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Review

Arganiculture beyond the Native Range of *Argania spinosa*: Framework for Dryland Restoration, Climate Resilience, and Territorial Development

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Abstract: The expansion of *Argania spinosa* (L.) Skeels cultivation beyond its native range has attracted increasing attention as a strategy for dryland restoration, climate adaptation, and sustainable rural development. However, successful arganiculture outside traditional argan ecosystems is constrained by interactions among ecological suitability, water availability, agronomic management, and governance capacity. This systematic review evaluates the opportunities and limitations of expanding arganiculture by integrating evidence from ecological, physiological, agronomic, genetic, hydrological, and socio-economic research. A structured literature search was conducted using major scientific databases, and studies were screened according to predefined eligibility criteria. The review shows that *Argania spinosa* possesses important drought-adaptive traits and physiological mechanisms that enable survival under severe water stress, supporting its potential for dryland rehabilitation and agroforestry development. Nevertheless, expansion remains limited by frost sensitivity, water requirements during establishment, ecological dependencies, and the potential loss of genetic diversity under intensive cultivation. Evidence from international experiences indicates that successful cultivation beyond Morocco is highly site-specific and depends on climatic suitability, sustainable water management, appropriate agronomic practices, and effective institutional support. This review proposes a conceptual framework that considers arganiculture as a socio-ecological transition system integrating biophysical suitability, ecological integrity, agronomic feasibility, and governance capacity to guide evidence-based planning. Overall, arganiculture offers significant potential for sustainable development in dryland regions, provided that context-specific management strategies effectively balance agricultural productivity with ecosystem conservation and long-term resource sustainability.

Keywords: *Argania spinosa*; Arganiculture; Dryland Restoration; Land Management; Agroforestry; Climate Adaptation; Water Governance; Sustainable Development

1. Introduction

Dryland ecosystems are increasingly exposed to multiple and interacting pressures, including climate change, prolonged drought events, land degradation, biodiversity loss, and increasing competition for natural resources. In these environments, the identification of resilient tree species capable of supporting ecological restoration and sustainable livelihoods has become a major research and policy priority. Among Mediterranean dryland species, *Argania spinosa* (L.) Skeels, commonly known as the argan tree, occupies a particularly important position due to its ecological, economic, and cultural significance [1,2].

The argan tree native to the semi-arid and arid regions of southwestern Morocco, where its natural distribution is centered within the UNESCO Arganeraie Biosphere Reserve and extends into adjacent areas of west-central Morocco. Traditionally managed by local communities, argan landscapes provide multiple ecosystem services, including soil protection, biodiversity conservation, livestock support, and production of argan oil, one of the most valuable non-timber forest products of the Mediterranean region [1, 3, 4]. Beyond its economic importance, the species represents an important example of adaptation to harsh environmental conditions, particularly through its ability to tolerate prolonged drought and survive under low rainfall regimes [5,6].

The increasing recognition of *Argania spinosa* as a drought-resistant species has stimulated interest in its cultivation beyond its natural range. Experimental plantations and suitability assessments have been conducted in several Mediterranean and dryland regions, including Tunisia, Spain, Italy, and other semi-arid environments [7–9]. These initiatives are driven by several objectives: restoration of degraded lands, diversification of agricultural systems, development of climate-resilient crops, and creation of new economic opportunities in marginal regions. However, the transfer of a species adapted to a specific ecological niche into new environments raises important questions regarding climatic suitability, water availability, genetic conservation, and long-term ecosystem sustainability.

Previous research has mainly focused on specific aspects of argan biology, including propagation methods, physiological responses to drought, genetic diversity, oil production, and socio-economic value chains [6, 10]. Although these studies have significantly improved understanding of the species, there remains a need for an integrated assessment that considers arganiculture as a broader land-use system involving ecological, agronomic, hydrological, and governance dimensions.

The expansion of arganiculture presents both opportunities and challenges. On one hand, managed cultivation may contribute to dryland restoration, carbon storage, rural income diversification, and sustainable agroforestry development. On the other hand, poorly planned expansion may generate unintended consequences, including increased pressure on scarce water resources, genetic simplification, habitat fragmentation, and dependence on intensive management inputs. Therefore, evaluating the sustainability of arganiculture requires moving beyond species-level performance and considering the wider socio-ecological context in which cultivation occurs.

This review addresses this knowledge gap by examining arganiculture through an integrated land-management perspective. Unlike previous reviews that primarily emphasize the biological characteristics, propagation techniques, or economic value of *Argania spinosa*, this study synthesizes ecological, agronomic, hydrological, genetic, and socio-economic evidence to evaluate the conditions required for sustainable expansion beyond the native range.

The objectives of this review are therefore to:

1. Assess the ecological adaptation potential and environmental constraints affecting *Argania spinosa* cultivation outside its native distribution;
2. Analyze agronomic opportunities and sustainability trade-offs associated with domestication and intensification;
3. Evaluate the role of water availability, genetic diversity, and governance systems in determining long-term viability;
4. Compare international experiences of argan cultivation in different dryland contexts;
5. Propose an integrated land-use framework to guide sustainable arganiculture development under current and future climatic conditions.

By addressing these objectives, this review aims to provide a decision-support perspective for researchers, land managers, and policymakers interested in using arganiculture as a component of sustainable dryland transformation strategies.

2. Materials and Methods

2.1. Literature Search Strategy

A systematic literature review was conducted to evaluate the ecological, agronomic, hydrological, genetic, and socio-economic dimensions influencing the development of arganiculture beyond the native range of *Argania spinosa*. The review followed a structured approach based on transparent identification, screening, and evaluation procedures to ensure methodological consistency and reproducibility.

The literature search was performed using internationally recognized scientific databases, including Web of Science, Scopus, and ScienceDirect, complemented by additional searches in Google Scholar to identify relevant studies that may not have been indexed in major databases. The search covered publications available from the beginning of scientific indexing until May 2026, which was defined as the final search date for this review.

The search strategy was developed using combinations of keywords related to the species, cultivation systems, environmental adaptation, and sustainable land management. The main search strings included combinations of the following terms:

("Argania spinosa" OR "argan tree" OR "argan") AND ("cultivation" OR "arganiculture" OR "domestication" OR "plantation" OR "agroforestry") AND ("dryland" OR "arid" OR "semi-arid" OR "Mediterranean") AND ("adaptation" OR "drought tolerance" OR "climate suitability" OR "water stress" OR "land management" OR "sustainability")

Additional searches were conducted using combinations related to specific thematic dimensions:

- Ecological adaptation: drought tolerance, physiological response, bioclimatic suitability, climate change.
- Agronomic development: propagation, grafting, orchard management, yield improvement.
- Genetic resources: genetic diversity, conservation, breeding.
- Water resources: irrigation, water-use efficiency, hydrological constraints.
- Socio-economic dimensions: rural development, cooperatives, value chains, governance.

The search strategy was designed to capture both studies conducted within the native Moroccan argan ecosystem and experimental or modelling studies evaluating cultivation potential in other dryland regions.

2.2. Eligibility Criteria

Studies were selected according to predefined inclusion and exclusion criteria.

Inclusion criteria:

The review included scientific publications that:

- Focused on *Argania spinosa* or argan-based cultivation systems;
- Examined ecological adaptation, cultivation practices, restoration potential, genetic resources, water requirements, socio-economic aspects, or land-use implications;
- Evaluated either native argan ecosystems or cultivation attempts outside the native range;
- Provided original research findings, systematic reviews, modelling approaches, or scientifically supported analyses;
- Were published in peer-reviewed journals, academic books, or recognized scientific proceedings.

Exclusion criteria:

Studies were excluded when they:

- Focused exclusively on chemical composition or pharmaceutical properties of argan products without relevance to cultivation or land management;
- Lacked sufficient methodological information;
- Consisted only of commercial descriptions or non-scientific reports;
- Did not directly address *Argania spinosa* or its cultivation potential;
- Duplicated information already available in more complete publications.

The selection process aimed to maintain a balance between biological studies and broader land-management research, reflecting the multidisciplinary nature of arganiculture.

2.3. Data Extraction

Information was extracted systematically from selected studies and organized according to the main themes identified during the review process.

For each publication, the following information was recorded:

- Bibliographic information (authors, year, and publication source);
- Geographic location of the study;
- Research objective and methodological approach;

- Environmental conditions, including climate and soil characteristics;
- Cultivation practices and management strategies;
- Reported ecological responses and adaptation mechanisms;
- Genetic diversity and conservation aspects;
- Water requirements and hydrological constraints;
- Socio-economic implications and governance considerations.

The extracted information was then synthesized according to five major analytical dimensions:

1. Ecological adaptation;
2. Agronomic management and productivity;
3. Hydrological sustainability;
4. Genetic and ecological resilience;
5. Socio-economic and governance factors.

This thematic organization allowed comparison between studies conducted in different geographical and environmental contexts.

2.4. Quality Assessment

The methodological quality and relevance of the selected studies were evaluated by a single reviewer according to predefined criteria reflecting their scientific rigor and contribution to the objectives of this review. Because the included studies comprised diverse study designs (experimental, observational, modelling, and socio-economic research), no standardized risk-of-bias checklist was considered appropriate. Instead, a structured qualitative appraisal was applied.

Each study was assessed against five criteria:

- Clarity of research objectives;
- Adequacy of the experimental or analytical methods;
- Reliability of the reported data;
- Relevance to arganiculture development;
- Contribution to understanding ecological, agronomic, hydrological, genetic, governance, or socio-economic processes.

For each criterion, studies were rated as high, moderate, or low quality. Studies rated as low quality because of insufficient methodological description or limited relevance were excluded, whereas studies rated as moderate or high quality were retained for qualitative synthesis.

Greater emphasis was placed on peer-reviewed studies reporting empirical measurements, experimental findings, spatial analyses, or validated modelling approaches. Studies providing complementary contextual information were also included when they contributed to understanding historical management practices, governance structures, policy frameworks, or socio-economic dynamics relevant to sustainable arganiculture.

A limitation of this review is that literature screening, study selection, and quality appraisal were conducted by a single reviewer. Consequently, reviewer bias cannot be completely excluded, although predefined eligibility criteria and a structured appraisal framework were applied consistently throughout the review process.

2.5. Study Selection Process

The study selection process followed the principles of the PRISMA 2020 framework to ensure transparency in identification, screening, eligibility assessment, and final inclusion of scientific studies.

Initially, all records identified through database searches were compiled into a reference management database. Duplicate records were removed before the screening stage. Titles and abstracts were subsequently evaluated according to the eligibility criteria described above. Studies considered potentially relevant were retained for full-text assessment.

During the full-text screening phase, publications were evaluated for methodological relevance and their contribution to understanding arganiculture as a land-use system. Studies lacking sufficient information or not addressing the objectives of the review were excluded. The final dataset consisted of studies selected for qualitative synthesis.

The complete selection process is presented in **Figure 1** below.

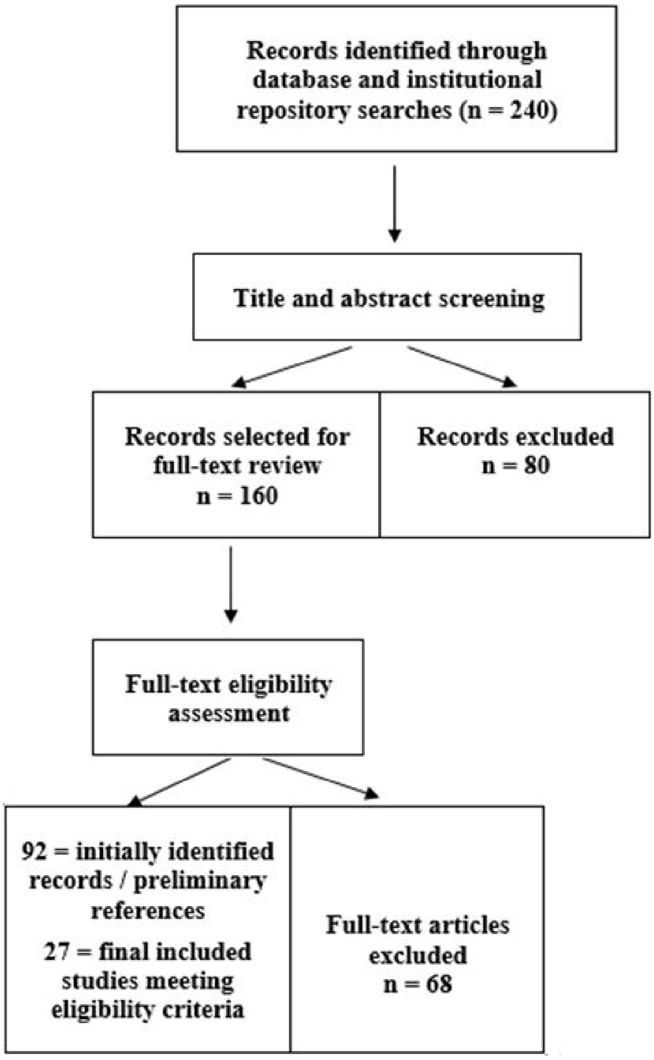

Figure 1. PRISMA 2020 Flow Diagram of the Literature Selection Process.

3. Results

3.1. Ecological Characteristics and Adaptive Capacity of *Argania spinosa*

The ecological success of *Argania spinosa* within southwestern Moroccan landscapes is largely associated with its capacity to persist under severe climatic constraints. The species naturally occurs in environments characterized by irregular rainfall, high evaporative demand, prolonged dry periods, and heterogeneous soil conditions. These characteristics have contributed to the recognition of the argan tree as a drought-adapted species with significant ecological value in Mediterranean dryland ecosystems [1,3,11].

Unlike many woody species that experience substantial physiological decline under water limitation, *A. spinosa* exhibits several adaptive mechanisms that contribute to drought survival. These include deep and extensive root systems, regulation of stomatal conductance, maintenance of water-use efficiency, and physiological adjustments that allow seedlings and mature trees to tolerate periods of water deficit [5,6]. Such characteristics explain the species' importance in soil protection, landscape stabilization, and restoration initiatives in degraded semi-arid environments.

However, drought tolerance does not imply unlimited ecological adaptability. The species occupies a relatively specific climatic niche, and environmental factors such as temperature extremes, frost occurrence, rainfall seasonality, and soil conditions strongly influence establishment success [12]. In particular, low-temperature sensitivity represents an important constraint for expansion into continental climates, where winter frost events may negatively affect juvenile plants and reduce plantation viability.

Recent climatic suitability assessments indicate that *A. spinosa* may potentially establish in selected Mediterranean environments outside Morocco, but successful introduction depends on a close match between climatic requirements and local environmental conditions [8]. Therefore, ecological plasticity should be interpreted as a capacity for adaptation within specific environmental boundaries rather than evidence of unlimited geographic expansion.

3.2. Agronomic Development, Domestication, and Cultivation Practices

The transition from traditional argan forest management toward intensified cultivation has stimulated research on domestication, propagation, and productivity improvement. Traditional argan systems are characterized by extensive management practices, whereas modern arganiculture increasingly incorporates nursery production, orchard establishment, selection of productive genotypes, and improved management techniques [13,14].

Propagation remains a major technical challenge due to the species' slow growth rate and long juvenile phase. Studies on seed propagation, vegetative multiplication, and nursery management have demonstrated progress toward improving plant production and reducing establishment limitations [15,16]. The development of grafting techniques has also contributed to shortening the production cycle and improving yield consistency in cultivated systems [13,14].

However, intensification introduces important ecological considerations. The transition from diverse traditional landscapes to highly managed plantations may reduce genetic variability, simplify habitat structure, and alter ecological interactions such as pollination networks. Maintaining a balance between productivity improvement and conservation of biological diversity is therefore essential for sustainable arganiculture development [6,17].

Agronomic improvement strategies should consequently prioritize locally adapted genetic material, ecological compatibility, and management practices that maintain ecosystem functions rather than focusing exclusively on yield maximization.

3.3. Water Requirements and Hydrological Constraints

Water availability represents one of the main factors determining the success of arganiculture, particularly outside the native range. Although mature *A. spinosa* trees demonstrate remarkable drought resistance, young plants are considerably more vulnerable during establishment phases and may require supplementary water inputs under cultivated conditions [5].

Experimental plantations in non-native environments have shown that irrigation can improve early survival, growth rates, and productivity. However, dependence on irrigation raises questions regarding long-term sustainability, especially in regions already affected by groundwater depletion and increasing water scarcity [7,8].

The distinction between ecological drought resistance and agricultural water demand is therefore critical. Natural argan ecosystems have developed under low-input conditions, while commercial plantations often require additional management interventions to achieve economically viable production levels. This difference highlights the need for integrated water management approaches that evaluate both ecological water availability and production objectives.

Future expansion of arganiculture should therefore prioritize water-efficient cultivation systems, including optimized irrigation strategies, rainwater management, and site selection based on hydrological suitability.

3.4. Genetic Diversity and Ecosystem Resilience

Genetic diversity constitutes a fundamental component of the long-term resilience of *Argania spinosa* populations. Genetic variability allows populations to maintain adaptive potential under changing environmental conditions and provides opportunities for selecting traits associated with drought tolerance, productivity, and environmental adaptation [6,17].

Research conducted across Moroccan and Tunisian populations has demonstrated significant genetic and morphological variability within the species. This diversity represents an important resource for conservation programs and future breeding strategies aimed at developing resilient cultivation systems [6,18].

Nevertheless, intensive cultivation practices may create risks of genetic erosion if plantations rely on a limited number of selected genotypes. The widespread use of uniform planting material could reduce adaptive capacity and increase vulnerability to future climatic uncertainties.

Consequently, sustainable arganiculture requires strategies that combine genetic improvement with conservation principles, including protection of natural populations, maintenance of genetic diversity, and integration of locally adapted materials into cultivation programs [9,17].

3.5. Socio-Economic Importance and Value Chain Development

Beyond ecological functions, arganiculture represents an important socio-economic system supporting rural livelihoods, particularly in southwestern Morocco. The production and commercialization of argan oil have contributed to income diversification, employment generation, and the development of cooperative structures, especially among rural women [1,10,19].

The expansion of argan-based value chains has transformed argan oil from a locally consumed product into an internationally recognized commodity. This transition has encouraged innovation in processing, product diversification, and market development [10].

However, socio-economic benefits are strongly influenced by governance structures, market organization, infrastructure, and access to technical knowledge. Unequal distribution of benefits may occur where institutional support and local participation are limited. Therefore, sustainable arganiculture requires not only technical improvements but also inclusive governance mechanisms capable of ensuring equitable participation and long-term resource management [20,21].

3.6. International and Comparative Dryland Systems

Although *Argania spinosa* remains primarily associated with Moroccan ecosystems, increasing interest has emerged regarding its cultivation potential in other Mediterranean and dryland regions. Studies from Tunisia, Spain, Italy, and other experimental locations provide valuable insights into the ecological requirements and limitations associated with transferring arganiculture beyond its native environment (**Table 1**).

Table 1. Current status of *Argania spinosa* cultivation and evaluation beyond its native range.

Region	Environmental Context	Main Opportunities	Major Constraints	Evidence/Status
Morocco (native range)	Mediterranean semi-arid ecosystems	Traditional management, biodiversity conservation, established value chains	Climate stress, land degradation, and water limitations	Established productive cultivation
Tunisia	Mediterranean drylands	Adaptation studies, genetic and morphological diversity assessments	Water availability and long-term productivity uncertainty	Experimental cultivation
Spain	Semi-arid Mediterranean zones	Climate suitability assessments and restoration potential	Frost risk and climatic variability	Climate suitability modelling and pilot plantings
Italy	Mediterranean environments	Evaluation of climatic suitability under Mediterranean conditions	Limited experimental evidence	Climate suitability modelling and limited experimental trials
United States	Arid and semi-arid environments	Evaluation of adaptation potential	Water requirements and climatic constraints	Experimental introductions

Note: Evidence/status categories distinguish between established productive cultivation, experimental introductions, and modelling-based assessments. Experimental and modelling-based evidence should not be interpreted as representing commercial-scale arganiculture.

In Tunisia, experimental cultivation has demonstrated that *A. spinosa* can survive under Mediterranean conditions outside Morocco, with observed variation in morphological characteristics, genetic diversity, and adaptation responses depending on environmental conditions [7,18]. However, long-term establishment remains influenced by soil properties, climatic suitability, and water availability.

In the Iberian Peninsula, climate modelling approaches indicate that certain semi-arid regions may provide suitable conditions for argan cultivation under current and future climate scenarios. Nevertheless, temperature variability and frost risk remain important limiting factors that constrain large-scale expansion [8].

Small-scale trials in other Mediterranean countries, including Italy, suggest potential opportunities for integrating argan trees into agroforestry systems, but available evidence remains limited and largely experimental. Similarly, cultivation attempts in arid regions outside the Mediterranean demonstrate that survival is possible under managed conditions, although irrigation requirements may reduce ecological and economic feasibility.

These comparisons demonstrate that arganiculture transferability is highly context-dependent. Environmental compatibility, particularly temperature regime, frost frequency, soil conditions, and water availability, determines whether cultivation can progress from experimental establishment to sustainable production [6].

Frost sensitivity emerges as a major biophysical limitation for expansion beyond Mediterranean-type climates. While management interventions can improve establishment success, they cannot fully compensate for unsuitable climatic conditions. Therefore, future arganiculture development should be guided by spatial suitability assessments rather than simple geographical expansion.

Outside Morocco, current evidence remains largely limited to experimental trials, pilot plantings, and suitability assessments rather than established commercial-scale arganiculture.

4. Discussion

4.1. Arganiculture as a Socio-Ecological Land-Use Strategy

The findings of this review demonstrate that arganiculture should not be considered solely as an agricultural production system but rather as a complex socio-ecological land-use strategy integrating ecological restoration, resource management, economic development, and institutional coordination. Historically, argan landscapes have been shaped by interactions between natural ecological processes and traditional management practices, resulting in multifunctional systems that provide both environmental and socio-economic benefits [3,11,21].

The increasing interest in expanding arganiculture beyond its native range reflects broader efforts to identify resilient tree-based systems capable of addressing challenges associated with climate change and land degradation. However, the transfer of argan cultivation into new environments requires recognition that the ecological performance of the species is strongly influenced by local climatic, hydrological, and socio-economic conditions. The success of arganiculture therefore depends not only on the biological characteristics of *A. spinosa*, but also on the capacity of land-management systems to maintain ecological functions and resource sustainability.

This perspective changes the interpretation of arganiculture from a simple crop introduction approach to a territorial planning challenge. Sustainable implementation requires coordination between agricultural development, biodiversity conservation, water management, and rural governance.

4.2. Ecological Adaptation: Strengths and Environmental Boundaries

The ecological characteristics of *Argania spinosa* explain its attractiveness as a candidate species for dryland restoration and climate adaptation. The species demonstrates strong tolerance to drought conditions through physiological mechanisms that allow maintenance of water status and photosynthetic activity during periods of limited water availability [5,6]. These characteristics support its role in soil stabilization, ecosystem rehabilitation, and maintenance of ecological functions in semi-arid environments.

Nevertheless, drought tolerance should not be interpreted as complete environmental independence. The species remains sensitive to specific ecological constraints, particularly during early developmental stages. Seedlings require adequate moisture conditions for successful establishment, and young trees are more vulnerable to climatic stress compared with mature individuals [5].

Temperature limitations represent another major constraint. Studies evaluating bioclimatic suitability indicate that frost events and low winter temperatures may substantially reduce cultivation potential outside Mediterranean-type environments [8,12]. Therefore, ecological suitability assessments are essential before promoting arganiculture in new regions.

The evidence indicates that *A. spinosa* possesses ecological flexibility within a defined environmental range. Sustainable expansion requires identifying locations where natural conditions support long-term survival without excessive dependence on external inputs.

4.3. Agronomic Intensification and Sustainability Trade-Offs

Advances in domestication, propagation, and orchard management have created new opportunities for improving argan productivity. Techniques such as grafting, nursery production, improved planting materials, and optimized cultivation practices can reduce the juvenile phase and enhance economic returns [13–16]. These advances also reflect the growing diversification of argan research and cultivation systems reported in recent bibliometric analyses.

However, increased productivity through intensification may create important sustainability trade-offs. Highly managed plantations may differ significantly from traditional argan ecosystems by reducing structural complexity, modifying biodiversity interactions, and increasing dependence on irrigation and external inputs.

A central challenge is therefore to achieve a balance between agricultural efficiency and ecological integrity. Intensification strategies should not replace traditional ecological knowledge but rather integrate scientific improvements with conservation principles. Maintaining genetic diversity, supporting pollinator communities, and preserving landscape heterogeneity are essential components of resilient arganiculture systems [6,17].

Furthermore, integrating ecosystem-service assessments into land-use planning can improve decision-making by identifying areas where arganiculture contributes simultaneously to biodiversity conservation, carbon sequestration, soil protection, and rural livelihoods.

4.4. Water Governance as a Central Sustainability Challenge

Among the different factors influencing arganiculture development, water availability represents one of the most important determinants of long-term feasibility. Although mature argan trees are adapted to drought conditions, cultivated systems often require additional water inputs during establishment and productivity optimization phases [5].

This distinction creates a major management challenge. Natural argan ecosystems function under low-input conditions, whereas commercial cultivation may increase water demand. In water-limited regions, expanding irrigated arganiculture without appropriate planning may intensify competition between agricultural production, ecosystems, and local communities.

Therefore, water management should be considered a fundamental component of arganiculture planning. Sustainable approaches should prioritize:

- Selection of sites with appropriate natural water availability;
- Efficient irrigation technologies;
- Conservation of soil moisture;
- Integration with broader watershed management strategies.

The future development of arganiculture will depend strongly on the ability to align production objectives with hydrological sustainability.

Recent studies emphasize that successful arganiculture development requires integrated governance frameworks capable of reconciling ecological conservation, climate-change adaptation, sustainable water management, and local socio-economic development. Bibliometric evidence also indicates a growing international shift toward interdisciplinary research combining ecology, agronomy, socio-economics, and territorial planning, highlighting the increasing importance of integrated approaches for the sustainable expansion of arganiculture.

4.5. Genetic Diversity and Pollination as Foundations of Resilience

The long-term sustainability of arganiculture depends on maintaining biological diversity within cultivated and natural populations. Genetic variation provides the adaptive capacity required for populations to respond to environmental changes, including increasing drought intensity and climatic variability [6,17].

The use of genetically narrow planting materials may increase short-term productivity but reduce long-term resilience. Conservation-oriented approaches should therefore combine selection for desirable agronomic traits with preservation of genetic variability.

Pollination processes represent another essential ecological component. Although argan cultivation can be managed for production purposes, ecosystem functionality depends on maintaining biodiversity networks that support reproduction and landscape resilience. Habitat simplification and intensive management practices may negatively affect these ecological interactions.

Consequently, sustainable arganiculture should integrate genetic conservation and biodiversity management into cultivation strategies rather than treating them as separate conservation objectives.

4.6. Socio-Economic Opportunities and Governance Requirements

Arganiculture provides important opportunities for rural development through employment creation, income diversification, and value-chain development. The expansion of argan oil production has particularly demonstrated the capacity of argan-based activities to support local communities and cooperative structures [1,10,19].

However, socio-economic benefits are strongly influenced by governance conditions. Market access, institutional support, technical training, and equitable participation determine whether economic benefits contribute to sustainable rural development or reinforce existing inequalities.

Participatory governance is therefore essential. Local communities, farmers, women's cooperatives, researchers, and policymakers should be involved in decision-making processes related to land management and resource allocation. Such approaches improve legitimacy, incorporate local knowledge, and increase the effectiveness of sustainability strategies [20,21].

Beyond ecological and governance considerations, the long-term sustainability and economic competitiveness of arganiculture also depend on maintaining high product quality throughout harvesting, post-harvest handling, processing, and certification. Previous studies have shown that inappropriate post-harvest practices, particularly prolonged fruit drying, can adversely affect argan oil quality, emphasizing the importance of good production practices across the value chain [22]. Recent bibliometric analyses further indicate that international argan research is increasingly focused on integrated themes combining ecosystem management, climate adaptation, sustainable production systems, value-chain development, and territorial planning [23]. These trends are consistent with broader studies highlighting the importance of resilient forest ecosystems, ecosystem-service conservation, and sustainable landscape management for supporting long-term socio-economic and environmental sustainability [24–27].

4.7. International Comparisons and Transferability Limits

The international experiences reviewed demonstrate that arganiculture cannot be transferred universally across dryland regions. While *A. spinosa* shows capacity for survival outside Morocco, successful establishment depends on environmental compatibility and management intensity.

Mediterranean regions with similar climatic conditions provide the greatest potential for introduction. However, even within these areas, differences in temperature regimes, rainfall distribution, and soil characteristics influence cultivation outcomes [7,8].

The main limitation to expansion remains climatic mismatch, particularly frost exposure. Management interventions such as irrigation, soil improvement, and protective measures may increase survival, but they cannot eliminate fundamental ecological limitations.

Therefore, arganiculture expansion should be based on scientifically supported suitability assessments rather than assumptions regarding drought resistance alone.

4.8. Conceptual Land-Use Framework for Sustainable Arganiculture

Based on the integrated analysis of ecological, agronomic, hydrological, and governance dimensions, this review proposes a conceptual framework positioning arganiculture as a multidimensional land-use system.

The framework identifies four interconnected dimensions required for sustainable implementation:

1) **Biophysical Suitability**
Includes:

- temperature conditions;
- rainfall patterns;
- soil characteristics;
- water availability.

These factors define the fundamental environmental limits of cultivation.

2) **Ecological Integrity**
Includes:

- biodiversity conservation;
- pollination networks;

- genetic diversity;
- ecosystem resilience.

This dimension ensures that cultivation remains compatible with broader ecological processes.

3) **Agronomic Feasibility**
Includes:

- propagation methods;
- orchard management;
- yield improvement;
- cultivation practices.

This dimension determines technical and economic viability.

4) **Governance Capacity**
Includes:

- land-use planning;
- water regulation;
- institutional coordination;
- stakeholder participation;
- certification mechanisms.

Sustainable arganiculture can only be achieved when these four dimensions are simultaneously addressed (**Figure 2** below).

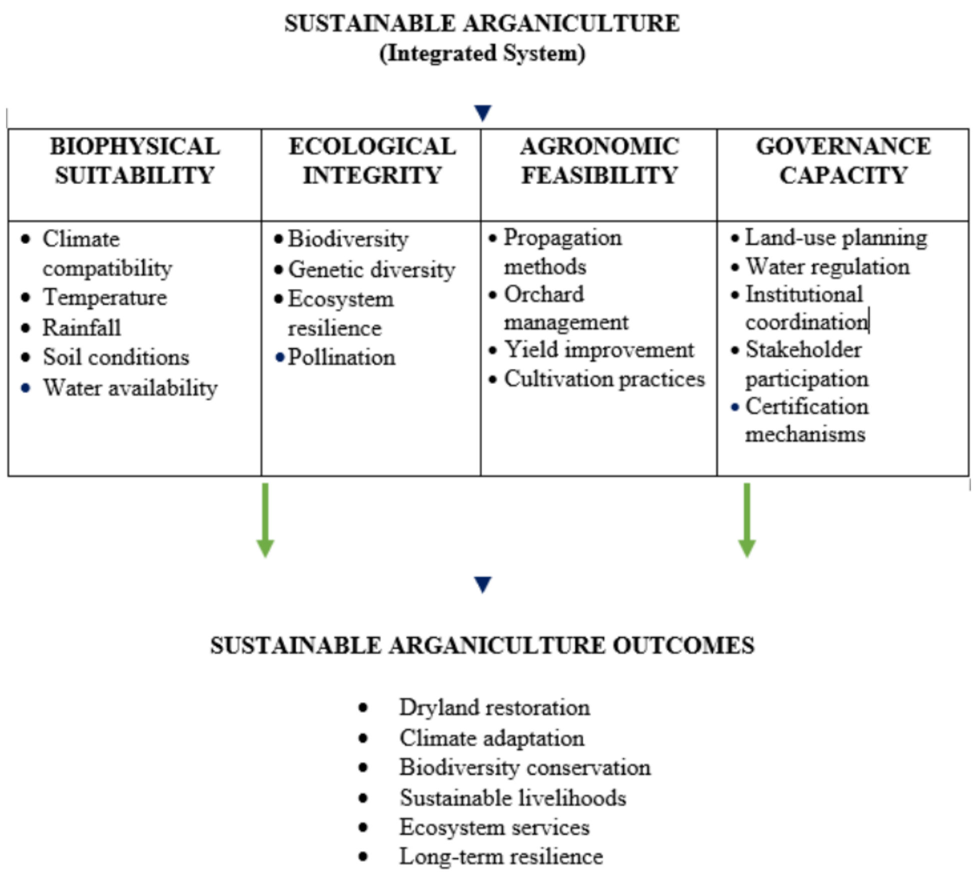

Figure 2. Conceptual Framework for Sustainable Arganiculture.

4.9. Synthesis of Key Discussion Insights

The synthesis of available evidence indicates that arganiculture represents a promising but highly context-dependent land-use strategy for dryland environments. Its potential extends beyond agricultural production, encompassing ecological restoration, climate adaptation, biodiversity conservation, and rural development. However, the success of arganiculture depends on maintaining a balance between productive objectives and the ecological processes that support long-term system stability.

First, the review confirms that *Argania spinosa* possesses valuable adaptive characteristics that explain its ecological importance in semi-arid landscapes [28–31]. Its drought tolerance, capacity to survive under water-limited conditions, and contribution to ecosystem functioning make it a relevant species for restoration-oriented approaches [5,6,11,32–35]. Nevertheless, these advantages are restricted by environmental thresholds, particularly temperature limitations, frost sensitivity, and the vulnerability of young plants during establishment phases [8,12].

Second, the findings demonstrate that arganiculture development requires careful consideration of land suitability. The species' successful establishment outside Morocco depends on the interaction between climatic compatibility, soil conditions, hydrological resources, and management capacity. Consequently, expansion strategies based only on drought resistance characteristics are insufficient and may lead to inappropriate land-use decisions.

Third, water availability emerges as a central factor determining the sustainability of cultivated systems. While mature trees can tolerate severe drought, productive plantations often require additional water inputs during critical growth stages. Therefore, water governance and resource-efficient management must be integrated into any strategy aiming to expand arganiculture in dryland regions.

Fourth, genetic diversity and ecological connectivity are essential components of long-term resilience. Conservation of genetic resources, maintenance of diverse populations, and protection of ecological interactions such as pollination are necessary to ensure adaptive capacity under future environmental changes [6,17].

Finally, the socio-economic contribution of arganiculture depends strongly on governance structures and institutional organization. Economic benefits from argan-based products are more likely to support sustainable development when combined with participatory management, equitable value-chain organization, and effective land-use policies [10,20].

Overall, the evidence indicates that arganiculture should be approached as an integrated socio-ecological system rather than as a simple tree-crop expansion model. Sustainable development requires coordination between ecological knowledge, agronomic innovation, hydrological management, and governance frameworks.

4.10. Research Gaps and Future Perspectives

Although research on *Argania spinosa* has increased considerably, several knowledge gaps remain regarding its sustainable expansion and long-term management. Future research should move beyond species performance assessments and focus on integrated approaches capable of supporting evidence-based land-use planning.

4.10.1. Climate Research and Future Suitability Assessment

Future studies should improve climate suitability modelling by incorporating high-resolution spatial data, future climate scenarios, and extreme climatic events. Existing assessments provide valuable information on potential distribution patterns, but additional research is required to evaluate long-term plantation performance under increasing temperature variability and changing precipitation regimes [8,12].

Long-term monitoring networks should also be established to evaluate:

- tree survival and growth dynamics;
- productivity changes over time;
- soil responses;
- ecosystem impacts;
- adaptation under climate stress.

Such monitoring is essential to distinguish short-term establishment success from long-term ecological sustainability.

4.10.2. Genetic Conservation and Breeding Strategies

Future genetic research should focus on maintaining and utilizing the diversity present within natural argan populations. Genetic resources represent a critical foundation for developing resilient cultivation systems capable of responding to future environmental pressures [6,17].

Priority areas include:

- characterization of additional populations;
- conservation of genetic variability;
- identification of drought-adaptive traits;
- development of improved planting materials;
- integration of breeding programs with conservation objectives.

A balanced approach is required to avoid genetic homogenization associated with intensive cultivation.

4.10.3. Water Management and Irrigation Optimization

Water availability remains one of the major constraints limiting arganiculture expansion. Future research should therefore prioritize strategies aimed at improving water-use efficiency while reducing pressure on limited resources.

Important research directions include:

- deficit irrigation strategies;
- drought-resistant cultivation systems;
- soil moisture conservation techniques;
- rainwater harvesting approaches;
- integration of arganiculture within watershed-scale planning.

Water management should become a central component of land suitability evaluation rather than a secondary consideration.

4.10.4. Socio-Economic Development, Certification, and Governance

Further studies are needed to better understand how arganiculture contributes to rural livelihoods and how benefits are distributed among stakeholders. Particular attention should be given to:

- cooperative models;
- women's participation in value chains;
- market organization;
- certification systems;
- institutional coordination.

Sustainable development requires governance frameworks capable of linking local practices with broader environmental and economic objectives [10,20].

4.10.5. Spatial Planning, GIS, and Decision-Support Tools

The future expansion of arganiculture requires the development of spatially explicit planning tools capable of integrating multiple environmental and socio-economic factors.

Priority approaches include:

- GIS-based suitability mapping;
- remote sensing monitoring;
- hydrological modelling;
- climate scenario analysis;
- multi-criteria decision-support systems.

Figure 3 provides an operational synthesis of the ecological, agronomic, and socio-economic management components that support the four-dimensional conceptual framework (**Figure 2**), where governance capacity provides the overarching institutional context for implementation.

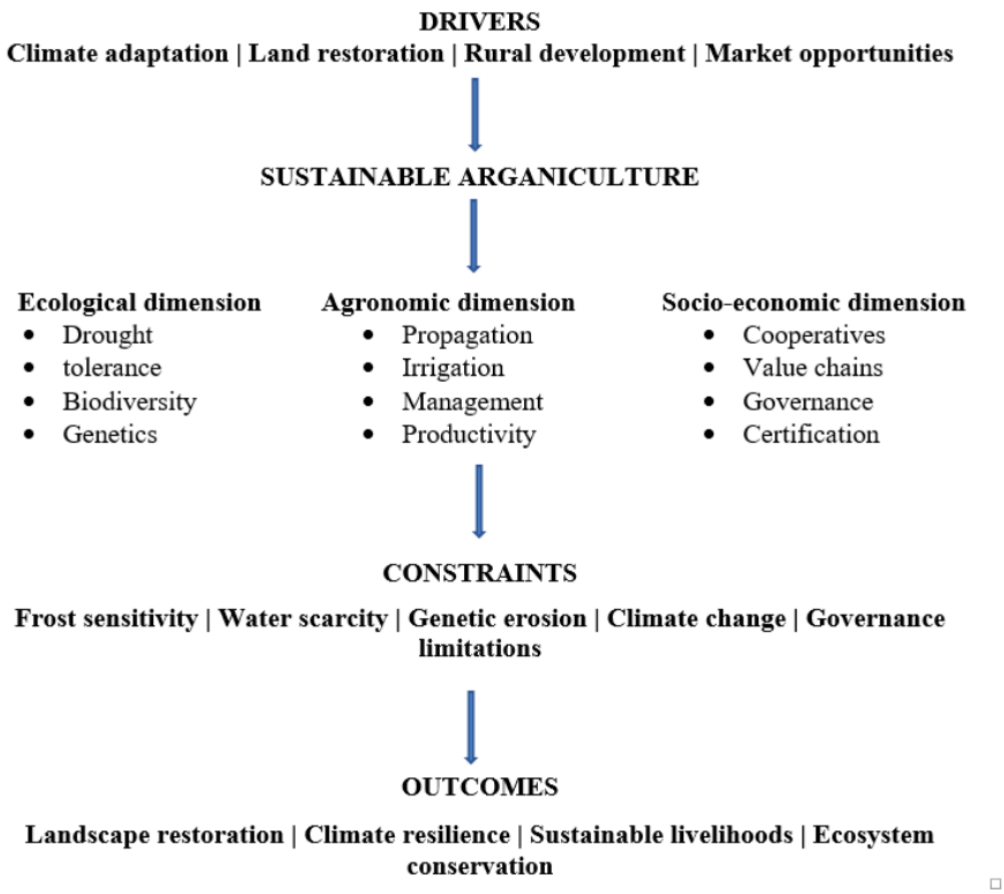

Figure 3. Integrated synthesis of the key drivers, management components, constraints, and outcomes of sustainable arganiculture.

These tools can support decision-makers by identifying suitable areas, avoiding ecological mismatches, and optimizing resource allocation (**Figure 3**).

5. Conclusions

This systematic review demonstrates that arganiculture has considerable potential to contribute to dryland restoration, climate adaptation, and sustainable rural development beyond the native range of *Argania spinosa*. However, successful expansion is highly context-dependent and requires compatibility between local environmental conditions and the ecological requirements of the species.

The findings show that sustainable arganiculture depends on integrating ecological suitability, sustainable water management, agronomic innovation, genetic conservation, and participatory governance within a comprehensive land-management framework. Rather than representing a universally transferable agricultural model, arganiculture should be implemented through evidence-based spatial planning and site-specific suitability assessments.

The conceptual framework proposed in this review provides a foundation for evaluating sustainable arganiculture while balancing productivity, ecosystem conservation, and resource sustainability. Future research should prioritize long-term field experiments, climate suitability modelling, ecosystem-service assessment, and integrated governance approaches to support resilient arganiculture under changing climatic conditions.

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Conflicts of Interest

The author declares that there are no conflicts of interest related to the publication of this article. This research was conducted independently and objectively, without any commercial, financial, institutional, or personal relationships that could be perceived as influencing the study's design, analysis, interpretation, or reporting. The author confirms that no competing interests exist.

AI Use Statement

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