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Morphological Variability and Socio-Economic Roles of Moringa Oleifera in Hyper-Arid Environment (Adrar: Algerian Sahara Desert)

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Abstract
The introduction of Moringa oleifera Lam. in hyper-arid regions of Algeria was assessed through morphological, nursery, and socio-economic studies in Adrar Province. Field data showed high germination (95%) and good seedling growth, confirming adaptability to extreme conditions. Morphological traits of mature trees revealed strong variability, suggesting genetic diversity. A survey of 30 respondents indicated multiple uses: medicinal (100%), nutritional (43%), cosmetic (23%), and fodder (minor). Principal Component Analysis highlighted that older farmers dominate cultivation, while younger respondents focus on marketing. Overall, M. oleifera demonstrates ecological adaptation and socio-economic potential as a multi-purpose species for food security, health, and rural livelihoods in Saharan Algeria.

Keywords: Moringa oleifera, hyper-arid, morphology, socio-economic impact, Sahara, Algeria.

Introduction

Arid and hyper-arid regions cover vast areas of the world and are characterised by low biological productivity, extreme climatic stress, and fragile socio-ecological systems. In Algeria, Saharan ecosystems occupy more than 80% of the national territory [1]. Despite their vast extent, these landscapes host a relatively poor flora due to severe ecological constraints, including extremely high summer temperatures, scarce and irregular rainfall, low humidity, and nutrient-deficient soils [2]. The challenge of introducing and successfully establishing new plant species in such environments is therefore considerable, yet it represents a crucial strategy for ecological restoration, food security, and sustainable development in desert regions.

In recent decades, efforts have been made in Algeria to introduce species of high ecological and socio-economic interest into Saharan areas. In Adrar Province, one of the hottest regions globally, several exotic and native species have been tested with encouraging results, including Argania spinosa [3], Atlas pistachio, false mimosa, and Prosopis(spp.) [4]. These trials highlight the potential of strategic afforestation and agroforestry initiatives to improve biodiversity, stabilise soils, and provide additional sources of food and income to local communities.

Moringa oleifera Lam. (family: Moringaceae) has attracted global attention as a “miracle tree” due to its multipurpose uses. Native to the Indian subcontinent, it has spread widely across Africa, Asia, and Latin America, being cultivated for its high nutritional value, medicinal applications, fodder potential, and even cosmetic products [5–8]. Its leaves are exceptionally rich in vitamins (A, C, E), minerals (Ca, K, Fe), proteins, and antioxidants, making it a promising natural resource for addressing malnutrition and chronic diseases [8,9]. Furthermore, M. oleifera is recognised for its resilience to drought and poor soils, features that make it particularly suited for marginal lands [7,13].

While M. oleifera has been extensively studied in semi-arid and tropical environments [10,11], little is known about its performance under the extreme hyper-arid conditions of the central Sahara. Its ecological behavior, morphological variability, and socio-economic contribution in such regions remain under-documented. In Algeria, where desertification and rural poverty remain major challenges, introducing M. oleifera could represent a transformative opportunity, both for environmental resilience and for improving livelihoods.

This study therefore aims to investigate the adaptation and integration of M. oleifera in Adrar Province, Algeria, through three complementary objectives:
Morphological characterisation of plantations established since 2017, to assess growth variability under Saharan conditions.
Nursery performance analysis of seedlings to evaluate propagation potential.
Socio-economic survey of local communities to document uses, perceptions, and market opportunities.
By combining ecological and socio-economic perspectives, this work provides the first comprehensive assessment of M. oleifera in hyper-arid Algeria. The findings are expected to contribute to discussions on sustainable agriculture, desert greening strategies, and the promotion of multi-purpose species in arid regions.

2. Materials and Methods

2.1. Study site

The study was conducted at the National Institute for Forestry Research (NIFR) experimental station in Adrar Province, south-western Algeria (27°51′7.95″N; 0°18′48.10″W). The region has a hyper-arid climate, with an average annual rainfall of 33.5 mm, maximum relative humidity of 39%, and temperatures ranging from 5 °C in winter to 49 °C in summer[3].

2.2. Plantation establishment

M. oleifera was planted in 2017 on a 0.16 ha plot at the Adrar's NIFR station. The soil was sandy-loam with an average depth of 40 cm, flat, and previously used for cereals and vegetables [3]. Drip irrigation was applied. Survival rate was calculated as the proportion of living trees to total trees planted.

2.3. Morphological characterisation

Eight parameters were measured in April 2018: tree height (H), crown width (C), diameter at breast height (DBH), leaf length (LL), pod length (PL), fresh leaf weight (FLW), dry leaf weight (DLW), and number of flowers per cluster (NFC). Measurements were taken with a Blum-Leiss dendrometer, forest compass, precision balance, and measuring tape.

2.4. Nursery experiment

Fifty seeds, collected in April 2023 from mature trees, were sown in August 2023 at the National Institute for Forestry Research nursery. Germination rate, speed, seedling height, and collar diameter were recorded after four months of growth.

2.5. Socio-economic survey

A field survey was conducted in May 2025 using structured questionnaires administered to 30 respondents. Data collected included age, cultivated area, usage types (food, medicinal, cosmetic, fodder), daily consumption, health benefits, and market price. Statistical analysis was performed with PCA (ExcelStat) to identify correlations between variables.

3. Results

3.1. Morphological variability

PCA of the eight morphological variables explained 66.5% of the total variance (36.5% for Axis 1 and 30.04% for Axis 2), indicating that the first two axes capture most of the structure in the dataset. Axis 1 mainly opposed trees with large size and high biomass production (high values of H, C, DBH and FLW on the positive side) to individuals with higher dry matter allocation in leaves (negative contribution of DLW). Axis 2 contrasted individuals with higher reproductive and foliar traits (NFC, DLW and LL on the positive side) against those characterised by longer pods (negative contribution of PL) (**Fig. 1**).

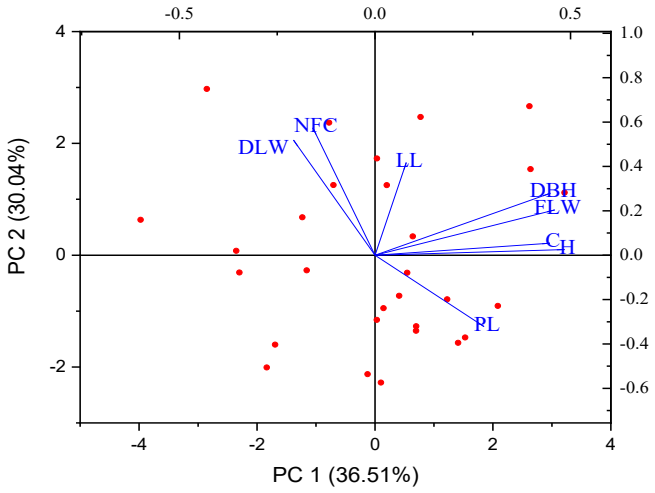

Figure 1. PCA analysis of the eight morphological variables.

These results suggest the existence of at least two main functional strategies among M. Oleifera trees under hyper-arid conditions: one group of individuals prioritising vegetative growth and fresh biomass, and another more oriented towards dry matter accumulation and reproductive investment.

Hierarchical clustering confirmed this pattern by separating two main groups of variables: a first cluster associating NFC, DLW and LL, and a second cluster subdivided into a pod-length subgroup (PL) and a growth–biomass subgroup (FLW, DBH, C and H). This structure reveals marked morphological variability within the plantation, which may reflect underlying genetic diversity and/or micro-environmental heterogeneity in the experimental plot (**Fig.2**).

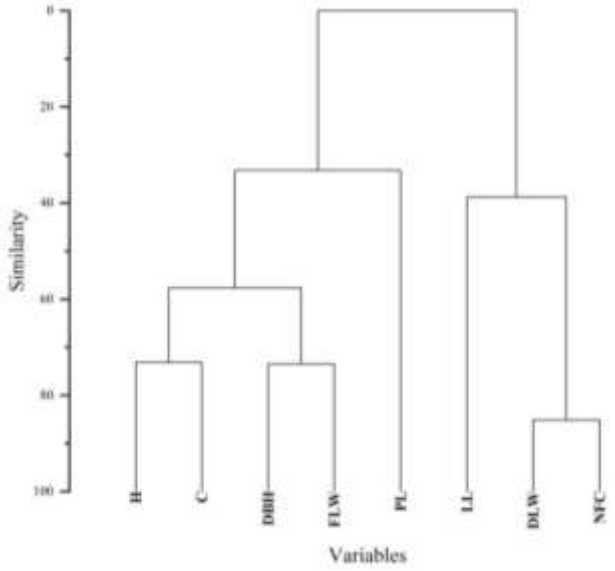

Figure 2. CAH of the eight variables.

3.2. Nursery performance

Nursery measurements showed a moderate and significant positive correlation between seedling height and collar diameter (R = 0.63; p = 0.0117), indicating that taller seedlings also tended to have thicker stems. This relationship suggests a balanced allocation between axial growth and mechanical support, which is a favourable indicator for field establishment under stressful Saharan conditions. The overall germination and early growth performance therefore confirm the good propagation potential ofM. oleifera in nursery conditions in the Adrar region (**Fig.3**).

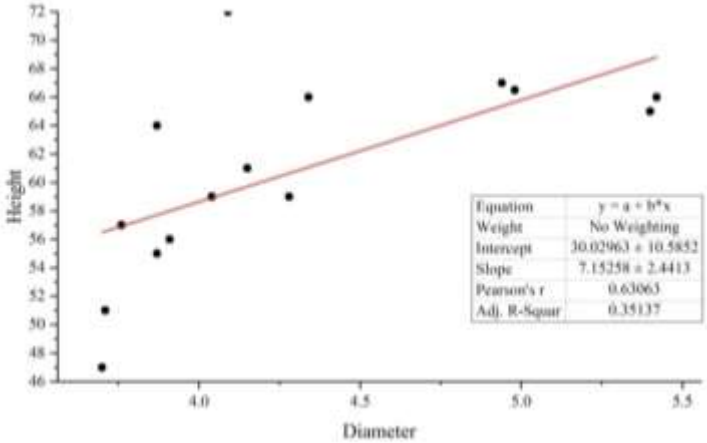

Figure 3. Correlation graph between Diameter and Height.

So, student test validate that the correlation is significant at alpha level under 0.05 (**Table 1**).

Table 1. Pearson correlation result between Diameter and Height.

		Pearson Corr.	p-value
"Diameter"	Pearson Corr.	0.63063	0.01172
		--	
"Height"	Pearson Corr.		1
	p-value	0.01172	--

Socio-economic impact

PCA of the socio-economic variables explained 65.4% of the total variance and revealed three distinct respondent profiles. The first group corresponded to older farmers managing relatively larger cultivated areas and reporting moderate but regular sales, pointing to a more production-oriented use of M. oleifera. A second, singular profile

represented a large-scale cultivation unit (400 m²), illustrating an emerging form of semi-intensive production. The third group comprised younger respondents more engaged in marketing activities and obtaining higher prices, highlighting a stronger orientation towards commercial valorisation and niche markets.
Overall, the analysis shows that production is mainly ensured by older farmers, whereas the downstream stages of commercialisation are increasingly driven by younger actors. This intergenerational complementarity suggests that M. oleifera is already integrated both into family farming systems and into emerging local value chains, even if these remain informal.

3.4. Uses and commercialisation

Among the 30 respondents, medicinal use was universal (100%), confirming the central role of M. oleifera in local health practices. Nutritional use was reported by 43% of respondents, mainly through leaf consumption, while cosmetic applications concerned 23% and fodder use remained marginal. These figures underline a clear hierarchy of uses, with health benefits perceived as the primary interest of the species, followed by its contribution to diet diversification and, to a lesser extent, to cosmetics and animal feeding.
Commercialisation remains informal, mainly in local markets, but shows potential for expansion when compared to international examples [11,16], suggests a significant potential for future expansion if appropriate structuring and marketing strategies are developed.

3.5. Environmental and Socio-Economic Implications

Environmental resilience: Potential role in desertification control, soil protection, and agroforestry systems.
Food security: A low-cost source of vitamins and minerals in remote Saharan communities.
Health benefits: Affordable natural supplement for chronic diseases.
Economic diversification: Opportunities for rural employment and niche markets.

4. Discussion

The high survival rates observed in the plantation, together with the good nursery performance and the positive correlation between seedling height and diameter, confirm the strong adaptability of M. oleifera to the hyper-arid conditions of Adrar. These findings are in line with previous studies in other dry regions, which emphasise the drought tolerance and growth plasticity of the species under water and nutrient stress in hyper-arid Saharan conditions, consistent with results from West Africa [7, 13]. In the context of the central Sahara, such performance indicates that M. oleifera can be a robust candidate for afforestation and agroforestry programmes aiming at rehabilitating degraded lands.
The marked morphological variability highlighted by PCA and hierarchical clustering reveals contrasted growth and allocation strategies among trees within the same plantation. This variability may result from both genetic differences between seed sources and micro-variations in soil and water availability, as often reported for woody species in arid environments. That, suggests genetic diversity, offering opportunities for selection and breeding [15].
From a management perspective, the coexistence of individuals with high vegetative growth and others with higher reproductive or dry-matter allocation opens interesting prospects for selection and breeding according to targeted objectives (leaf biomass, seed production, or combined uses).
Medicinal uses dominate, reflecting its integration into traditional healthcare, similar to findings in Senegal and Burkina Faso [10]. Nutritional use highlights its potential against micronutrient deficiencies [9]. Emerging cosmetic and fodder applications reflect diversification aligned with global market growth [17].
The socio-economic results show that M. oleifera has already found a place in local livelihood strategies, despite its relatively recent introduction in the region. The predominance of medicinal use and the significant, though less frequent, nutritional use confirm that the species is perceived primarily as a health resource, but also as a complementary food source rich in micronutrients. The emergence of cosmetic uses and the first, still limited, fodder uses indicate a gradual diversification of practices in line with patterns observed in other African and Asian countries where Moringa has been promoted for multiple value chains.
The generational structuring of actors, with older farmers mainly ensuring production and younger respondents more involved in marketing, illustrates a dynamic of transition from subsistence-oriented use towards more entrepreneurial initiatives. However, the current predominance of informal circuits, the absence of organised cooperatives, and the lack of standardisation and certification remain major constraints to scaling up. Without institutional support and better organisation of value chains, the socio-economic potential of M. Oleifera risks remaining underexploited in hyper-arid Algeria.
Taken together, the ecological and socio-economic findings suggest that M. oleifera can play a dual role in the study area: as a resilient component of agroforestry systems contributing to environmental restoration, and as a multi-purpose resource capable of improving food security, health, and income opportunities for rural households. In this perspective, the species represents a promising lever for integrated strategies that combine desert greening, climate change adaptation, and rural development in Saharan regions.

5. Conclusion

This study demonstrated that Moringa oleifera can successfully adapt to the hyper-arid conditions of Adrar Province, with high seedling survival, vigorous nursery growth, and strong morphological variability among mature trees. Such results confirm the species' ecological plasticity and highlight its potential as a resilient tree for arid-zone afforestation and agroforestry programmes.

Beyond its ecological adaptation, the socio-economic survey showed that M. oleifera is already integrated into the daily lives of local communities, primarily through medicinal applications, followed by nutritional, cosmetic, and fodder uses. This diversity of applications confirms its status as a "multi-purpose species" with potential to contribute simultaneously to food security, health improvement, and rural livelihoods.

Nevertheless, the study also revealed constraints, notably the informal nature of commercialisation, lack of structured value chains, and absence of certification mechanisms. Without institutional support and organised cooperatives, scaling up production and accessing wider markets will remain limited.

From an environmental perspective, M. oleifera could be strategically integrated into desert greening initiatives, soil restoration efforts, and climate change adaptation strategies in Algeria and beyond. From a socio-economic perspective, it represents a promising avenue for diversifying rural economies and enhancing resilience in vulnerable desert communities.

Future research should focus on long-term monitoring of plantations, comparative trials with both native and exotic species, and genetic selection to identify high-performing varieties. In parallel, policies supporting farmer organisations, market structuring, and certification are urgently needed to transform M. oleifera from an experimental introduction into a sustainable development resource for hyper-arid Algeria.

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