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ENHANCING EARLY GROWTH AND ROOT DEVELOPMENT OF *Faidherbia albida* (DELILE) A.CHEV. SEEDLINGS USING *moringa oleifera* LAM. LEAF EXTRACT IN A SEMI-ARID NURSERY ENVIRONMENT

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ABSTRACT

Natural biostimulants are gaining attention as sustainable alternatives to synthetic growth regulators, particularly for dryland tree species. *Faidherbia albida* is a keystone species in semi-arid Africa, but early nursery establishment is often limited by slow growth and poor root development. This study evaluated *Moringa oleifera* leaf extract (MLE) as a natural biostimulant to enhance early seedling growth of *F. albida* compared with indole-3-acetic acid (IAA) and an untreated control. A nursery experiment was conducted using a completely randomized design with three treatments and five replicates over eight weeks. Plant height and leaf number were recorded at Weeks 2, 4, 6, and 8, while biomass, root length, and root–shoot ratio were measured at Week 8. Data were analyzed using one-way ANOVA. Although treatment effects were not statistically significant ($P > 0.05$), consistent biological trends were observed. MLE-treated seedlings exhibited greater mean height (13.06 ± 1.56 cm), leaf number (23.00 ± 4.87), dry biomass (0.40 ± 0.05 g), root length (14.96 ± 2.81 cm), and a more balanced root–shoot ratio (0.94 ± 0.23) compared with IAA and control. IAA treatments showed high variability and partial seedling mortality. These coherent trends indicate a stable growth-promoting effect of MLE, highlighting its potential as a low-cost, environmentally friendly biostimulant for improving early seedling quality of *F. albida* in semi-arid nurseries and dryland restoration programs.

Keywords: *Faidherbia albida*; *Moringa oleifera*; leaf extract; biostimulant; seedling growth; dryland restoration

INTRODUCTION

Dryland and semi-arid landscapes across sub-Saharan Africa face increasing pressure from climate variability, land degradation, and declining soil fertility, making successful tree establishment a persistent challenge for agroforestry and restoration programs. *Faidherbia albida* is a keystone agroforestry species widely recognized for its capacity to improve soil fertility, enhance crop productivity, and buffer farming systems against climatic extremes (Barnes and Fagg, 2003; Bayala *et al.*, 2010; Sida *et al.*, 2018). Through nitrogen inputs, litter contribution, and microclimatic moderation, the species plays a central role in climate-smart and evergreen agriculture systems in African drylands (Barnes and Fagg, 2003; Bayala *et al.*, 2010; Sida *et al.*, 2018). However, slow early growth and poor seedling establishment at the nursery and post-transplant stages continue to limit its wider adoption (Barnes and Fagg, 2003; Bayala *et al.*, 2010; Sida *et al.*, 2018).

Improving nursery-stage seedling quality is therefore critical for enhancing field survival and long-term performance of *F. albida*. In low-input and community-based nursery systems, the use of plant biostimulants has emerged as a promising strategy to support early growth and establishment. Plant biostimulants are defined as substances that stimulate endogenous plant processes to improve nutrient use efficiency, stress tolerance, and overall growth quality, independently of their direct nutrient content (du Jardin, 2015). Recent scientific advances emphasize the role of multi-component, nature-based

biostimulants in promoting plant resilience and functional stability, particularly under variable environmental conditions (Mannino *et al.*, 2025; Khoulati, 2025; Mashabela, 2025).

Among plant-derived biostimulants, *Moringa oleifera* leaf extract (MLE) has attracted growing attention due to its rich biochemical composition, including cytokinins (notably zeatin), amino acids, minerals, vitamins, and antioxidant compounds. These constituents act synergistically to promote cell division, leaf development, photosynthetic efficiency, and stress buffering (Foidl *et al.*, 2001; Fuglie, 2001; Mashamaite *et al.*, 2022; Sadak and El-Lethy, 2024). Empirical studies across a range of crops have shown that MLE enhances growth consistency, biomass accumulation, and physiological efficiency under both optimal and stress-prone conditions (Hasan *et al.*, 2017; Mashamaite *et al.*, 2024; Abdelhameed *et al.*, 2025).

In contrast, the application of synthetic growth regulators such as indole-3-acetic acid (IAA) often produces variable outcomes depending on concentration, timing, and species sensitivity. Auxin-mediated growth responses require precise regulation of synthesis, transport, and signaling pathways, and external application can disrupt endogenous hormonal balance, particularly during early seedling development (El-Saed *et al.*, 2010; Hussain *et al.*, 2011; Batista-Silva *et al.*, 2024). Such variability presents practical limitations in community and smallholder nursery contexts where precision dosing and close monitoring are constrained.

Against this background, this study evaluates the effectiveness of *Moringa oleifera* leaf extract as a natural biostimulant for improving early growth, biomass accumulation, and root development of *Faidherbia albida* seedlings under nursery conditions, in comparison with indole-3-acetic acid and an untreated control. By focusing on nursery-relevant growth and root traits, the study contributes evidence to support nature-based solutions for agroforestry establishment and dryland restoration.

THEORETICAL FRAMEWORK

This study is anchored on the plant biostimulant framework, which explains growth enhancement as the outcome of stimulating endogenous physiological processes (e.g., hormonal regulation, photosynthetic efficiency, antioxidant defense, and assimilate partitioning) rather than simply supplying nutrients (du Jardin, 2015). Within this framework, multi-component biostimulants such as *Moringa oleifera* leaf extract can promote coordinated shoot–root development because they contain diverse bioactive compounds (including cytokinins such as zeatin, amino acids, vitamins, minerals, and antioxidants) that act synergistically to regulate growth, improve metabolic stability, and strengthen stress buffering (Foidl *et al.*, 2001; Fuglie, 2001; Mashamaite *et al.*, 2022). This is particularly relevant for dryland agroforestry species such as *Faidherbia albida*, where early root development and physiological resilience are decisive for nursery establishment and post-transplant survival in moisture-limited environments (Barnes and Fagg, 2003; Bayala *et al.*, 2010).

MATERIALS AND METHODS

Study area

The experiment was conducted at the Faculty of Agriculture Research Farm, Usmanu Danfodiyo University, Sokoto, Nigeria (13°07'N, 5°12'E). The site lies within the Sudan Savanna ecological zone, characterized by a unimodal rainfall pattern with mean annual rainfall ranging from 553 to 629 mm and high ambient temperatures, which may exceed 40 °C during the dry season. Soils in the area are predominantly sandy loam with low organic matter content and limited inherent fertility, typical of semi-arid savanna environments (Ojanuga, 2006; Abdullahi *et al.*, 2020). The experiment was conducted under open-nursery conditions. Seedlings were watered uniformly once daily to field capacity, and no supplementary fertilizers were applied during the experimental period.

Experimental design

A completely randomized design (CRD) was employed with three treatments:

- (i) *Moringa oleifera* leaf extract (MLE),
- (ii) indole-3-acetic acid (IAA), and
- (iii) distilled water (control).

Each treatment was replicated five times, giving a total of 15 experimental units. Each replicate consisted of one *Faidherbia albida* seedling raised in a perforated plastic pot filled with topsoil. Pots were randomly

repositioned weekly to minimize micro-environmental bias within the nursery.

Preparation and application of treatments

Moringa oleifera leaf extract (MLE)

Fresh, healthy leaves of *Moringa oleifera* were collected from the nursery of the Department of Forestry and Environment, Usmanu Danfodiyo University, Sokoto. The leaves were thoroughly washed to remove adhering dust and debris and air-dried under shade at ambient temperature to eliminate surface moisture before extraction. Thirty grams of fresh *Moringa oleifera* leaves were crushed using a mortar and pestle and homogenized in 100 mL of distilled water to obtain a 30% (w/v) aqueous extract. The homogenate was filtered through muslin cloth to obtain a clear extract, following established protocols for plant-based biostimulants (Yasmeen *et al.*, 2013; Hasan *et al.*, 2017).

Indole-3-acetic acid (IAA)

Indole-3-acetic acid was prepared as a stock solution by dissolving the appropriate quantity of IAA in a small volume of ethanol and diluting with distilled water. A working concentration of 50 mg L⁻¹ (50 ppm) was used, consistent with concentrations commonly reported to enhance early seedling growth without inducing phytotoxic effects (Hussain *et al.*, 2011; Taiz *et al.*, 2015). The final ethanol concentration was negligible and uniform across treatments.

Application protocol

Treatments were applied as soil drenches at a uniform volume per seedling once weekly for eight weeks, beginning two weeks after seedling emergence. Control seedlings received distilled water only.

Data collection

Plant height (cm) and number of leaves were recorded fortnightly for eight weeks using a graduated ruler and direct leaf count, respectively. At final harvest (Week 8), seedlings were carefully uprooted and washed to remove adhering soil. Root length was measured using a ruler. Fresh biomass was determined immediately after harvest using a digital balance. Samples were then oven-dried at 70 °C to constant weight to determine dry biomass. Root–shoot ratio was calculated as the ratio of root dry weight to shoot dry weight.

Statistical analysis

Data were subjected to one-way analysis of variance (ANOVA) at a 5% level of significance using SPSS version 16.0. Prior to analysis, data were checked for normality and homogeneity of variance to satisfy ANOVA assumptions. Where significant treatment effects were observed, mean separation was carried out using the Least Significant Difference (LSD) test. Results are presented as means ± standard error, with F-statistics, degrees of freedom, and P-values reported. Seedling survival at Week 8 was expressed as the number and percentage of seedlings with measurable growth relative to the total number of replicates per treatment.

RESULTS AND DISCUSSION

4.1 Growth performance (plant height and number of leaves)

Plant height and number of leaves of *Faidherbia albida* seedlings increased progressively from Week 2 to Week 8 across all treatments (Tables 1 and 2), indicating that the nursery conditions supported normal physiological growth and ontogenetic development (Barnes and Fagg, 2003; Bayala *et al.*, 2010). Although one-way ANOVA at Week 8 showed no statistically significant treatment effects ($P > 0.05$), consistent directional biological trends were evident across growth stages. Across all measurement periods, seedlings treated with *Moringa oleifera* leaf extract (MLE) recorded higher mean plant height and leaf number compared with indole-3-acetic acid (IAA) and the control (Tables 1 and 2; Figures 1 and 2). Similar trend-level improvements under moringa-based biostimulants have been widely reported, particularly where biological consistency rather than strict statistical separation is emphasized (du Jardin, 2015; Mashamaite *et al.*, 2022; Mannino, 2025). Mean values further indicated consistently higher growth and biomass accumulation under MLE across all measured traits (Tables 1–4), despite the absence of statistical

significance, suggesting a stable growth-promoting influence of the extract. The enhanced shoot growth under MLE is consistent with the biochemical composition of *M. oleifera* leaves, which are rich in cytokinins (especially zeatin), amino acids, minerals, vitamins, and antioxidants that collectively stimulate cell division, leaf initiation, and photosynthetic activity (Foidl *et al.*, 2001; Fuglie, 2001; Sadak and El-Lethy, 2024). Recent studies further confirm that moringa extracts improve physiological efficiency and growth stability under both optimal and stress-prone conditions (Mashamaite *et al.*, 2024; Abdelhameed *et al.*, 2025). In contrast, IAA-treated seedlings exhibited pronounced variability, including zero growth in some replicates, reflecting poor establishment and early mortality. Similar inhibitory or unstable responses to exogenous auxin application have been documented when concentration or exposure timing disrupts endogenous hormonal balance, particularly in woody seedlings (El-Saed *et al.*, 2010; Hussain *et al.*, 2011). These outcomes underscore the limitations of single-hormone approaches relative to complex natural biostimulants.

Table 1. Effect of treatments on plant height (cm) of *Faidherbia albida* seedlings at different growth stages

Treatment	Week 2	Week 4	Week 6	Week 8
MLE	9.66 ± 1.19	10.60 ± 1.44	11.94 ± 1.59	13.06 ± 1.56
IAA	6.34 ± 3.86	6.50 ± 3.96	6.90 ± 3.91	7.60 ± 3.74
Control	7.66 ± 0.87	8.06 ± 0.94	8.84 ± 0.97	9.58 ± 0.99

Values are means ± standard error (SE), n = 5.

Table 2. Effect of treatments on number of leaves of *Faidherbia albida* seedlings at different growth stages

Treatment	Week 2	Week 4	Week 6	Week 8
MLE	11.60 ± 0.75	15.00 ± 1.01	17.60 ± 2.87	23.00 ± 4.87
IAA	6.60 ± 2.45	8.00 ± 2.79	10.80 ± 4.52	12.80 ± 5.49
Control	8.60 ± 1.47	11.20 ± 1.39	13.00 ± 1.78	14.80 ± 2.71

Values are means ± standard error (SE), n = 5.

Biomass accumulation

Fresh and dry biomass accumulation at Week 8 followed patterns consistent with vegetative growth responses (Table 3). Seedlings treated with MLE recorded higher mean dry weight compared with both the control and IAA treatments, while fresh weight was lowest under IAA. Although ANOVA detected no statistically significant differences ($P > 0.05$), biomass accumulation under MLE was notably more uniform across replicates.

Dry weight is a more reliable indicator of assimilate accumulation and structural growth than fresh weight because it reflects net carbon fixation rather than tissue water content (Squire, 1990). The higher dry biomass observed under MLE therefore suggests improved photosynthetic efficiency and assimilate partitioning,

likely driven by enhanced leaf development and metabolic regulation. Comparable increases in dry matter accumulation following MLE application have been reported in cowpea, tomato, and other crops, where moringa extracts enhanced carbon assimilation and nutrient utilization (Hasan *et al.*, 2017; Mashamaite *et al.*, 2022; Abdelhameed *et al.*, 2025). Conversely, reduced and inconsistent biomass under IAA treatment may reflect physiological stress or hormonal imbalance, particularly in seedlings that failed to establish successfully. Such responses align with earlier reports that inappropriate auxin concentrations can suppress biomass accumulation and compromise seedling vigor (El-Saed *et al.*, 2010; Hussain *et al.*, 2011).

Table 3. Effect of treatments on biomass accumulation of *Faidherbia albida* seedlings at Week 8

Treatment	Fresh weight (g)	Dry weight (g)
MLE	1.04 ± 0.09	0.40 ± 0.05
IAA	0.60 ± 0.26	0.27 ± 0.13
Control	1.06 ± 0.19	0.38 ± 0.11

Values are means ± standard error (SE), n = 5.

Root development and root–shoot balance

Root length and root–shoot ratio varied among treatments but did not differ significantly according to ANOVA ($P > 0.05$) (Table 4). Nevertheless, seedlings treated with MLE exhibited greater mean root length and a more balanced root–shoot ratio compared with IAA and the control.

Root system development is a key determinant of seedling establishment, particularly for *F. albida*, a keystone agroforestry species widely used in African dryland systems due to its positive effects on soil fertility and crop productivity (Barnes and Fagg, 2003; Bayala *et al.*, 2010; CABI, 2023). The relatively longer roots observed under MLE treatment indicate greater below-ground investment, which is commonly associated with improved water and nutrient acquisition and enhanced post-transplant survival (Squire, 1990).

Recent biostimulant research shows that moringa extracts enhance root growth by improving antioxidant activity, hormonal balance, and stress-buffering capacity during early development (Mashamaite *et al.*, 2022; Sadak and El-Lethy, 2024; Mashabela, 2025). In contrast, IAA-treated seedlings showed high variability in root traits, with several individuals failing to produce measurable

roots. Excessive auxin exposure has been shown to inhibit root elongation and distort root architecture when concentrations exceed optimal thresholds, thereby reducing seedling stability (El-Saed *et al.*, 2010; Hussain *et al.*, 2011).

Across shoot growth, biomass accumulation, and root development, MLE consistently produced positive directional responses relative to IAA and the control. Such coherence across multiple growth attributes is characteristic of biostimulant action, which operates through stimulation of endogenous plant processes rather than direct nutrient supply or single-hormone effects (du Jardin, 2015; Mannino, 2025). Recent reviews emphasize that this multi-pathway mode of action often yields biologically meaningful improvements even when statistical separation is limited under controlled experimental conditions (Mashamaite *et al.*, 2022; Liaqat, 2025).

Within this framework, the results suggest that *Moringa oleifera* leaf extract represents a biologically robust and environmentally compatible approach to improving early seedling quality of *F. albida*, particularly under nursery conditions relevant to agroforestry and dryland restoration systems.

Table 4. Effect of treatments on root traits of *Faidherbia albida* seedlings at Week 8

Treatment	Root length (cm)	Root–shoot ratio
MLE	14.96 ± 2.81	0.94 ± 0.23
IAA	9.44 ± 3.55	0.80 ± 0.39
Control	12.98 ± 2.41	0.76 ± 0.18

Values are means ± standard error (SE), n = 5.

Seedling survival

Seedling survival at Week 8 varied among treatments and reflected differences in early establishment success (Table 5). Seedlings treated with MLE recorded the highest survival rate, with all replicates exhibiting measurable growth. In contrast, survival was reduced under the IAA treatment, where some seedlings failed to establish and recorded zero growth, while the control treatment showed intermediate survival.

The higher survival observed under MLE treatment suggests enhanced physiological stability and stress tolerance during early seedling development. Moringa-based biostimulants contain a broad spectrum of bioactive compounds—including cytokinins, antioxidants, amino acids, and micronutrients—that collectively enhance metabolic regulation and buffering against establishment stress (du Jardin, 2015;

Mashamaite *et al.*, 2022). Such effects are particularly important for *Faidherbia albida*, a dryland agroforestry species whose successful field performance depends strongly on early nursery vigor and survival.

The reduced survival under IAA treatment, despite the use of a moderate and literature-supported concentration (50 mg L⁻¹), indicates that exogenous auxin application alone may not reliably support early establishment of woody agroforestry species. Similar reductions in survival and establishment following auxin application have been reported where hormonal imbalance or poor coordination between root and shoot development occurs (El-Saed *et al.*, 2010; Hussain *et al.*, 2011). These findings further emphasize the advantage of complex natural biostimulants over single-hormone treatments in nursery systems.

Table 5. Seedling survival of *Faidherbia albida* at Week 8 under different treatments

Treatment	Surviving seedlings (n)	Survival (%)
MLE	5/5	100
IAA	3/5	60
Control	4/5	80

CONCLUSION

This study assessed the effectiveness of *Moringa oleifera* leaf extract (MLE) as a natural biostimulant for enhancing early growth and establishment of *Faidherbia albida* seedlings under nursery conditions in the Sudan Savanna zone of Nigeria. Although statistical differences among treatments were not significant, MLE consistently produced positive and coherent directional responses across key growth parameters, including plant height, leaf production, biomass accumulation, root development, and seedling survival.

The higher survival rate and more stable growth observed under MLE treatment indicate improved physiological efficiency and stress tolerance during early seedling development. In contrast, seedlings treated with indole-3-acetic acid (IAA) showed high variability, reduced biomass accumulation, and lower survival, highlighting the limitations of single-hormone approaches for woody agroforestry species. The superior performance of MLE is attributable to its complex composition of cytokinins, antioxidants, amino acids, and essential nutrients, which collectively stimulate endogenous growth processes and promote balanced shoot–root development. Overall, the findings demonstrate that *Moringa oleifera* leaf extract offers a biologically robust, low-cost, and environmentally compatible alternative to synthetic growth regulators for improving nursery performance of *Faidherbia albida*, a keystone species in dryland agroforestry systems.

RECOMMENDATIONS

Based on the results of this study, the following recommendations are made:

1. *Moringa oleifera* leaf extract should be adopted as a natural biostimulant in agroforestry nurseries to enhance early growth, root development, and survival of *Faidherbia albida* seedlings, particularly in semi-arid environments.
2. The use of single synthetic hormones such as indole-3-acetic acid should be approached with caution for woody agroforestry species, as their isolated application may lead to unstable growth responses and reduced establishment success.
3. Further studies should investigate different concentrations and application frequencies of MLE to optimize its effectiveness across diverse nursery conditions.
4. Field-level trials are recommended to evaluate the long-term performance, survival, and

agroforestry benefits of MLE-treated seedlings after transplanting under farmer-managed conditions.

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