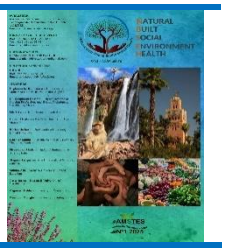
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Micrografting and Other Regeneration Techniques for the Argan Tree (*Argania spinosa*): A PRISMA-Based Systematic Review and Meta-Analysis

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Graphical Abstract

This study presents a systematic review and meta-analysis of propagation methods for the argan tree (*Argania spinosa*) using the PRISMA approach. It compares seed germination, which has low success rates, with cutting and grafting, which ensure faster rooting and genetic stability, and in vitro micropropagation, which shows promise but requires careful acclimatization. A bibliometric analysis highlights growing research interest since 2016, particularly in conservation. In response to environmental pressures, this study emphasises the need for an integrated approach that balances productivity and the sustainable preservation of this valuable resource.



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Abstract: The argan tree (*Argania spinosa*), native to southwestern Morocco, is essential for arid and semi-arid ecosystems, providing key products such as argan oil, which is vital for the local economy. But, it is facing increasing pressures from modern agriculture, deforestation, and climate change. This systematic review, using the PRISMA approach, evaluates various propagation methods, including seed germination and micropropagation. Seed germination is straightforward, but it has low success rates, whereas cutting and grafting offer faster rooting and preserve genetic characteristics. Bibliometric analyses indicate a growing research interest in the argan tree since 2016, particularly in the context of conservation. The acclimatization of in vitro plants is crucial for their success outside the laboratory. Collaboration among stakeholders is essential to balance economic viability and ecological sustainability.

Keyword: *Argania Spinosa, Propagation methods, PRISMA.*

Introduction

The argan tree (*Argania spinosa*) is a unique species of the Sapotaceae family, emblematic of the ecosystems in the arid and semi-arid climate regions of southwestern Morocco [1]. This tree is not only a symbol of resilience but also an economic pillar for rural communities, which have been exploiting its products and by-products since antiquity [2,3]. Argan oil has become one of the most sought-after and expensive vegetable oils worldwide, thanks to its diverse applications ranging from culinary use to cosmetic care [4–6]. Over the centuries, the distribution range of the argan tree has significantly declined, mainly because of pressure from modern agriculture, wood exploitation, and overgrazing, exacerbated by climate change [7,8].

The international recognition of the argan tree (*Argania spinosa*) was reinforced by its designation as a UNESCO Biosphere Reserve in 1998 and its inclusion in the Intangible Cultural Heritage list. Furthermore, the United Nations General Assembly, through Resolution 75/262 of 3 March 2021, proclaimed 10 May as the International Day of the Argan Tree [9,10], highlighting the global recognition of the tree's cultural and environmental significance. These initiatives not only underscore the ecological value of the argan tree but also emphasize its role in supporting traditional livelihoods.

Although the "Argan Oil Project", launched in the 1980s, has promoted sustainable development and the commercial use of argan oil [11,12], a thorough evaluation of the trade-offs between production and conservation remains essential. Understanding current threats and opportunities for innovation is crucial to ensuring a balance between economic profitability and ecosystem preservation. This requires collaboration among stakeholders, including local producers, researchers, and non-governmental organisations, to develop sustainable strategies that support both the community and the environment.

To meet the growing demand for argan oil, efforts are increasingly focused on improving propagation techniques. Traditionally, the generation of new plants relies on seed germination; but contemporary methods such as vegetative propagation through cutting, grafting, and tissue culture [13–15] offer promising opportunities for sustainability and yield enhancement.

This systematic review and meta-analysis assesses the effectiveness and sustainability of different propagation methods for the argan tree (*Argania spinosa*) using the PRISMA approach. The analysis compares the advantages and limitations of each technique, evaluating their potential for orchard revitalisation, support for circular economy initiatives, and the improvement of local livelihoods. The

ultimate goal is to identify optimal propagation strategies that contribute to the long-term sustainability of argan tree cultivation.

Materials and Methods

As part of this research, we adopted a systematic review method known as PRISMA (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*). This approach was designed to ensure more rigorous and less biased systematic reviews, thereby providing reliable data for scientists, stakeholders, and policymakers. We developed a rigorous internal protocol based on four stages:

Search Strategy

A systematic search strategy was developed to identify relevant literature. This strategy was adapted for two databases: Scopus and Web of Science. The search was conducted using the same keywords across both databases (Table 1), resulting in a higher number of retrieved articles. The study was designed to examine qualitative research findings published between 2000 and 2024, in accordance with specific eligibility criteria for inclusion and exclusion, detailed in Table 2.

Selection Criteria

The selection criteria were based on the PRISMA statement [16]. The search focused on identifying existing literature on the various propagation methods of the argan tree, exploring their advantages and limitations. These steps helped build a comprehensive database of qualitative studies published in reputable journals over the past 24 years. The definition of inclusion and exclusion criteria was crucial to ensuring that our research question remained focused, unique, and free from selection bias. All articles published before 2000 were excluded. The search was mainly limited to English and French articles, resulting in the exclusion of four research articles at this stage. A total of 63 records were extracted at this stage.

Quality Assessment

The study relied exclusively on original research articles and review papers. To maintain the quality of the review, all duplicate entries were carefully checked. Abstracts were reviewed to filter and analyse articles, ensuring the academic relevance of the included literature. A rigorous assessment of each research article was conducted at a later stage. Additionally, after filtering out duplicate records, 19 more articles were removed from the study. Ultimately, 63 articles were selected based on the previously defined inclusion and exclusion criteria. Figure 1 illustrates the inclusion and exclusion process at each stage, following the PRISMA statement.

Data Extraction

During the data extraction phase, eight articles were excluded as they did not focus on argan tree propagation. Thus, a total of 55 articles were retained. Each relevant article was read multiple times to validate the findings. Data were extracted by reviewing abstracts, identifying study objectives, and conducting a thorough reading of the articles. This systematic review was organised according to the identified theme, which focuses on the various propagation methods of the argan tree, along with their advantages and limitations.

Table 1. Research Approach for Systematic Review Process.

Database	**Research Approach**
Scopus	Title-Abstract-Keywords ("*Argania spinosa*" OR "*Argania spinosa* L." OR "argan tree") AND ("bouturage" OR "greffage" OR "propagation" OR "germination" OR "tissue culture")
Web of Science	Title-Abstract-Keywords ("*Argania spinosa*" OR "*Argania spinosa* L." OR "argan tree") AND ("bouturage" OR "greffage" OR "propagation" OR "germination" OR "tissue culture")

Table 2. Inclusion and Exclusion Criteria for the Systematic Review.

Criteria	**Inclusion**	**Exclusion**
Publication period	Between 2000 and 2024	Before 2000
Language	English, French	Languages other than English or French
Document Type	Articles, reviews	Reports, book chapters

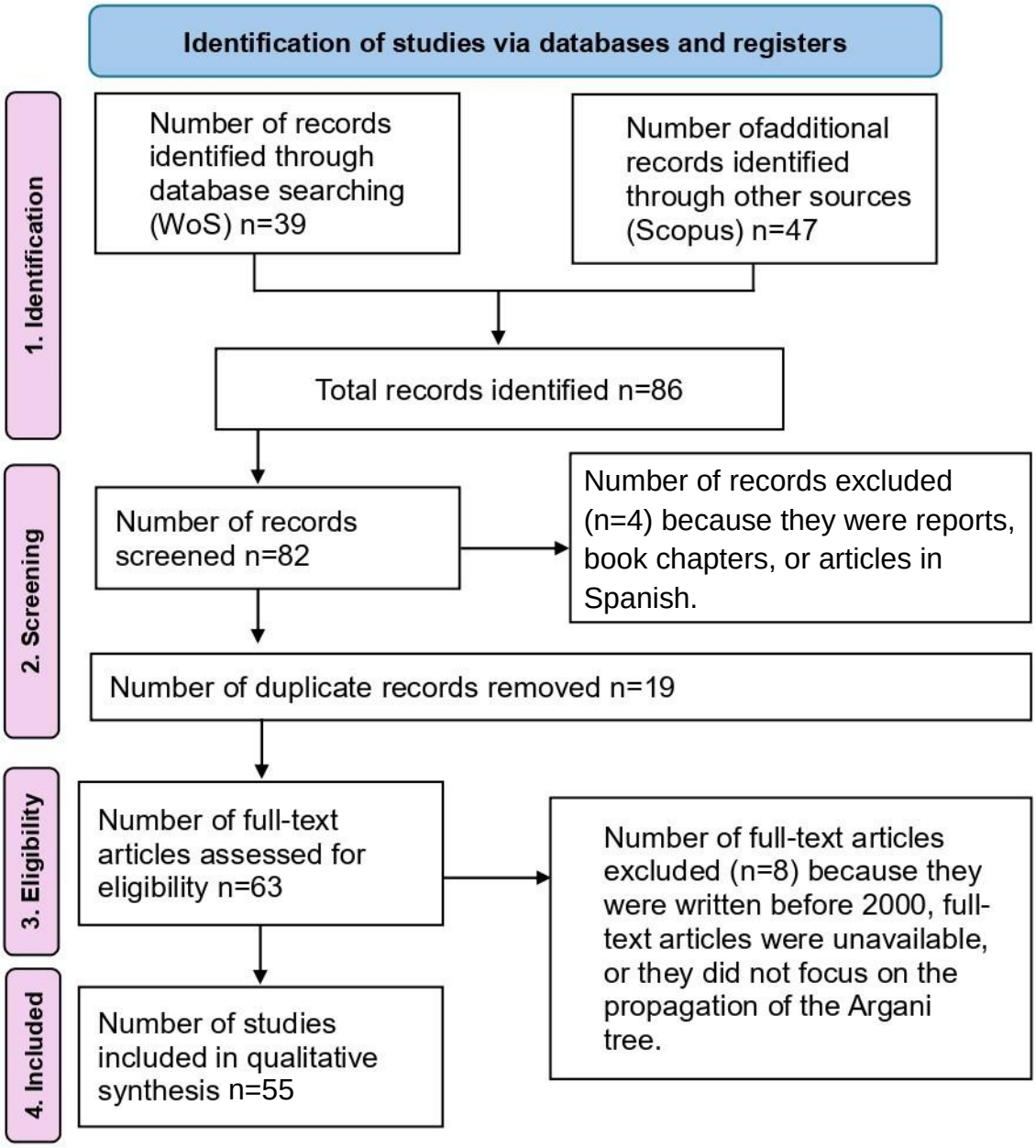


Figure 1. PRISMA 2020: flow diagram for new systematic reviews which included searches of databases and registers

Bibliometric Analysis

The primary objective of our bibliometric analysis and mapping [17] is to survey the scientific literature on *Argania spinosa* propagation. To achieve this, we used metadata extracted from published studies, such as the number of citations, the number of articles per year, titles, and keywords, obtained from various databases. In this study, our aim is to map and highlight the key trends in the literature regarding argan tree propagation methods, assessing their advantages and limitations.

We employed several tools to conduct comprehensive bibliometric analysis. VOSviewer13 (version 1.6.17) was used to perform various types of bibliometric analyses, including co-occurrence analysis, co-citation analysis, and bibliographic coupling analysis. Statistica® 10 software was used to generate response surface plots and perform statistical analysis of the data, including principal component analysis (PCA) (StatSoft, Inc., www.statsoft.com).

Results

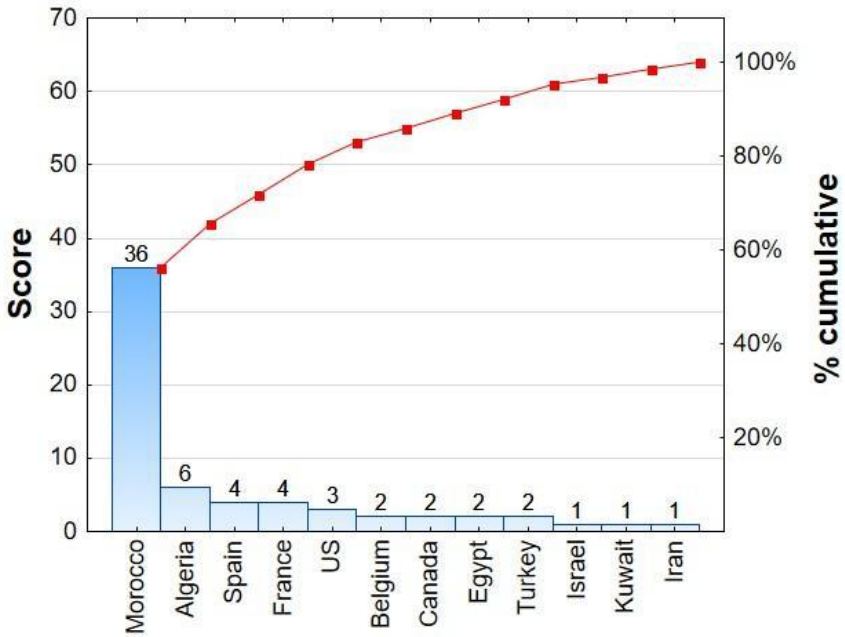


Figure 2. Publication distribution of reviewed articles by country.

The diagram represents the distribution of scores for articles on the argan tree by country, highlighting significant disparities in research on this topic.

Morocco stands out with a high score of 36, reflecting its importance as the native country of the argan tree and a leader in related research. In contrast, Algeria (6), Spain and France (4 each), as well

as the United States (3), show significantly lower contributions. The cumulative curve, reaching 100%, also illustrates that the majority of publications originate from Morocco. Other countries play a marginal role.

It is also important to note that in countries such as France, Spain, Germany, and the United States, most relevant publications are produced through international collaborations. This underscores the importance and potential of increased cooperation. Therefore, Moroccan researchers interested in argan tree studies are encouraged to strengthen their international collaborations in the future to maximize research and conservation efforts for this valuable species. By fostering these partnerships, they will be better equipped to safeguard the argan tree and its associated ecosystems while enriching collective knowledge of its benefits.

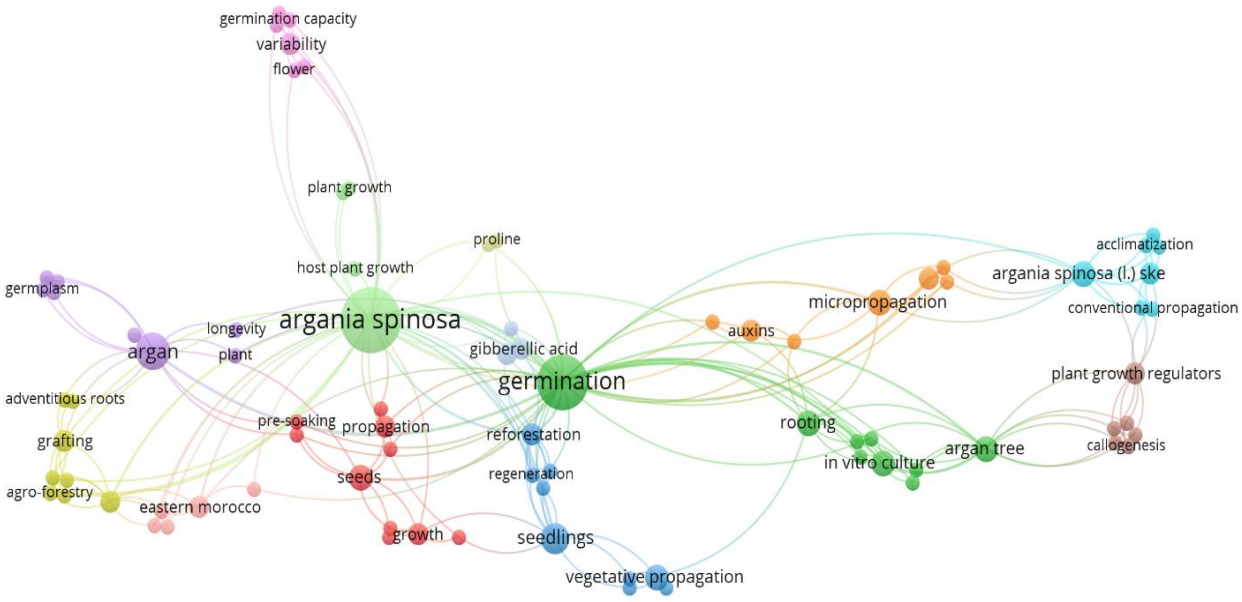


Figure 3. Co-occurrence analysis of author's keyword in VOSviewer.

Keywords play a crucial role in indexing scientific literature databases, as they suggest themes or aspects addressed in specific research articles. A co-occurrence network of author keywords was visualized using VOSviewer software (Figure 3). This analysis aimed to examine the frequency and co-occurrence of these keywords found in the retrieved data, with a total of 157 author keywords identified.

The mapping highlights the complex relationships between various keywords associated with research on the argan tree (*Argania spinosa*) and its germination process. At the centre of the network lies the term "germination", emphasizing its fundamental role in understanding seed development mechanisms. Surrounding this node, several clusters emerge, notably those related to propagation

methods such as micropropagation, sowing, tissue culture, and vegetative propagation (cutting and grafting).

Tissue culture enables laboratory reproduction under optimal conditions, ensuring high-quality, disease-resistant plants. Vegetative propagation, on the other hand, uses parts of the mother plant to generate new plants, making it an effective method for preserving desirable genetic traits.

Keywords such as "germination capacity" and "climatic conditions" highlight the impact of environmental factors on germination success. These interconnections reveal how a deeper understanding of these processes can enhance propagation strategies, which are essential for the conservation of the argan tree.

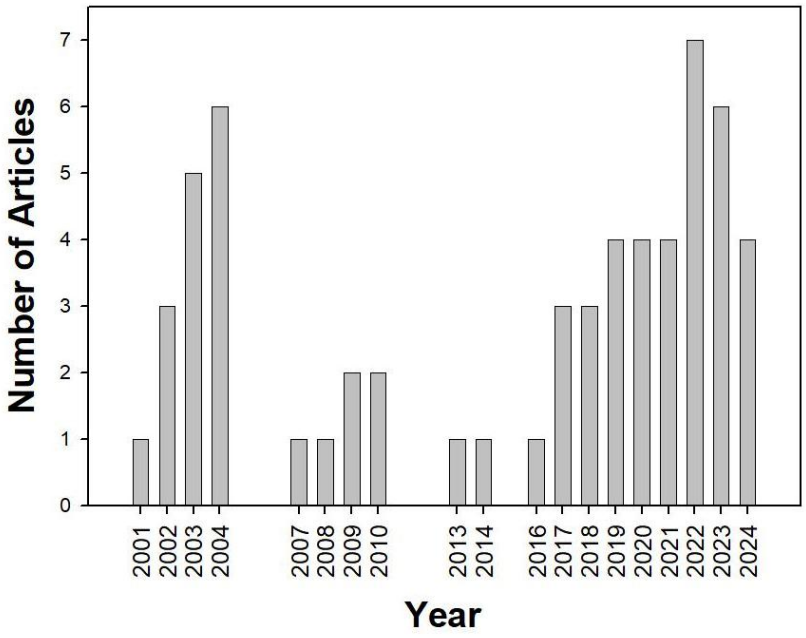


Figure 4. Publication distribution of reviewed articles by year.

Figure 4 illustrating the number of published articles on the argan tree from 2001 to 2024 reveals a significant evolution in research interest.

Between 2001 and 2005, academic output was very limited, often below two articles per year, suggesting a low level of interest in this topic. From 2006 to 2015, the number of publications remained relatively low, with some fluctuations, indicating diverse research priorities.

From 2016 onwards, a notable increase was observed, peaking at seven publications in that year, which could reflect a growing awareness of environmental issues and the socio-economic benefits associated with the argan tree. The years following, up to 2022, maintained sustained research interest, highlighted by another peak in 2022. Projections for 2023 and 2024 suggest a continuation of this momentum. This positive trend underscores the increasing importance of the argan tree,

encouraging researchers to strengthen their national and international collaborations to advance studies on its conservation and sustainable use

Discussion

Many relevant articles have focused on studying and evaluating various techniques aimed at overcoming challenges related to the germination, propagation, and cultivation of this unique species. These studies seek not only to promote the sustainable cultivation of the argan tree but also to support reforestation and restoration efforts for the precious argan forests.

Conventional Propagation of the Argan Tree

Seed Germination

The propagation of the argan tree (*Argania spinosa*) through seeds is a conventional method of great ecological and economic significance, particularly in the context of the semi-arid regions of Morocco.

Sexual propagation via seeds is crucial for maintaining the genetic diversity of argan tree populations. This is especially important for genetic improvement programmes. Elite lines resistant to biotic and abiotic stress can be identified and selected from seed-derived populations. Various studies have aimed to select argan tree genotypes with high resistance and resilience to drought [18,19] and salinity [20,21].

The advantages of propagating the argan tree via seeds are numerous. Firstly, this method is relatively simple, economically viable, and does not require advanced technology, making it accessible to local communities. Various authors agree that ecotypes from inland areas appear to be more drought tolerant. Consequently, they hold greater potential for the regeneration of Moroccan argan forests compared to coastal populations, which may be subjected to higher water stress [22-24].

Nevertheless, the propagation of the argan tree through seeds also presents certain drawbacks. One of the main problems is the low germination rate of seeds, which can be influenced by various external factors. Seed dormancy in the argan tree, often caused by its hard seed coat, represents a significant obstacle to germination. Gibberellins (GA) stimulate seed germination by suppressing the inhibitory effect of abscisic acid and promoting the release from dormancy [15,25-27].

Several factors influence the germination of argan seeds, including environmental conditions, pre-sowing treatments, and genetic characteristics. Among these factors, soil moisture, temperature, shade, and light availability are fundamental [28,29]. Studies indicate that the optimal temperature for argan seed germination is generally about 25°C [30,31]. Other research shows that the highest

germination rate (85.28%) is observed under non-shaded conditions, and a peat-based substrate supports a germination rate of 78.75% [32].

Moreover, certain agricultural practices, such as scarification, which alters the outer seed coat, can be implemented to improve germination rates. Additionally, physical or chemical pre-treatments facilitate water penetration into the endosperm, thereby enhancing the germination process [15,26].

To maintain the viability of argan seeds, it is essential to store them at low temperatures. Storage at ambient temperature significantly reduces their germination rate [33], whereas refrigeration at 4°C immediately after harvest helps preserve their effectiveness over a prolonged period [28,34,35]. Additionally, the viability of argan seeds stored for an extended period, up to 17 years, was determined for the first time using the tetrazolium staining test [36].

From an ecological interaction standpoint, the presence of other plant species can also influence the germination of argan seeds. Some plants can create a favourable microenvironment by providing shade and moisture, which facilitates germination, and others may compete for essential resources needed for the development of young seedlings [37].

Vegetative Propagation of the Argan Tree: Cutting and Grafting

The vegetative propagation of the argan tree (*Argania spinosa*) is an effective propagation strategy that enables the production of new plants from somatic parts of the mother plant, thereby bypassing the seed germination phase. Among the commonly used techniques, cutting and grafting are the most favoured because of their speed and efficiency, as they produce plants with the same genetic characteristics as the original plant [38].

Research on argan tree cutting and rooting has identified several factors influencing the success of this propagation method. Environmental parameters such as temperature, humidity, and light exposure, as well as the age of the plants, are crucial in the rooting capacity of cuttings. According to Ait Hammou *et al.* [39], moderate temperatures and high humidity, depending on the age of the cuttings, significantly improve the rooting rate.

Furthermore, the diameter and quality of cuttings are also crucial. Benbya *et al.* [13] found that the optimal vegetative propagation of argan trees occurs with semi-hardwood cuttings measuring 0.4 cm in diameter and bearing four leaves, initially planted in fine sand substrate for root initiation, followed by cultivation in a mixture of fine sand and peat moss for hardening. Similarly, Nouaim *et al.* [40] noted that the success of vegetative multiplication depends on the age of the mother plant, whether from mature trees or young shoots from three-year-old mother plants, and that rooting rates vary depending on genotype. The mass propagation of argan tree cuttings is limited because of fungal diseases [41] and challenges related to rooting and survival during field transplantation [13,42,43].

Ait Hammou *et al.* [44] determined that better establishment of argan seedlings results from herbaceous cuttings irrigated at 120% of field capacity (FC), leading to optimal height growth (28.0 cm) and leaf development (79.6 leaves) compared to other propagation methods.

Regulatory hormones such as indole-3-butyric acid (IBA) and naphthalene acetic acid (NAA) are commonly used to stimulate rooting. When applied correctly, these phytohormones can significantly increase the rooting percentage and accelerate root development in cuttings.

Benbya *et al.* [13] demonstrated that cuttings treated with 3000 mgL^{-1} of IBA produced optimal results, achieving a germination rate of 81.75%, a rooting rate of 60.75%, and a survival rate of 96.25%. It is essential to define species-specific optimal concentrations for the argan tree, as excessive doses may have adverse effects. The substrate used for cutting cultivation also influences their rooting. The physico-chemical properties of the soil, particularly water retention capacity, pH, and nutrient availability, are essential for root growth, thereby determining the success of seedling establishment [40,45].

Grafting is an ancient plant propagation technique that plays a vital role in modern agriculture owing to its numerous advantages. This method joins a rootstock, which forms the root system, with a scion, which determines the plant's characteristics, such as fruit or flower variety. The success of grafting relies on establishing continuity between the vascular systems of both parts, facilitating the flow of nutrients and water. This, in turn, enhances plant productivity, vigour, and disease resistance. For the argan tree (*Argania spinosa*), grafting offers significant benefits, including a reduction in the fruiting period, increased yields, and improved resistance to environmental stress, a crucial factor in the arid regions where it is cultivated [46]. The selection of compatible varieties between the rootstock and the scion, the use of efficient grafting techniques such as simple cleft grafting, *which can achieve success rates exceeding 90%* [47], and optimal growing conditions are all critical factors for the survival and development of grafted plants [48].

Considered a symbol of Morocco, the argan tree is also valued for its precious oil and its multiple applications. Grafting has proven to be the most effective technique for producing vigorous and homogeneous plants. Studies indicate that the success rate of grafting can reach up to 95.8%, whereas the highest rooting rate obtained through cuttings does not exceed 66.7% [49]. This technique combines the desirable fruit qualities of the scion with the strong root system of the rootstock, overcoming the limitations of cuttings, which often suffer from high failure rates because of rooting difficulties [50]. The cleft grafting method has been identified as the most suitable for the argan tree and has been recognized as the most effective in multiple trials [51].

Challenges in grafting and cutting techniques are all solvable. The success of grafting depends on the compatibility between the rootstock and the scion. Studies have shown that climatic differences between the scion's origin and the rootstock's growing site can lead to physiological incompatibilities,

affecting the overall success of the grafting process [38]. To maximize success rates, it is advisable to select rootstocks adapted to local conditions and scions from trees with advantageous agronomic characteristics. Although cutting is a traditional vegetative propagation method, it presents considerable technical challenges. Results vary depending on the age of the plant material and environmental conditions [52]. Mature Argan cuttings often require a return to a juvenile state to promote effective rooting, a lengthy process that requires controlled conditions [52].

Micropropagation of the Argan Tree

In Vitro Germination

In vitro culture has emerged as a promising alternative for the propagation of the argan tree, enabling not only rapid multiplication but also the preservation of desirable genetic characteristics. In vitro culture methods provide strict control over environmental conditions, which can be beneficial in overcoming challenges related to seed germination, particularly seed dormancy and low viability rates in natural conditions. Furthermore, this process can facilitate the evaluation and conservation of the argan tree's genetic diversity, crucial in maintaining the resilience of populations against climate change and other environmental stresses.

Several factors are necessary for the success of in vitro germination techniques, including the composition of culture media, the use of plant hormones, light, temperature, and humidity [28]. Studies have shown that manipulating these variables can significantly improve germination rates and seedling growth. For instance, the application of cytokinins and auxins in culture media has been identified as a critical factor in stimulating bud and root development [42].

Sterilization is an essential step in in vitro techniques, aimed at eliminating contaminants that could compromise the integrity of the culture. Various methods are used to sterilize seeds or explants, including surface sterilization with sodium hypochlorite solutions, ethanol, and Tween-20, followed by rinsing with sterile distilled water [25,53]. Research has demonstrated that effective sterilization techniques can greatly enhance the germination rates of argan seeds by preventing microbial growth, which could inhibit seedling establishment [14].

Then the step of choosing the culture medium becomes crucial for successful germination and subsequent growth. Murashige and Skoog medium [54] is widely used; its comprehensive nutritional composition includes auxins and cytokinins that promote cell division and differentiation. Variations of this medium have been explored, particularly regarding plant growth regulator (PGR) concentrations, such as indole-3-butyric acid (IBA) and benzyl- aminopurine (BAP), which are essential for optimal shoot regeneration and root formation [25]. Additionally, the pH of the medium, generally maintained between 5.6 and 6.0, is significant for nutrient availability and absorption [55].

Incubation conditions also have a profound impact on the success of in vitro germination. Factors such as temperature, light intensity, and photoperiod are critical variables. Studies indicate that a controlled temperature range of 25 to 28°C, combined with a 16-hour light cycle, optimizes the growth of argan tissue cultures by simulating natural conditions favorable for germination [14].

The influence of genotype on the success of in vitro germination has drawn the attention of recent researchers. Variability among argan tree genotypes can lead to significant differences in germination rates and early growth characteristics. Genetic diversity plays a crucial role in adaptation to environmental stress, a factor that may contribute to variable responses to in vitro conditions [14,25,42]. Some genotypes have been identified as having higher germination potential, suggesting that the selection of specific genetic lines can not only enhance productivity but also preserve the genetic integrity of the species [28].

The germination capacity of argan seeds is strongly influenced by storage conditions, with high germination rates in freshly harvested seeds, but a significant decline when seeds are stored at 24°C for several months [14]. Furthermore, the hard shell of the nut, which surrounds the seeds, acts as a barrier to germination, and it must be removed to improve germination rates, particularly for in vitro cultures [15,57].

Propagation of the Argan Tree via Microcutting

In vitro propagation is a viable technique for the conservation and multiplication of *Argania spinosa*, particularly through methods such as microcutting. This technique uses nodal segments as explants to generate new plantlets under controlled conditions, thereby preserving the genetic integrity of the species. The ability to propagate argan trees in vitro not only facilitates the restoration of degraded habitats but also enables the production of uniform, disease-free plant material, essential for commercial cultivation [25]. In vitro methods can rapidly generate many plants, overcoming the limitations of conventional propagation techniques, which are often slow and dependent on environmental factors.

Microcutting is a vegetative propagation technique in which nodal segments excised from elongated shoots are cultured in vitro culture [56]. This method aims to stimulate shoot development and consists of several key steps:

- **Cutting Collection**

The selection of plant material is essential for successful microcutting. According to Bousselmame *et al.* [43], cuttings should be collected from mature trees, although some studies have also examined young trees, yielding varied results in terms of explant viability [40].

- **Culture Conditions**

Culture conditions, particularly the choice of medium, play a crucial role in the development of microshoots. Koufan *et al.* [14] observed that argan shoots cultivated on full-strength modified MS

medium exhibited high budburst rates, highlighting the importance of nutrient selection in optimizing growth.

- **Sterilization**

Sterilization of cuttings is essential for establishing axenic cultures. Koufan *et al.* [5] demonstrated that immersion for 10 minutes in a commercial bleach solution (2.5% NaOCl) resulted in high budburst rates and reduced the risk of contamination.

- **Budburst and Multiplication**

Budburst stimulation can be influenced by the plant growth regulators (PGRs) present in the culture medium. Tesse *et al.* [15] successfully induced 100% budburst on modified MS medium supplemented with PGRs, and other studies reported similar rates using specific PGR concentrations, such as 1 mg L^{-1} of indole-3-acetic acid (IAA) and 2 mg L^{-1} of benzylaminopurine (BAP) [43].

- **Microshoot Elongation**

The use of PGRs for microshoot elongation has proven to be effective. According to Lamaoui *et al.* [58], the addition of 1.5 mg L^{-1} of BAP significantly enhanced shoot multiplication and elongation, confirming the importance of growth regulators in the process.

- **Root Induction**

Rooting is generally promoted by auxins. Koufan *et al.* [5] recommend a ½ MS medium containing 0.5 mg L^{-1} of naphthalene acetic acid (NAA), achieving a rooting rate of 40%. Other studies, such as those by Bousselmame *et al.* [43], reported rooting rates of up to 85% using 5 mg L^{-1} of NAA and 5 mg L^{-1} of indole-3-butyric acid (IBA), demonstrating the need for further research to refine efficient rooting protocols

Micrografting of Argan Tree

Micrografting is an innovative technique that provides an efficient regeneration system for the argan tree (*Argania spinosa* (L.) Skeels), a threatened species, by enabling the preservation of valuable genotypes. The study by Koufan *et al.* [14] demonstrated that rootstocks, obtained from in vitro-germinated seeds of the G27 genotype, exhibited a maximum germination rate of 91.6% when cultivated immediately after harvest. By transferring the seedlings to a half-strength Murashige and Skoog (½MS) culture medium supplemented with gibberellic acid (GA3) and 6-benzylaminopurine (BAP), shoot and root lengths reached 2.05 cm and 5.73 cm, respectively. Using the wedge grafting technique on axillary shoots of the G41 genotype, a survival rate of 65% to 100% was observed for the micrografted plants after two months of cultivation. The presence of GA3 was crucial in ensuring successful grafting and promoting shoot growth. Histological analyses confirmed the successful union between rootstocks and scions, with active cell division and vascular tissue formation. These

results highlight the importance of micrografting as a strategic tool for the recovery and sustainable conservation of the argan tree

Propagation of Argan Tree by Adventitious Organogenesis

Amghar *et al.* [42] developed an efficient in vitro propagation system through adventitious organogenesis for the argan tree (*Argania spinosa* (L.) Skeels). Their study demonstrated that immersing seeds in gibberellic acid (GA3) for 12 hours accelerates germination. A medium devoid of sucrose, free of ammonium, and with a low nitrate concentration also enhances the germination rate. Amghar *et al.* [42] observed that only epicotyl segments of the explants were capable of regenerating adventitious buds, with the highest organogenesis rate (79.17%) obtained on a Murashige and Skoog (MS) medium containing 2 mg L^{-1} of 6-benzylaminopurine (BAP) under dark conditions. The multiplication of adventitious buds was successfully achieved on a medium supplemented with BAP and GA3. Rhizogenesis required a combination of indole-3-butyric acid (IBA) and putrescine, reaching a rooting rate of 56.66% for the 'R'zwa' genotype. The regenerated plantlets were successfully acclimatized, exhibiting normal growth and development.

Acclimatization of Argan Tree Vitro-Plants

The acclimatization of argan trees (*Argania spinosa*) vitro-plants is a crucial step in the micropropagation process. It facilitates the transition from in vitro conditions, where plants are cultivated in a laboratory, to an ex-vitro environment, which is the external setting. This phase is essential to ensure the survival and growth of the plants after their transfer to outdoor conditions. Vitro-plants must adapt to various environmental factors, including light, humidity, and temperature.

Tesse *et al.* [15] tested the acclimatization of plantlets immersed in IBA at 2000 ppm, using a substrate mixture of coconut fibre, blonde peat, and perlite. They maintained temperatures not exceeding 35°C and humidity levels between 80% and 100%, achieving a survival rate of 90%. Lamaoui *et al.* [58] acclimatized plantlets in a peat and sand mixture, successfully obtaining a 100% survival rate.

Further studies are necessary to optimize these protocols so they can be replicated for different argan tree genotypes. Successful acclimatization of vitro-plants is essential not only for the conservation of this endangered species but also to support local communities that economically depend on the argan tree

Table 3. Summary of Argan Tree Propagation Methods, Their Advantages, and Limitations [10].

Propagation Method	**Advantages**	**Limitations**
Conventional methods (seed germination and seedling establishment)	1. Preserves genetic variability.	1. Does not guarantee plant conformity to the original type.
	2. Relatively simple compared to other methods.	2. Long juvenile period.
	3. Usable for genetic improvement.	3. Dependent on climatic and edaphic conditions.
	4. Low production cost.	4. Germination rate is influenced by genotype.
Propagation by stem cuttings	1. Produces genetically homogeneous clones.	1. Low rooting rate.
	2. Simpler than in vivo grafting.	2. Rooting success depends on genotype, age, cutting type, planting season, and substrate.
In vivo grafting propagation	1. Preserves the rootstock's desirable characteristics (soil adaptation, stress tolerance, etc.).	1. Risk of incompatibility between rootstock and scion.
	2. Maintains the genetic characteristics of mother plants.	2. Requires specific conditions.
	3. Overcomes the rooting challenges of stem cuttings.	3. Requires skilled labour.
Tissue culture techniques (in vitro germination and seedling development)	1. Relatively fast and simple process.	1. Genetic variability of produced plants.
	2. Preserves genetic variability.	2. Long juvenile period.
	3. Can produce rootstocks for micrografting.	3. Germination frequency varies depending on genotype.
Tissue culture techniques (in vitro propagation through nodal segment elongation)	1. Rapid multiplication of selected genotypes.	1. Low rooting rate.
	2. Production of disease-free and pathogen-free plants.	2. High production cost.
	3. Produces genetically homogeneous clones.	
Micrografting	1. Preserves the desirable characteristics of the rootstock.	1. Plant acclimatization needs improvement.
	2. Maintains the genetic characteristics of mother plants.	2. High production cost.
	3. Overcomes the rooting reluctance of microshoots.	3. Complex procedure, not well suited for routine use.
Adventitious organogenesis	1. Enables rapid and large-scale propagation of the argan tree.	1. Requires explants of zygotic origin.
	2. High survival rate during acclimatization.	2. Genetic variability of the obtained plants.
	3. Can be used for genetic improvement.	

Conclusion

The argan tree (*Argania spinosa*) is a vital component of the arid and semi-arid ecosystems of southwestern Morocco, providing not only crucial economic resources for local communities but also playing a key role in biodiversity and soil conservation. In the face of growing challenges caused by intensive agriculture, resource exploitation, and climate change, it is imperative to adopt and optimize sustainable propagation methods. This review highlights the distinct effectiveness of both traditional and modern propagation techniques, emphasizing that a combination of methods such as cutting, grafting, and micropropagation can offer viable solutions for revitalising and preserving the argan tree. By fostering collaboration between researchers, farmers, and policymakers, it becomes possible to ensure not only the economic sustainability associated with the argan tree but also the long-term conservation of this emblematic species for future generations. It is essential to integrate the research and conservation efforts so that the people who live with and harvest this economic resource will benefit from improvements in its propagation and commercial use, and the ecosystem also.

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Ethics Approval

This study was conducted in full compliance with ethical principles. All experimental protocols were carried out in accordance with the relevant guidelines and regulations.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code Availability

Not applicable.

Conflict of Interest

All authors declare no conflicts of interest

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