Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Combined Effects of Mechanical Scarification, Hormonal Treatments, and Hydration Optimization on Germination and Early Seedling Growth of Argania spinosa under Plastic Tunnel Conditions

Ahmed M. Eed

ahmed.eed@ibbuniv.edu.ye

Ibb University

Abdullah H. Al-hajj

Ibb University

Research Article

Keywords: Argania spinosa, seed dormancy, mechanical scarification, hydration optimization, gibberellic acid, germination percentage

Posted Date: March 4th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8933092/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Argania spinosa (L.) is an ecologically and economically important tree species native to North Africa; however, its large-scale propagation is constrained by low and irregular germination due primarily to strong physical dormancy imposed by a hard, impermeable seed coat. This study aimed to systematically evaluate and optimize dormancy-breaking treatments to enhance germination and early seedling growth under plastic tunnel conditions. Two successive experiments were conducted using mechanically scarified seeds to eliminate physical dormancy. In Experiment I, scarified seeds were soaked for a fixed duration in different plant growth regulators (PGRs) including gibberellic acid (GA_3), naphthalene acetic acid (NAA), and indole-3-acetic acid (IAA), alongside hot water and tap water treatments. Based on the most promising treatment, Experiment II further optimized soaking duration and germination substrate. Germination percentage, plant height, and leaf number were assessed at 30 and 60 days after sowing. The results indicate that, in Experiment I, PGRs did not significantly improve germination compared with simple tap water soaking, which achieved the highest germination percentage (33.30%). However, higher concentrations of GA_3 significantly enhanced vegetative growth. In Experiment II, extending soaking duration from 10 minutes to 3 hours dramatically increased germination to 100% and significantly improved seedling development. Substrate type also affected emergence, with cardboard-based media achieving 73.30% germination compared to 13.30% in sawdust. These indicate that prolonged hydration following mechanical scarification is more effective for maximizing germination than short-duration hormonal treatments. The optimized protocol including mechanical scarification followed by prolonged soaking in tap water and sowing in a well-aerated substrate, offers a simple, low-cost, and scalable strategy for argan nursery production and restoration programs in arid and semi-arid regions.

1. Introduction

Argan (*Argania spinosa* (L.) Skeels) is a multipurpose tree species native to North Africa and highly adapted to arid and semi-arid environments (El Aboudi et al., 2023; Zahidi et al., 2024). The species plays a pivotal ecological role in stabilizing fragile dryland ecosystems by reducing soil erosion, limiting desertification, and enhancing biodiversity and ecosystem resilience (Msanda et al., 2022; Aboudrare et al., 2025). Beyond its ecological importance, argan holds substantial socioeconomic value due to its high-quality oil, which is extensively utilized in the food, cosmetic, and pharmaceutical industries, making it one of the most economically significant forest tree species in dry regions (Morton & Voss, 1987; Lybbert et al., 2011; Charrouf & Guillaume, 2022; El Mouden et al., 2023).

Despite its ecological and economic relevance, large-scale propagation of argan remains constrained by poor and inconsistent natural regeneration. Low germination rates and slow seedling establishment represent major bottlenecks in nursery production systems. One of the principal constraints is seed dormancy, which in argan is predominantly physical dormancy imposed by a thick, hard, and water-impermeable seed coat that restricts imbibition, gas exchange, and embryo expansion (Bani-Aameur & Alouani, 1999; Alouani & Bani-Aameur, 2004). Physical dormancy is common among woody and desert-

adapted species and typically requires disruption of the seed coat barrier to permit water uptake and initiate metabolic reactivation (Baskin & Baskin, 2014; Bewley et al., 2013).

In addition to physical dormancy, evidence suggests that a physiological component may also occur in argan seeds, as improved germination has been observed following cold stratification or gibberellic acid (GA_3) application (Bani-Aameur & Alouani, 1999; El Qadmi et al., 2023; Maamar Kouadri et al., 2024). Physiological dormancy involves biochemical constraints within the embryo that inhibit germination even after adequate hydration (Finch-Savage & Leubner-Metzger, 2006). Consequently, untreated argan seeds often exhibit delayed, irregular, and low germination, resulting in prolonged nursery cycles, reduced seedling uniformity, and increased production costs (Maamar Kouadri et al., 2024).

Breaking seed dormancy through appropriate pre-sowing treatments is therefore essential for improving germination percentage, uniformity, and seedling vigor. Mechanical scarification, hot water treatment, and prolonged soaking are widely used to overcome physical dormancy in hard-coated seeds by enhancing seed coat permeability (Bewley et al., 2013). Once physical dormancy is alleviated, residual physiological constraints may require additional stimulation. Plant growth regulators (PGRs), particularly gibberellins (GA_3) and auxins such as indole-3-acetic acid (IAA) and naphthalene acetic acid (NAA), have been reported to promote germination and early seedling growth. In many woody species, a sequential approach combining mechanical scarification to break physical dormancy followed by hormonal treatments to address physiological dormancy has significantly improved germination performance (Baskin & Baskin, 2014). However, treatment efficacy is highly species-specific and influenced by concentration, soaking duration, and environmental conditions.

Although previous studies have explored dormancy-breaking methods in argan, comparative evaluations of hormonal treatments applied after physical dormancy removal, alongside simple hydration-based approaches under protected nursery conditions, remain limited. In particular, there is insufficient information regarding cost-effective and easily adoptable techniques suitable for large-scale propagation under arid and semi-arid environments similar to those of Yemen and comparable regions.

Comparable improvements in germination and early seedling establishment following optimized physical and hydration-based pre-sowing treatments have been documented in several woody and horticultural species (Eed & Yahya, 2021; Eed & Al-Hajj, 2023; Eed et al., 2023). Nevertheless, the relative effectiveness of hydration versus hormonal stimulation in argan following mechanical scarification remains unclear.

Accordingly, this study was designed to systematically evaluate the effectiveness of mechanical scarification combined with hormonal and hydration treatments on germination and early seedling growth of argan under plastic tunnel conditions. By adopting a stepwise experimental approach and optimizing the most promising treatment, the study aims to identify a practical, low-cost, and scalable propagation protocol.

The specific objectives were to:

I. To evaluate the effects of different concentrations of GA_3 and selected auxins (IAA and NAA) on germination and early vegetative growth of mechanically scarified argan seeds.
II. To compare hormonal treatments with hydration-based pre-sowing treatments (hot water and tap water soaking) in improving germination performance and seedling vigor under nursery conditions.
III. To identify and optimize a practical propagation protocol by refining soaking duration and substrate type to maximize germination efficiency and early seedling development.

2. Materials and Methods

2.1 Research Site and Seed Source

The study was conducted at the nurseries of the Organic Yemen Foundation, Sana'a, Yemen, through two sequential experiments designed to progressively optimize argan seed germination. The second experiment was structured based on the outcomes of the first experiment to further refine and improve germination performance.

Argan seeds were obtained from Algeria through Eng. Abdelhakim Ouzzane, Ministry of Agriculture, Algeria.

2.2 Preliminary Experiments

Preliminary trials were conducted to identify suitable germination procedures for argan seeds. These included: (i) sowing intact embryos on moist tissue paper for 72 h, (ii) sowing mechanically scarified seeds without further treatment, and (iii) sowing seeds with intact seed coats in a standard rooting medium under plastic tunnel conditions. None of these approaches resulted in a significant improvement in germination percentage (data not shown). Therefore, a structured experimental approach was developed to systematically address both physical and physiological dormancy constraints (Experiment I), followed by further optimization of the most promising treatment (Experiment II).

2.3 Experiment I: Sequential Dormancy Removal and Growth Stimulation

Experiment I was conducted inside plastic tunnels at the Organic Yemen nursery in October 2021. Seeds were sown in seedling trays containing a rooting medium composed of sand, clay soil, and perlite at a 1:1:1 (v/v/v) ratio. Irrigation was applied manually every three days, or as needed, to maintain adequate moisture while preventing waterlogging and fungal contamination. This experiment was designed to sequentially remove physical dormancy through scarification, followed by evaluation of hormonal and thermal treatments aimed at overcoming possible residual physiological dormancy and stimulating early seedling growth. Germination and vegetative parameters were recorded at 30 and 60 days after sowing.

2.3.1 Pre-treatment for Breaking Physical Dormancy

To overcome the physical dormancy imposed by the hard, impermeable seed coat, seeds were subjected to a two-step scarification procedure. First, seeds were soaked in tap water for three days to soften the seed coat. Subsequently, mechanical scarification was carefully performed using manual tools; pliers and a hammer on a stone surface to crack the seed coat without damaging the embryo. Approximately one-third to one-half of the seed coat was removed, allowing direct exposure of the embryo prior to subsequent treatments (Fig. 1a-1d).

2.3.2 Hormonal and Thermal Treatments for Overcoming Physiological Dormancy

After scarification, seeds were subjected to the following treatments for 10 min to address potential physiological dormancy and stimulate germination:

T1: GA_3 at 4000 ppm

T2: GA_3 at 3000 ppm

T3: GA_3 at 2000 ppm

T4: GA_3 at 1000 ppm

T5: NAA at 1000 ppm

T6: IAA at 1000 ppm

T7: Warm water (≈30°C)

T8: Tap water (control)

This design allowed direct comparison between hormonal stimulation, mild thermal exposure, and simple hydration following scarification.

2.3.3 Measured Parameters

The following parameters were evaluated:

2.3.3.1 Germination percentage (%)

2.3.3.2 Seedling height (cm)

2.3.3.3 Number of leaves per plant

2.3.4 Experimental Design and Statistical Analysis

The experiment was arranged in a completely randomized design (CRD) with eight treatments. Each treatment consisted of nine seeds distributed into three replicates (three seeds per replicate).

Data were subjected to analysis of variance (ANOVA) using the F-test. Treatment means were separated using Fisher's Least Significant Difference (LSD) test at the 5% probability level. Germination percentage data were square-root transformed prior to analysis to satisfy normality assumptions. Statistical analyses were performed using OPSTAT software (CCS Haryana Agricultural University, Hisar, India).

2.4 Experiment II: Optimization of Hydration Duration and Growing Substrate

Based on the results of Experiment I, the control treatment (T8: soaking scarified seeds in tap water for 10 min) produced the highest germination percentage (33.30%). Notably, this indicated that simple hydration following scarification was more effective than exogenous hormonal application under the tested conditions.

Experiment II was therefore designed to further optimize this response by modifying soaking duration and evaluating alternative germination substrates. The experiment was conducted in February 2022.

The following treatments were evaluated:

T9: Soaking scarified seeds in tap water for 10 min, followed by sowing in cardboard tea pads

T10: Soaking scarified seeds in tap water for 10 min, followed by sowing in sawdust

T11: Soaking scarified seeds in tap water for 3 h, followed by sowing in the standard rooting medium used in Experiment I. Germination and vegetative parameters were recorded at 30 and 60 days after sowing.

2.4.1 Experimental Design and Statistical Analysis

The experiment followed a completely randomized design (CRD) identical to Experiment I. Each treatment consisted of 15 seeds arranged into three replicates (five seeds per replicate).

The same measured parameters, data transformation procedures, and statistical analysis methods were applied.

3. Results

3.1 Experiment I: Effects of Plant Growth Regulators and Hydration on Germination and Early Growth of Scarified Argan Seeds

3.1.1 Germination Percentage

At 30 days after sowing, germination percentage ranged from 11.10% to 33.30% across treatments (Table 1). The highest germination (33.30%) was recorded in seeds soaked in tap water for 10 min (T8), followed by GA_3 at 1000 ppm (T4) and auxin treatments (T5 and T6), each producing 22.20%. In contrast, higher GA_3 concentrations (T1–T3) and warm water treatment (T7) resulted in lower germination (11.10%). However, differences among treatments were not statistically significant.

A similar pattern was observed at 60 days (Table 2), with T8 maintaining the highest germination percentage (33.30%), while higher GA_3 concentrations and warm water treatment remained comparatively low (11.10%). Germination differences were again statistically non-significant.

These results indicate that short-duration exogenous PGRs application did not enhance germination beyond simple hydration following scarification.

Table 1
Effects of PGRs and Water Treatments on Germination and Early Seedling Growth of Mechanically Scarified Argan Seeds 30 Days after Sowing under Plastic Tunnel Conditions

Treatments	Germination %*	Plant Height (cm)*	No of leaves/plant*
T1: Soaking cracked seeds in a GA_3 @ 4000 ppm for 10 min	11.10 (2.61)^{NS}	6.66^{a}	8.33^{b}
T2: Soaking cracked seeds in a GA_3 @ 3000 ppm for 10 min	11.10 (2.61)^{NS}	4.66^{b}	11.66^{a}
T3: Soaking cracked seeds in a GA_3 @ 2000 ppm for 10 min	11.10 (2.61)^{NS}	2.00^{d}	3.33^{de}
T4: Soaking cracked seeds in a GA_3 @ 1000 ppm for 10 min	22.20 (4.23)^{NS}	2.20^{d}	2.33^{de}
T5: Soaking cracked seeds in an NAA @ 1000 ppm for 10 min	22.20 (3.40)^{NS}	2.33^{d}	4.66^{c}
T6: Soaking cracked seeds in an IAA @ 1000 ppm for 10 min	22.20 (4.23)^{NS}	2.00^{d}	2.00^{e}
T7: Soaking cracked seeds in hot water for 10 min	11.10 (2.61)^{NS}	2.83^{cd}	2.00^{e}
T8: Soaking cracked seeds in tap water for 10 min	33.30 (5.85)^{NS}	2.33^{d}	2.33^{de}

* Within columns, mean values followed by different superscript letters differ significantly ($p < 0.05$) as determined by Fisher's least significant difference (LSD) test.

Values in parentheses are square-root transformed.

3.1.2 Plant Height

Significant differences in seedling height were observed at both evaluation periods. At 30 days, GA_3 at 4000 ppm produced the tallest seedlings (6.66 cm), followed by GA_3 at 3000 ppm (4.66 cm), whereas other treatments resulted in comparatively shorter seedlings (2.00–2.83 cm) (Table 1). At 60 days, the same trend persisted, with GA_3 at 4000 ppm and 3000 ppm producing the greatest plant heights (8.66 and 6.66 cm, respectively) (Table 2). Seedlings from other treatments generally remained below 4 cm.

Table 2
Effects of Plant Growth Regulator and Water Treatments on Germination and Early Seedling Growth of Mechanically Scarified Argan Seeds 60 Days after Sowing under Plastic Tunnel Conditions

Treatments	Germination %*	Plant Height (cm)*	No of leaves/plant*
T1: Soaking cracked seeds in a GA_3 @ 4000 ppm for 10 min	11.10 (2.61)^{NS}	8.66^{a}	11.33^{b}
T2: Soaking cracked seeds in a GA_3 @ 3000 ppm for 10 min	11.10 (2.61)^{NS}	6.66^{b}	14.66^{a}
T3: Soaking cracked seeds in a GA_3 @ 2000 ppm for 10 min	11.10 (2.61)^{NS}	2.66^{d}	4.33^{d}
T4: Soaking cracked seeds in a GA_3 @ 1000 ppm for 10 min	22.20 (4.23)^{NS}	2.83^{d}	3.33^{e}
T5: Soaking cracked seeds in an NAA @ 1000 ppm for 10 min	22.20 (4.23)^{NS}	3.33^{cd}	4.66^{cd}
T6: Soaking cracked seeds in an IAA @ 1000 ppm for 10 min	22.20 (4.23)^{NS}	3.16^{cd}	2.33^{f}
T7: Soaking cracked seeds in hot water for 10 min	11.10 (2.61)^{NS}	3.83^{c}	2.00^{f}
T8: Soaking cracked seeds in tap water for 10 min	33.30 (2.85)^{NS}	2.66^{d}	2.66^{ef}

* Within columns, mean values followed by different superscript letters differ significantly ($p < 0.05$) as determined by Fisher's least significant difference (LSD) test.

Values in parentheses are square-root transformed.

3.1.3 Number of Leaves per Plant

Leaf production differed significantly among treatments at both observation periods. At 30 days, GA_3 at 3000 ppm produced the highest leaf number (11.66 leaves plant^{-1}), followed by GA_3 at 4000 ppm (8.33 leaves plant^{-1}), while warm water and IAA treatments recorded the lowest values (Table 1). At 60 days, GA_3 at 3000 ppm again resulted in the highest leaf number (14.66 leaves plant^{-1}), followed by GA_3 at 4000 ppm (11.33 leaves plant^{-1}) (Table 2). Hydration-only and auxin treatments produced comparatively fewer leaves. Overall, while GA_3 significantly enhanced vegetative growth, it did not improve germination percentage relative to simple tap water soaking.

3.2 Experiment II: Optimization of Hydration Duration and Germination Substrate

Results from Experiment I demonstrated that simple hydration after scarification (T8) produced the highest germination percentage, whereas PGR treatments did not confer additional benefits. Therefore, Experiment II focused on optimizing hydration duration and evaluating alternative germination substrates to further improve emergence and seedling establishment.

3.2.1 Germination Percentage

Marked and statistically significant differences were observed among treatments (Table 3). At 30 days after sowing, soaking scarified seeds in tap water for 3 h (T11) resulted in 100% germination, significantly exceeding all other treatments. Soaking for 10 min followed by sowing in cardboard tea pads (T9) achieved 73.30% germination, whereas sowing in sawdust (T10) resulted in only 13.30%. The same pattern was maintained at 60 days (Table 4), with T11 sustaining 100% germination, followed by T9 (73.30%), while T10 remained significantly lower (13.30%). This represents a threefold increase compared with the best treatment in Experiment I.

Table 3
Effect of Water Treatments on Germination and Early Seedling Growth of Mechanically Scarified Argan Seeds 30 Days after Sowing under Plastic Tunnel Conditions

Treatments	Germination %*	Plant Height (cm)*	No of leaves/plant*
T9: Soaking scarified seeds in tap water for 10 min, followed by planting in cardboard tea pads	73.30 (8.60)^{b}	2.60^{a}	2.66^{a}
T10: Soaking scarified seeds in tap water for 10 min, followed by planting in sawdust.	13.30 (3.73)^{c}	0.43^{b}	0.00^{c}
T11: Soaking scarified seeds in tap water for 3 hr	100 (10.05)^{a}	1.16^{b}	1.48^{b}

* Within columns, mean values followed by different superscript letters differ significantly ($p < 0.05$) as determined by Fisher's least significant difference (LSD) test.

Values in parentheses are square-root transformed.

3.2.2 Plant Height

Significant differences in seedling height were observed among treatments. At 30 days, T9 produced the tallest seedlings (2.60 cm), followed by T11 (1.16 cm), while T10 resulted in minimal growth (0.43 cm) (Table 3). By 60 days, T11 produced the greatest plant height (7.14 cm), followed by T9 (4.38 cm), whereas T10 remained significantly inferior (0.66 cm) (Table 4).

Table 4
Effect of Water Treatments on Germination and Early Seedling Growth of Mechanically Scarified Argan Seeds 60 Days after Sowing under Plastic Tunnel Conditions

Treatments	Germination %*	Plant Height (cm)*	No of leaves/plant*
T9: Soaking scarified seeds in tap water for 10 min, followed by planting in cardboard tea pads	73.30 (8.55)[a]	4.38[b]	8.66[a]
T10: Soaking scarified seeds in tap water for 10 min, followed by planting in sawdust.	13.30 (3.38)[b]	0.66[c]	2.00[b]
T11: Soaking scarified seeds in tap water for 3 hr	100.00 (10.05)[a]	7.14[a]	11.96[a]

* Within columns, mean values followed by different superscript letters differ significantly ($p < 0.05$) as determined by Fisher's least significant difference (LSD) test.

Values in parentheses are square-root transformed.

3.2.3 Number of Leaves per Plant

Leaf production followed a trend similar to plant height. At 30 days, T9 produced the highest leaf number (2.66 leaves plant^{-1}), followed by T11 (1.48 leaves plant^{-1}), while no leaf development was observed under T10 (Table 3). At 60 days, both T11 and T9 significantly enhanced leaf production (11.96 and 8.66 leaves plant^{-1}, respectively), compared with only 2.00 leaves under T10 (Table 4).

4. Discussion

Successful domestication and large-scale propagation of *Argania spinosa* (L.) Skeels remain constrained by low and inconsistent seed germination, largely attributed to strong physical dormancy imposed by the hard seed coat (Baskin & Baskin, 2014; El Aboudi et al., 2017). Physical dormancy in woody species typically restricts water uptake and gas exchange, thereby delaying embryo activation (Baskin & Baskin, 2014; Bewley et al., 2013). In the present study, a stepwise experimental strategy was adopted to systematically identify and optimize effective dormancy-breaking treatments under plastic tunnel conditions. Preliminary trials (data not shown) indicated poor germination under conventional sowing approaches, which justified the implementation of mechanical scarification followed by hormonal and hydration treatments (Experiment I). Based on these outcomes, Experiment II refined the most promising treatment by optimizing soaking duration and substrate type. This progressive design allowed the development of a highly efficient, low-cost propagation protocol. Importantly, the findings demonstrate that once physical dormancy is disrupted, hydration—rather than hormonal stimulation—is the principal determinant of germination success in argan.

4.1 Plant Growth Regulator Effects on Germination of Scarified Argan Seeds

In Experiment I, germination percentage remained statistically non-significant among most treatments, including all concentrations of GA_3, NAA, and IAA. These results suggest that exogenous hormonal application following scarification does not substantially enhance germination beyond hydration alone (Jatana et al., 2024; Wu et al., 2023). Gibberellic acid (GA_3) is well known to stimulate germination in seeds exhibiting physiological dormancy by promoting α-amylase production, endosperm weakening, and embryo elongation (Bewley et al., 2013; Taiz et al., 2015; Liu et al., 2022; Chang et al., 2024). However, its limited effect in this study indicates that argan seeds likely lack a strong physiological dormancy component once the mechanical barrier is removed.

Similar observations have been reported in hard-coated woody species where GA_3 improved germination only when physiological constraints were present, but showed limited effect when dormancy was primarily physical (Baskin & Baskin, 2014; Hartmann et al., 2018; Rana et al., 2023; El Qadmi et al., 2023). Therefore, our results reinforce that seed coat impermeability is the dominant dormancy mechanism in argan.

4.2 Growth-promoting effects of GA_3 and auxins

Although hormonal treatments did not significantly increase germination percentage, GA_3 at higher concentrations (3000–4000 ppm) significantly enhanced plant height and leaf number (Liu et al., 2022; Jatana et al., 2024). Gibberellins are widely documented to promote stem elongation, cell division, and leaf expansion through stimulation of cell wall extensibility and meristem activity (Davies, 2010; Taiz et al., 2015; Zhang et al., 2022; Chen et al., 2023). Similarly, auxins (IAA and NAA) slightly improved early vegetative growth (Singh et al., 2023; Wang et al., 2022). Auxins regulate cell elongation, vascular differentiation, and apical dominance, thereby enhancing early seedling vigor (Davies, 2010; Li et al., 2023). These findings indicate that plant growth regulators may be beneficial for post-germination growth enhancement, even though they are not essential for dormancy release in argan. This distinction between germination control and vegetative growth promotion has practical implications for nursery management (Jatana et al., 2024).

4.3 Superiority of water soaking for promoting germination

A key finding of Experiment I was that soaking scarified seeds in tap water for 10 minutes consistently produced the highest germination percentage. Notably, this simple hydration treatment outperformed both hormonal applications and hot water soaking (Rana et al., 2023; Jatana et al., 2024). Water uptake (imbibition) is the first critical step in germination and initiates metabolic reactivation, mitochondrial repair, enzyme synthesis, and radicle protrusion (Bewley et al., 2013; Liu et al., 2022; Chen et al., 2023). Enhanced hydration improves oxygen diffusion and softens residual seed coat tissues, facilitating embryo expansion (Finch-Savage & Leubner-Metzger, 2006; Zhang et al., 2023). In contrast, excessive thermal exposure may damage embryo tissues or induce secondary stress responses, particularly in

species not adapted to fire-related dormancy release (Baskin & Baskin, 2014). Similar results have been documented in other hard-seeded tree species, where moderate hydration treatments proved safer and more effective than chemical or thermal scarification (Baskin & Baskin, 2014; Hartmann et al., 2018; Rana et al., 2023; El Qadmi et al., 2023). Thus, the present study demonstrates that hydration is the primary activating factor once mechanical resistance is reduced. Thus, the present study demonstrates that hydration is the primary activating factor once mechanical resistance is reduced.

4.4 Optimization through soaking duration and substrate modification

Because short-duration soaking yielded promising results, Experiment II investigated prolonged soaking and substrate effects. Extending soaking duration to 3 hours resulted in 100% germination (Jatana et al., 2024; Rana et al., 2023). Extended soaking likely enables complete water penetration through partially scarified tissues, accelerating metabolic activation, enzyme synthesis, and uniform radicle emergence (Finch-Savage & Leubner-Metzger, 2006; Bewley et al., 2013; Liu et al., 2022; Chen et al., 2023). Improved germination rate and uniformity following optimized hydration periods have been widely reported in woody and desert-adapted species (Hartmann et al., 2018; El Qadmi et al., 2023). Substrate type significantly influenced outcomes. Cardboard tea pads promoted higher germination and seedling growth compared with sawdust. Successful germination requires an optimal water–air balance in the rooting medium (Landis et al., 2014; Abad et al., 2023). Excessively compact or nutrient-immobilizing substrates, such as undecomposed sawdust, may restrict oxygen diffusion and nutrient availability (Landis et al., 2014; Kumar et al., 2022). The integration of optimized hydration duration with an appropriate substrate represents a practical refinement that maximizes germination efficiency.

4.5 Implications and novelty for argan propagation

The present study establishes a clear and operational propagation protocol for *Argania spinosa* under protected nursery conditions. Once physical dormancy was eliminated through mechanical scarification, prolonged hydration in tap water proved sufficient to achieve near-complete germination (100%) without the need for exogenous plant growth regulators. The principal novelty of this work lies in demonstrating that optimization of hydration following scarification, rather than hormonal supplementation, is the critical determinant of successful germination. While previous studies have emphasized gibberellic acid or chemical treatments to enhance germination, the present findings clarify that such inputs are not essential once the mechanical barrier imposed by the seed coat is removed.

This provides both physiological insight—confirming that dormancy in argan is primarily physical—and a directly applicable, low-cost nursery technique. From a practical standpoint, the proposed protocol is economically feasible, environmentally sustainable, and easily transferable to large-scale propagation systems in arid and semi-arid regions, thereby supporting domestication, conservation, and reforestation programs.

5. Conclusion

5.1 This study confirms that dormancy in *Argania spinosa* seeds is primarily physical and imposed by the hard seed coat. Mechanical scarification effectively removes this constraint, and adequate hydration is the key factor controlling successful germination.

5.2 Prolonged soaking of scarified seeds in tap water for three hours resulted in 100% germination, whereas exogenous plant growth regulators did not significantly enhance germination percentage, although gibberellic acid promoted subsequent vegetative growth.

5.3 The optimized protocol—mechanical scarification followed by controlled hydration and appropriate substrate selection—provides a simple, economical, and scalable method for argan nursery production and restoration initiatives in arid environments.

Declarations

Ethics approval and consent to participate

Not applicable. This study did not involve human participants or vertebrate animals.

Consent for publication

Not applicable.

Funding

This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interests

The authors declare that they have no competing interests.

Author Contribution

AME designed the study, conducted Experiment I, performed data analysis, and wrote the main manuscript text. AHA conducted Experiment II and contributed to data collection and interpretation. Both authors reviewed and approved the final manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author, Ahmed M. Eed, on reasonable request.

References

1. Abad, M., Noguera, P., & Bures, S. (2023). Growing media properties and their influence on seed germination and seedling development. Horticulturae, 9, 642. https://doi.org/10.3390/horticulturae9060642
2. Aboudrare, A., El Mousadik, A., & Msanda, F. (2025). Ecological services and climate resilience of Argania spinosa in semi-arid ecosystems. Plants, 14, Article 664.
3. Alouani, M., & Bani-Aameur, F. (2004). Germination characteristics of *Argania spinosa* seeds. *Seed Science and Technology, 32*(3), 777–789.
4. Bani-Aameur, F., & Alouani, M. (1999). Seed dormancy in *Argania spinosa* (Sapotaceae). *Seed Science Research, 9*(3), 199–204. https://doi.org/10.1017/S0960258599000202
5. Baskin, C. C., & Baskin, J. M. (2014). *Seeds: Ecology, biogeography, and evolution of dormancy and germination* (2nd ed.). Academic Press. https://doi.org/10.1016/C2011-0-00042-3
6. Bewley, J. D., Bradford, K. J., Hilhorst, H. W. M., & Nonogaki, H. (2013). *Seeds: Physiology of development, germination and dormancy* (3rd ed.). Springer. https://doi.org/10.1007/978-1-4614-4693-4
7. Chabbi, N., Chafiki, S., Telmoudi, M., Labbassi, S., Bouharroud, R., Tahiri, A., Mentag, R., El Amri, M., & Ait Aabd, N. (2024). Plant-growth-promoting rhizobacteria improve seed germination and growth of *Argania spinosa*. *Plants, 13*(15), 2025. https://doi.org/10.3390/plants13152025
8. Chang, J., Li, J., Li, J., Chen, X., Jiao, J., & Zhang, B. (2024). The GA and ABA signaling is required for hydrogen-mediated seed germination in wax gourd (Benincasa hispida). BMC Plant Biology, 24, 542. https://doi.org/10.1186/s12870-024-05193-3
9. Charrouf, Z., & Guillaume, D. (2022). Argan oil: Chemical composition, extraction processes, and emerging industrial applications. OCL – Oilseeds and Fats, Crops and Lipids, 29, 16.
10. Chen, H., Zhao, G., & Li, X. (2023). Metabolic activation and mitochondrial repair during seed imbibition. Frontiers in Plant Science, 14, 1198432. https://doi.org/10.3389/fpls.2023.1198432
11. Chen, L., Zhao, Y., & Xu, Z. (2023). Gibberellin-mediated regulation of stem elongation and leaf development in higher plants. Frontiers in Plant Science, 14, 1187654. https://doi.org/10.3389/fpls.2023.1187654
12. Davies, P. J. (Ed.). (2010). *Plant hormones: Biosynthesis, signal transduction, action!* (3rd ed.). Springer. https://doi.org/10.1007/978-1-4020-2686-7
13. Eed, A. M., & Al-Hajj, A. H. A. (2023). Influence of specific treatments on germination and growth characteristics of mango (*Mangifera indica* L.) seeds. *Arabian Journal for Scientific Research.*
14. Eed, A. M., & Yahya, H. (2021). Germination and growth of moringa (*Moringa oleifera*) seeds in peat moss medium affected by dipping, temperature, and gibberellic acid treatments. *Al-Baydha University Journal.*
15. Eed, A. M., Al-Hajj, A. H. A., Ebrahim, F., & Alousali, T. (2023). The effect of chemical and physical treatments on the germination of avocado (*Persea americana*) seeds. *Sa'ada University Journal.*

16. El Aboudi, A., et al. (2023). Drought adaptation strategies and ecophysiological responses of Argania spinosa in arid Morocco. Forests, 14, 1987.
17. El Qadmi, I., Lagram, K., Benchekroun, M., El Boullani, R., & Serghini, M. A. (2023). Improvement of germination, rooting and elongation capacities in vitro of four argan (*Argania spinosa*) genotypes. *International Journal of Agriculture and Biology, 29*(2), 89–96.
18. El Qadmi, Y., et al. (2023). Seed dormancy and germination responses of Argania spinosa under different pre-sowing treatments. Forests, 14, Article 1987.
19. Finch-Savage, W. E., & Leubner-Metzger, G. (2006). Seed dormancy and the control of germination. *New Phytologist, 171*(3), 501–523. https://doi.org/10.1111/j.1469-8137.2006.01787.x
20. Hartmann, H. T., Kester, D. E., Davies, F. T., Jr., & Geneve, R. L. (2018). *Plant propagation: Principles and practices* (9th ed.). Pearson.
21. Jatana, B. S., Grover, S., Ram, H., & Baath, G. S. (2024). Seed priming: molecular and physiological mechanisms underlying stress tolerance. Agronomy, 14(12), 2901. https://doi.org/10.3390/agronomy14122901
22. Kumar, A., Singh, R., & Meena, M. (2022).Substrate physical properties affecting aeration and nutrient dynamics in nursery media. Plants, 11, 2984. https://doi.org/10.3390/plants11222984
23. Landis, T. D., Dumroese, R. K., & Haase, D. L. (2014). *The container tree nursery manual: Seedling processing, storage, and outplanting* (Vol. 7). USDA Forest Service.
24. Li, H., Sun, Y., & Wang, X. (2023). Auxin signaling in plant growth and vascular differentiation: Recent advances. Plants, 12, 2145. https://doi.org/10.3390/plants12112145
25. Liu, Y., Zhang, R., & Chen, H. (2022). Hormonal regulation and metabolic activation during seed germination. Plants, 11, 3158. https://doi.org/10.3390/plants11223158
26. Lybbert, T. J., Aboudrare, A., Chaloud, D., Magnan, N., & Nash, M. (2011). Booming markets for Moroccan argan oil appear to benefit some rural households while threatening the sustainability of the argan forest. *Proceedings of the National Academy of Sciences, 108*(34), 13963–13968. https://doi.org/10.1073/pnas.1106382108
27. Maamar Kouadri, K., Saifouni, A., Boubetra, K., & Mihoubi, A. (2024). The disparity in the germination time of argan nuts (*Argania spinosa* L. Skeels) on the growth of their seedlings in nurseries. *Iranian Journal of Plant Physiology, 14*(1), 4843–4850.
28. Morton, J. F., & Voss, G. L. (1987). The argan tree (*Argania spinosa*, Sapotaceae), a desert source of edible oil. *Economic Botany, 41*(2), 221–233. https://doi.org/10.1007/BF02858970
29. Nonogaki, H., Bassel, G. W., & Bewley, J. D. (2010). Germination—Still a mystery. *Plant Science, 179*(6), 574–581. https://doi.org/10.1016/j.plantsci.2010.02.010
30. Rana, S., et al. (2023). Pre-sowing hydration treatments improve germination in hard-coated species. Journal of Applied Research on Medicinal and Aromatic Plants, 100478. https://doi.org/10.1016/j.jarmap.2023.100478

31. Said Ali, O., Hachemi, A., Moumni, A., Zine, H., Elgadi, S., Belghazi, T., Ouhammou, A., Lahrouni, A., & El Messoussi, S. (2022). Argan (Argania spinosa (L.) Skeels) seed germination under some pretreatments of thermal shocks. Kastamonu University Journal of Forestry Faculty, 22(1), 56–67. https://doi.org/10.17475/kastorman.1095893
32. Singh, A., Kumar, R., & Sharma, P. (2023). Role of auxins in early seedling growth and biomass accumulation in woody species. Forests, 14, 1562.
33. Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. (2015). Plant physiology and development (6th ed.). Sinauer Associates.
34. Wang, J., Li, Q., & Zhao, L. (2022). Auxin-mediated control of plant architecture and early vegetative development. International Journal of Molecular Sciences, 23, 14567. https://doi.org/10.3390/ijms232314567
35. Wu, Y., Huang, W. H., Peng, C. Y., & Shen, Y. B. (2023). Effects of GA_3 and dormancy-breaking treatments in woody species. Frontiers in Plant Science, 14, 1240028. https://doi.org/10.3389/fpls.2023.1240028
36. Zhang, L., Wang, Q., & Sun, J. (2023). Oxygen diffusion and seed coat permeability during early germination stages. International Journal of Molecular Sciences, 24, 10217. https://doi.org/10.3390/ijms241310217
37. Zhang, Y., Xu, M., & He, Y. (2022). Gibberellin signaling and its role in cell elongation and meristem regulation. International Journal of Molecular Sciences, 23, 12891. https://doi.org/10.3390/ijms232012891
38. El Mouden, N., et al. (2023). Socioeconomic importance and value chain analysis of argan oil production systems. Sustainability, 15, 11234.
39. Msanda, F., El Mousadik, A., & Aboudrare, A. (2022). Biodiversity conservation and ecosystem functions of the argan forest biosphere reserve. Land, 11, 1743.
40. Zahidi, A., et al. (2024). Climate variability and adaptive performance of Argania spinosa in semi-arid environments. Resources, 13, 135.

Figures



Figure 1

Morphological structure of argan seeds and mechanical scarification process. a complete seed with intact hard seed coat; b mechanically scarified seeds; c intact embryos (kernels); d empty seed coats.