (10 \cdot n_1) + (9 \cdot n_2) + \cdots + (1 \cdot n_{10}) \qquad (3)$$

where, n_1, n_2 ... n_{10} is the number of seeds germinated on the 1st, 2nd, ..., and subsequent days until the 10th day; 10, 9 ... and 1 is the weight assigned to the number of seeds germinated on the 1st, 2nd and subsequent days, respectively.

Here, the maximum weight is assigned to seeds germinated on the first day, and less to those germinated later. So, GI emphasises both the percentage of germination and its speed. A higher GI reflects both greater germination percentage and faster germination[30,31].

CVG[32]: It is widely used to describe the rapidity of seed germination. CVG indicates the rapidity of germination. It increases when the number of germinated seeds increases and the time required for germination decreases.

$$\text{CVG} = \frac{\sum n_i}{\sum (n_i * d_i)} \times 100 \tag{4}$$

where, n_i is the number of seeds germinated on day i; d_i is the number of days from sowing.

Early seedling growth assessments

Four seedlings for each treatment were randomly chosen for growth assessment after 10–12 weeks. Growth parameters of seedlings were recorded. Seedling height (cm) was measured with a ruler, collar diameter (mm) at the root collar using a vernier calliper, and the number of leaves per seedling was counted manually. Seedlings were then carefully harvested and separated using secateurs into three parts: roots, shoots, and leaves. Then, samples were oven-dried at 70°C for 72–96 h until constant weight. Dry biomass of each component was measured using an electronic balance (Aczet, precision 0.001 g). Total dry weight was calculated as the sum of shoot, root, and leaf dry weights, while the root-to-shoot ratio was computed to assess biomass allocation.

Seedling quality index

The Dickson quality index (DQI) was used as a comprehensive measure of seedling vigour and morphological quality[33]. Seedling height was measured from the soil surface to the tip using a ruler (±0.1 cm accuracy). Oven-dried biomass of plant components at 70°C for 72–96 h until a constant weight has been recorded. The DQI incorporates height, collar diameter, and biomass allocation to provide an integrated measure of seedling quality. The DQI was calculated according to the following formula[34]:

$$DQI = \frac{Total\, dry\, weight (g)}{\left[\frac{Height\,(cm)}{Diameter\,(mm)} + \frac{Shoot\, dry\, weight\,(g)}{Root\, dry\, weight\,(g)}\right]} \tag{5}$$

where Height (cm) is the seedling height from the soil surface to the tip, and diameter (mm) refers to collar diameter measured at the root collar point.

Statistical analysis

Data on germination traits and seedling growth parameters under saline and control irrigation conditions were subjected to one-way analysis of variance (ANOVA) to test for treatment effects. Where significant differences were observed, means were compared using Tukey's honestly significant difference (HSD) test at a 95% confidence level ($P < 0.05$). Statistical analyses were performed using R software.

Results

Seed germination traits under salinity stress

Salinity stress significantly influenced both germination behaviour and early seedling growth of mahogany, with effects becoming more severe at higher salinity (EC_{iw}) levels. All germination parameters were adversely affected by increasing salinity (Table 1, Figures 1 and 2). The FGP % declined progressively with increasing salinity: highest in the control (28.0 ± 2.83%) and 4.0 dS m^{-1} (20.0 ± 2.83%), but markedly reduced at 6.0 dS m^{-1} (15.0 ± 1.91%) and lowest at 8.0 dS m^{-1} (7.0 ± 1.91%).

Germination onset was delayed under saline irrigation. While the FDG was similar across control and 4.0 dS m^{-1} (18.5–18.8 days), it was significantly prolonged at 6.0 dS m^{-1} (20.3 days) and 8.0 dS m^{-1} (24.0 days). The LDG did not vary greatly, but the TSG was sharply reduced at 8.0 dS m^{-1} (2.5 days) compared to the control (9.5 days), indicating a constrained and less uniform germination window under severe salinity stress.

Cumulative germination curves (Figure 1) further illustrated these patterns. Seeds in the control germinated rapidly and plateaued around 28% by 30 DAS, whereas germination slowed and plateaued at lower levels in 4.0 dS m^{-1} (∼20%) and 6.0 dS m^{-1} (∼15%). The most severe inhibition occurred in 8.0 dS m^{-1}, which showed only ∼7% final germination. Quantitative indices (Figure 2) further supported these trends: MGT was shortest in the control (22–23 days) and increased significantly under EC-08 (∼25 days), indicating delayed emergence under stress. Similarly, GI followed a similar pattern, with the control recording the highest value (∼165) and EC-08 the lowest (∼35). Likewise, the CVG was significantly reduced at higher salinity, with the control maintaining the fastest germination (4.5) compared to EC-08 (4.0). Together, these results demonstrate a salt-induced suppression of germination traits, with 8.0 dS m^{-1} imposing the strongest inhibitory effect.

Table 1. Seedling traits and germination under the influence of different salinity. The salinity level ranged from 4–8 dS m^{-1} for irrigation to seeds germination along with tap water irrigation as control (T1). Salinity level indicated by EC_04 stands ~4.0 dS m^{-1} (T2); EC_06 stands ~6.0 dS m^{-1} (T3); and EC_8 stands ~8.0 dS m^{-1} (T4). Table value (mean ± SE) is presented with Tukey's honestly significant difference (HSD) test by different letters. Statistical differences among treatments are indicated by letters (Tukey's test, $P < 0.05$)

Traits	Unit	Control (T1)	EC_04 (T2)	EC_06 (T3)	EC_08 (T4)
Final Germination Percentage (FGP)	%	28.00 ± 2.83 a	20.00 ± 2.83 ab	15.00 ± 1.91 bc	7.00 ± 1.91 c
First Day of Germination (FDG)	day	18.50 ± 0.50 b	18.75 ± 0.63 b	20.25 ± 0.63 b	24.00 ± 0.82 a
Last Day of Germination (LDG)	day	28.00 ± 0.82 a	28.50 ± 0.96 a	27.50 ± 0.96 a	26.50 ± 1.26 a
Time Spread of Germination (TSG)	day	9.50 ± 0.96 a	9.75 ± 0.48 a	7.25 ± 0.75 a	2.50 ± 1.50 b
Collar Diameter (CD)	mm	4.38 ± 0.21 a	3.90 ± 0.35 ab	3.25 ± 0.13 bc	2.85 ± 0.12 c
Seedling Height	cm	19.75 ± 1.80 a	14.00 ± 1.58 ab	14.50 ± 1.66 ab	12.75 ± 1.03 b
Number of Leaf	-	13.75 ± 2.56 a	13.00 ± 1.08 a	8.25 ± 0.85 ab	4.25 ± 0.75 b
Shoot Dry Weight	g	0.81 ± 0.11 a	0.69 ± 0.12 ab	0.42 ± 0.04 bc	0.27 ± 0.05 c
Root Dry Weight	g	0.44 ± 0.07 a	0.44 ± 0.09 a	0.30 ± 0.03 ab	0.18 ± 0.02 b
Total Dry Weight	g	1.81 ± 0.32 a	1.74 ± 0.40 a	0.84 ± 0.07 ab	0.54 ± 0.09 b

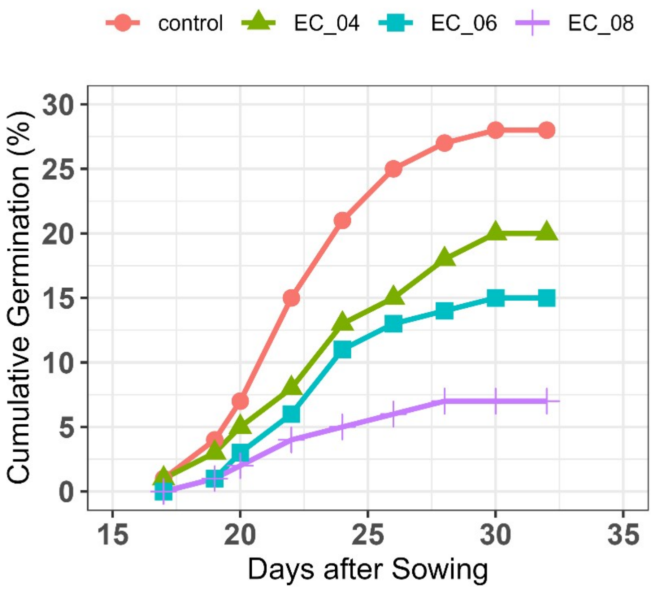

Figure 1. Cumulative germination (%) of *Swietenia macrophylla* (mahogany) seeds under different salinity treatments across days after sowing (DAS). Salinity levels correspond to EC_04 ~ 4.0 dS m^{-1}, EC_06 ~ 6.0 dS m^{-1}, and EC_08 ~ 8.0 dS m^{-1}.

Seedling growth traits

Early seedling development was also impaired under salinity (Table 1). Seedling height decreased from 19.8 cm in the control to 12.8 cm at 8.0 dS m^{-1}. Similarly, collar diameter declined from 4.38 mm (control) to 2.85 mm (8.0 dS m^{-1}). The number of leaves followed a parallel trend, dropping from 13.8 leaves in the control to only 4.3 leaves at 8.0 dS m^{-1}.

Biomass accumulation was strongly affected. Shoot dry weight (g) declined steadily with increasing EC, from 0.81 g in the control to 0.27 g at 8.0 dS m^{-1}. Root dry weight was significantly lower at 8.0 dS m^{-1} (0.18 g) compared to the control (0.44 g). Consequently, the total dry weight (g) decreased sharply, from 1.81 g in the control to 0.54 g at 8.0 dS m^{-1}. These reductions highlight that salinity not only limited vegetative growth but also compromised biomass allocation.

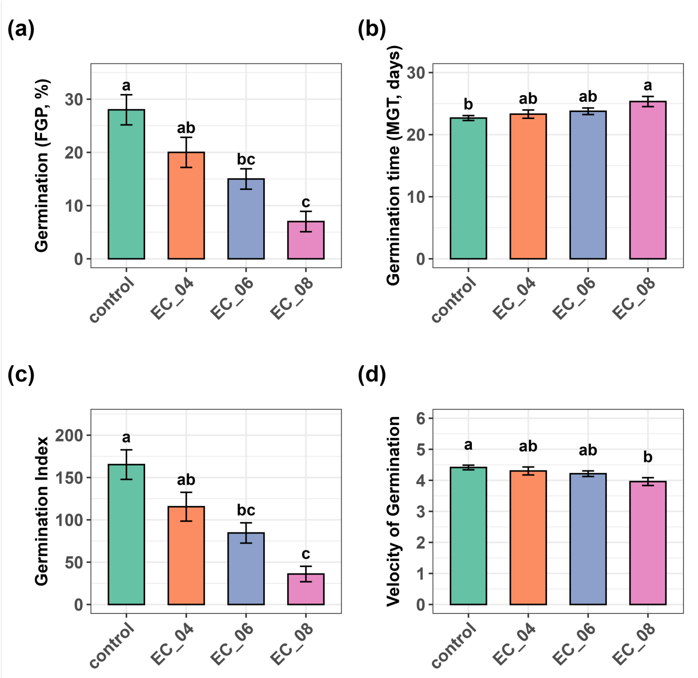

Figure 2. Effects of salinity stress (EC 4–8 dS m^{-1}) on germination parameters of *S. macrophylla*. Panels represent: (***a***) final germination percentage (FGP), (***b***) germination time (MGT), (***c***) germination index (GI) and (***d***) coefficient of velocity of germination (CVG). Different letters indicate significant differences among treatments according to Tukey's HSD test ($P < 0.05$).

Seedling quality indices

Seedling quality indices (Figure 3) provided further insight into stress responses. The DQI showed a clear reduction with increasing salinity. Control and 4 dS m^{-1} seedlings maintained the highest quality (≈2.1–2.3), while 6.0 dS m^{-1} and 8.0 dS m^{-1} seedlings had significantly lower values (≈1.5–1.6), reflecting reduced vigour under higher salinity.

Interestingly, the root-to-shoot ratio (R/S) responded differently. It increased significantly under moderate salinity (6.0 dS m^{-1}: ≈0.75) compared with the control (≈0.55), suggesting an adaptive allocation strategy to enhance water and nutrient uptake. Seedlings at 4.0 dS m^{-1} and 8.0 dS m^{-1} showed intermediate values without significant differences from either control or 6.0 dS m^{-1}. This shift in biomass partitioning suggests a potential stress adjustment mechanism, although it was insufficient to offset the overall decline in seedling quality at higher salinity levels.

Discussion

The present study has shown that high salinity in irrigation water significantly suppressed the germination and early seedling development of mahogany, with the extent of suppression directly proportional to the intensity of salinity. Salinity stress inhibits germination primarily by exerting osmotic and ionic toxicity, which disrupts water uptake, enzymatic functions and metabolism[35]. In the present study, the final percentage of germination decreased gradually as the salinity level increased, as well as the germination rate.

Germination sensitivity and seedling traits

The results showed that germination characters were more responsive to salinity compared to seedling growth parameters. The percentage germination dropped by around 46 per cent at 6.0 dS m^{-1} and nearly 75 per cent at 8.0 dS m^{-1} relative to the control, indicating that salinity severely limits seed sprouting. Conversely, seedling growth characteristics (height, collar diameter, biomass) were comparatively slow when salinity was moderate (4.0 dS m^{-1}, 6.0 dS m^{-1}), and harshly suppressed when salinity was at 8.0 dS m^{-1}. This trend suggests that although salinity inhibits germination, seedlings that germinate can initially withstand moderate stress levels, after which they exhibit strong growth inhibition at high salinity.

Significance in biomass partitioning also changed as indicated by a higher root to shoot ratio at 6.0 dS m^{-1}. This trend suggests that it is an adaptive mechanism, involving increased investment in roots to enhance water and nutrient acquisition in adverse habitats. Nevertheless, this modification was not enough to maintain the overall seedling vigour, as demonstrated by the fact that the DQI at 6.0 and 8.0 dS m^{-1} had reduced significantly.

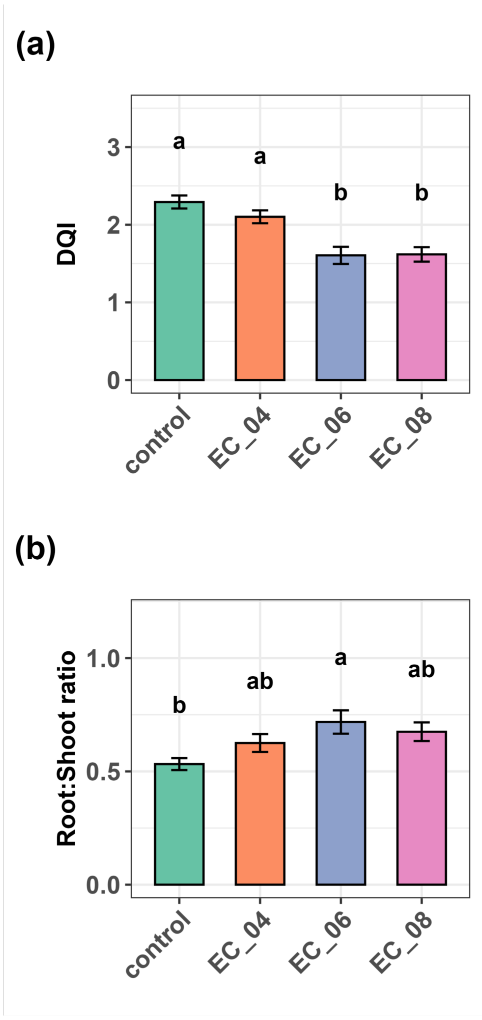

Figure 3. Seedling morphological quality under the influence of different salinity levels indicated by Dickson quality index and root-shoot ratio. Salinity levels correspond to EC_04 d̃S m^{-1}, EC_06 6̃.0 dS m^{-1}, and EC_08 8̃.0 dS m^{-1} and along with tap water irrigation as control.

Mechanisms of salt tolerance and evidence

Salt stress initiates a complex physiological process that affects the seeds and seedlings of osmotic stress, ion toxicity, and oxidative damage[6,13,15,35]. The germination percentage and delayed germination rate are similar to those reported in other species. As an example, *Acacia salicina* and *Acacia albida* had significant decreases in germination and seedling biomass with salinity[6], whereas *Dodonea viscosa*[13] and *Prosopis alba*[5] displayed retarded root and shoot growth. The first obstacle to germination is often osmotic stress due to the decrease of water potential in the soil solution, which slows down the imbibition of the seed and the activation of metabolism[36,37]. That is why GI is in many cases more sensitive to salinity than final germination percentage, as has been found in *Aspidosperma pyrifolium*[38] as well as various *Eucalyptus* species[7].

Increasing salinity levels make ion toxicity preeminent. Intrusion of excess Na^+ and Cl^- inhibits enzyme activity, membrane integrity and reserve mobilisation[35,36]. Although this seed coat may be protective at first, when exposed over long periods, ions enter, causing metabolic impairment to occur[39]. The high sensitivity of *Eucalyptus brassiana* to salinity and the high resistance of *Eucalyptus camaldulensis* to salinity explain the selection effects difference observed; thus, variation in salinity tolerance among species, such as the resistance of *E. camaldulensis* to salinity versus the sensitivity of *E. brassiana*[7], demonstrates the strength of salinity tolerance as a genetic component of its responses to salinity.

Plants adjust to salinity by osmotic adjustment, which is mainly achieved by building up of compatible solutes of proline, sugars and polyols that help reduce osmotic potential and protect proteins and membranes[15,35,36,40].

Finally, salinity resistance during the germination process is determined by a species' ability to reduce the accumulation of ions in sensitive tissues while maintaining osmotic balance[41]. Since the germination phase forms a crucial bottleneck in establishment in saline environments, understanding these physiological and metabolic responses can aid in identifying and utilising tolerant tree species in afforestation. It was also possible to explore seed provenances and choose superior planting material at the initial seedling phase[42–44]. A complex interaction of both genetic and environmental factors influences seed germination[3,8–10]. Although in certain species (e.g., *Jatropha curcas*[43]), genetic control may prevail[43], environmental factors, including rainfall, temperature, and altitude, usually have a more decisive impact on germination behaviour[3,4,9,17,45].

Practical implications for mahogany cultivation

The findings have significant practical implications for a silvicultural viewpoint. The germination and growth of mahogany were intermediate at 4.0 and 6.0 dS m^{-1} because of its tolerability to low-medium salinity. Nevertheless, above 6.0 dS m^{-1} and beyond, germination and seedling vigour decreased rapidly, implying that germination would be restricted in such environments. This is also an important site choice in agroforestry and afforestation projects in semi-arid and coastal areas where salinity is frequently a key limiting factor.

High salinity conditions significantly reduced germination, highlighting the importance of management measures to enhance germination. Pre-sowing treatments, including seed priming, have been effective in improving germination[2,4,46,47]. These methods can be adopted for mahogany to enhance germination and seedling establishment. Additionally, the shift in biomass distribution of roots under moderate stress could be utilised in breeding programs to enhance stress tolerance. Additional studies should also be conducted to determine the effectiveness of other interventions, such as dormancy breaking and hormone application, in promoting mahogany germination and early development. Lastly, it would be of great interest to evaluate the field performance of saplings grown from different seed sources and saline soils to understand how to scale up mahogany plantations in saline-prone regions.

Conclusion

The present study shows that salinity stress significantly inhibits germination and early seedling growth of *S. macrophylla*. Mild salinity (4.0 dS m^{-1}) allowed adequate establishment, whereas higher levels (8.0 dS m^{-1}) sharply reduced germination, growth, and seedling quality, identifying germination as the most sensitive stage. Mahogany can thus be considered moderately sensitive to salinity. Given mahogany's high economic and ecological importance, future research should explore pre-sowing treatments and provenance-based evaluations to enhance germination and salinity tolerance, thereby supporting its integration into afforestation and agroforestry systems in saline-prone regions.

Conflict of interest: The authors declare that there is no conflict of interest.

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ACKNOWLEDGEMENTS. The authors acknowledge the support of the Indian Council of Agricultural Research, Department of Agricultural Research and Education, Government of India (Project code: NRMA-CSSRISIL202301101076.).

Received 3 October 2025; accepted 18 November 2025.

doi: 10.18520/cs/v129/i12/1081-1088