Atlas Journal of Plant Biology 2025, pp. 122–133
https://doi.org/10.5147/ajpb.vi.259

Thriving Against the Odds: The Remarkable Story of *Acacia tortilis* ssp. *raddiana* in Southeastern Morocco and other Arid Landscapes

My Abdelmajid Kassem

Plant Genomics and Bioinformatics Lab, Department of Biological and Forensic Sciences, Fayetteville State University, Fayetteville, NC 28301, USA.

Received: April 20, 2025 / Accepted: May 24, 2025

Abstract

***Acacia tortilis* ssp. *raddiana* exemplifies resilience and ecological significance in arid and semi-arid landscapes, making it a focal point of research in biodiversity conservation, sustainable agriculture, and economic development. This review explores the multifaceted roles of *Acacia tortilis* ssp. *raddiana*, from its contributions to soil health and ecosystem services to its potential in agroforestry systems. The species' ability to fix nitrogen, sequester carbon, and support biodiversity underpins its ecological importance, while its durable wood and medicinal properties highlight its economic value. Conservation strategies are vital for maintaining the genetic diversity and habitat integrity of *A. tortilis* ssp. *raddiana*, particularly in the face of climate change and habitat degradation. In-situ and ex-situ conservation efforts, along with sustainable use practices and community involvement, are essential for the species' long-term survival. The review emphasizes the need for ongoing research into the genetic diversity, ecological interactions, and adaptive strategies of *Acacia tortilis* ssp. *raddiana* to inform conservation and management practices. By integrating scientific insights with innovative conservation strategies, we can ensure the preservation and sustainable use of *A. tortilis* ssp. *raddiana* for future generations, contributing to ecological restoration, food security, and economic sustainability.**

Keywords: *Acacia tortilis* ssp. *raddiana*, semi-arid region, arid region, Southeastern Morocco, conservation strategies, biodiversity.

* Corresponding author: mkassem@uncfsu.edu

1. Introduction

Acacia tortilis ssp. *raddiana* (Figure 1), also recognized under the taxonomic subspecies *Acacia tortilis* ssp. *raddiana*, emerges as a beacon of resilience and ecological importance across the varied landscapes of Africa and the Middle East. This species has garnered attention through numerous studies which highlight its adaptability and crucial role in sustaining biodiversity in ecosystems that are often challenging and harsh (Hnatiuk and Maslin, 1988; Rohner and Ward, 2001; Zaghloul et al., 2007; El Ayadi et al., 2011; Abdallah et al., 2012; Noumi et al., 2012; El-Sayed et al., 2013; Alatar et al., 2015). In the southeastern reaches of Morocco, particularly within the environs of the Drâa Valley, *Acacia tortilis* ssp. *raddiana* epitomizes the quintessence of life's enduring capacity to adapt and thrive under extreme environmental conditions (Zerhari et al., 2000; Alatar et al., 2015; Sakrouhi et al., 2016). The Drâa Valley, marked by its arid climate, scarce water resources, and wide temperature fluctuations, serves as a vivid canvas displaying the critical ecological functions of *Acacia tortilis* ssp. *raddiana* (Carrillo-Rivera et al., 2013; Chelleri et al., 2014).

The significance of *Acacia tortilis* ssp. *raddiana* in these ecosystems transcends mere survival, contributing profoundly to the sustainability of the ecosystem and the conservation of biodiversity. Its deep-rooting system allows it to access underground water, helping stabilize the soil and reduce erosion, a pivotal function in arid and semi-arid environments where soil degradation poses a significant threat (Abdallah and Chaieb, 2010; De Boever et al., 2015; Ma et al., 2019). Moreover, *Acacia tortilis* ssp. *raddiana* acts as a natural umbrella, offering shade and cooler ground temperatures that facilitate the growth of underbrush plants, enhancing plant diversity. Its role in biodiversity conservation is further underscored by its provision of habitat and nourishment for a wide array of species, from microorganisms in the soil to insects, birds, and mammals. This creates a complex web of interactions that bolster ecosystem resilience and functionality (Ma et al., 2019; Abdallah and Chaieb, 2010).

The adaptive strategies of *Acacia tortilis* ssp. *raddiana*, such as its tolerance to drought and heat, phenotypic plasticity, and ability to regenerate after damage, underscore its evolutionary success in challenging environments. These traits not only ensure its survival but also make *Acacia tortilis* ssp. *raddiana* a cornerstone species for ecological research and conservation efforts aimed at understanding and mitigating the impacts of climate change and desertification. By studying *Acacia tortilis* ssp. *raddiana* and its interactions within the ecosystem, researchers and conservationists gain insights into the processes that support ecological balance and biodiversity in some of the planet's most vulnerable habitats (Tran et al., 2018). The ongoing research and conservation efforts surrounding *Acacia tortilis* ssp. *raddiana* highlight the broader importance of this species in ecological restoration, sustainable land management practices, and the livelihoods of local communities that depend on this tree for fuel, fodder, and other ecosystem services it provides (Sanon et al., 2009).

Acacia tortilis ssp. *raddiana,* a species belonging to the large and diverse *Acacia* genus, plays a pivotal role in ecosystems across its range (Figure 2). These trees are not just central to the ecological fabric due to their role in supporting a myriad of species, including insectivorous bats and arthropods, but also hold significant potential for sustainable agriculture and economic benefits. Amidst the backdrop of environmental changes and the increasing importance of sustainable practices, the study of *Acacia tortilis* ssp. *raddiana* offers valuable insights into ecological balance, conservation, and the promotion of biodiversity (Zaghloul et al., 2007; Alatar et al., 2015; Alshahrani, 2021).

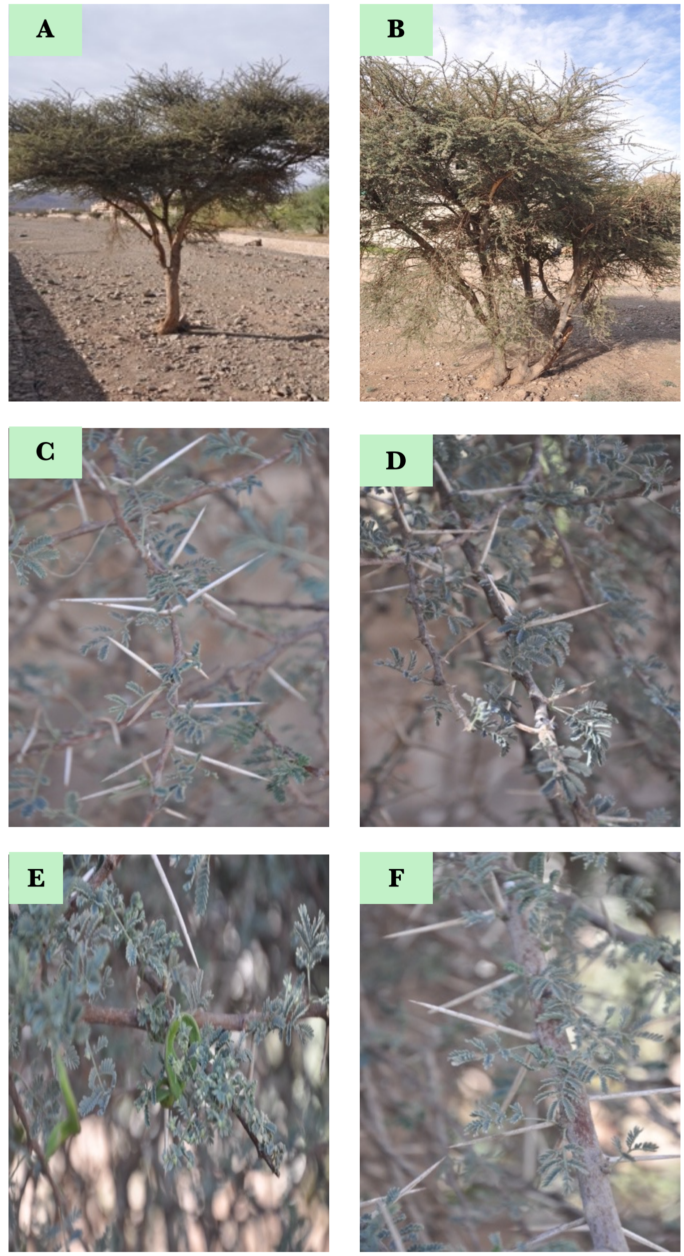

Figure 1. *Acacia tortilis* ssp. *raddiana* in its natural habitat in the Drâa Valley, Agdz, Zagora (Southeastern Morocco). (A) Single-stemmed tree with characteristic umbrella-shaped canopy, (B) Multi-branched growth form demonstrating structural variation, (C–F) Close-up views of vegetative structures, including compound leaves, sharp spines, and new leaf emergence, highlighting morphological adaptations to arid conditions. Photographs taken on February 26, 2024, by My Abdelhamid Kassem and Ait Si Alla El Hassan.

The ecological significance of *Acacia tortilis* ssp. *raddiana* is

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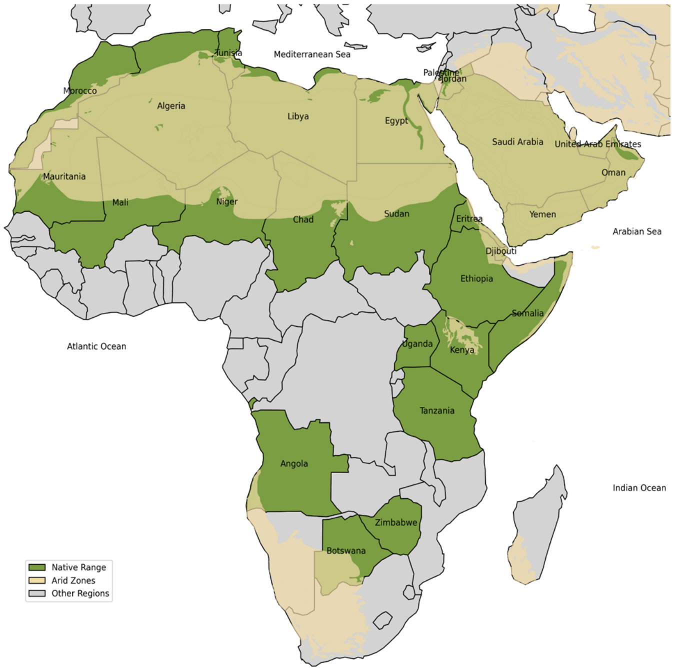

Figure 2. Geographic distribution of Acacia tortilis subsp. raddiana, also called Gum Arabic. Native distribution range of Acacia tortilis subsp. raddiana across North Africa and the Middle East, with overlay of regional arid zones. The map presented in Figure 2 was generated using Python programming language (v3.11+) (Python Software Foundation, 2023), incorporating the GeoPandas library for geospatial data handling (Jordahl et al., 2023) and Matplotlib for visualization (Hunter, 2007). Country boundaries and basemap features were sourced from the Natural Earth dataset (Natural Earth, 2023), a public domain map resource. Arid zone overlays were derived from the WWF Terrestrial Ecoregions shapefile, specifically filtering for biome ID 13 corresponding to "Deserts and Xeric Shrublands" (Olson et al., 2001). This open-source geospatial pipeline enabled the integration of species distribution data, political boundaries, and ecological zones into a reproducible, high-resolution map for publication and educational use.

multifaceted. It acts as a keystone species in its habitat, offering essential resources to various organisms. Research indicates that the decline of *Acacia* populations, including A. raddiana, due to factors such as water stress and habitat loss, could lead to considerable biodiversity losses. This underscores the need for focused studies on their ecological roles and conservation (Zaghloul et al., 2007; Alatar et al., 2015; Alshahrani, 2021).

From a genetic standpoint, the *Acacia* genus exhibits a rich diversity that is crucial for its adaptation to different environments and changing climates. Studies on related species, such as *Acacia ligulata*, provide a window into the genetic complexity and evolutionary history of these plants. Understanding the genetic foundation of *Acacia tortilis* ssp. *raddiana* is key to its conservation and the exploitation of its traits for agricultural and ecological benefits (Zaghloul et al., 2007; Alatar et al., 2015; Alshahrani, 2021).

In the realm of agriculture, Acacias, including *Acacia tortilis* ssp. *raddiana*, are increasingly recognized for their contribution to sustainable practices. Research into organic fertilization methods, for instance, has highlighted the potential benefits of organic versus mineral fertilizers in enhancing nutrient uptake and promoting healthy plant growth. While this study was focused on citrus trees, the principles and findings can be extrapolated to the cultivation of Acacias, suggesting a promising avenue for integrating these species into organic farming systems (Zaghloul et al., 2007; Alatar et al., 2015; Alshahrani, 2021).

As we delve deeper into the study of *Acacia tortilis* ssp. *raddiana* (and to an extent other *Acacia* species), it becomes clear that this species is not just a part of its ecosystem but a crucial player in the broader context of environmental sustainability, economic development, and the global pursuit of biodiversity conservation. The continuation of this review will explore the intricate roles and benefits of Acacia tortilis ssp. raddiana, aiming to shed light on its ecological importance, genetic diversity, and potential for sustainable agriculture, thereby contributing to a more comprehensive understanding of its place in the natural world and human society.

2. Ecological Roles

Acacia tortilis ssp. *raddiana*, like its counterparts in the *Acacia* genus, significantly contributes to its ecosystem's ecological balance and biodiversity. This section explores its ecological role, focusing on its importance for insectivorous bats and arthropods, its function in habitat creation, and its impact on biodiversity (Figure 3).

2.1. Insectivorous Bats and Arthropods Support

Acacia tortilis ssp. *raddiana* stands as a linchpin within its ecosystem, particularly in the critical support it provides to insectivorous bats and arthropods (Benda et al., 2010; Hackett et al.,

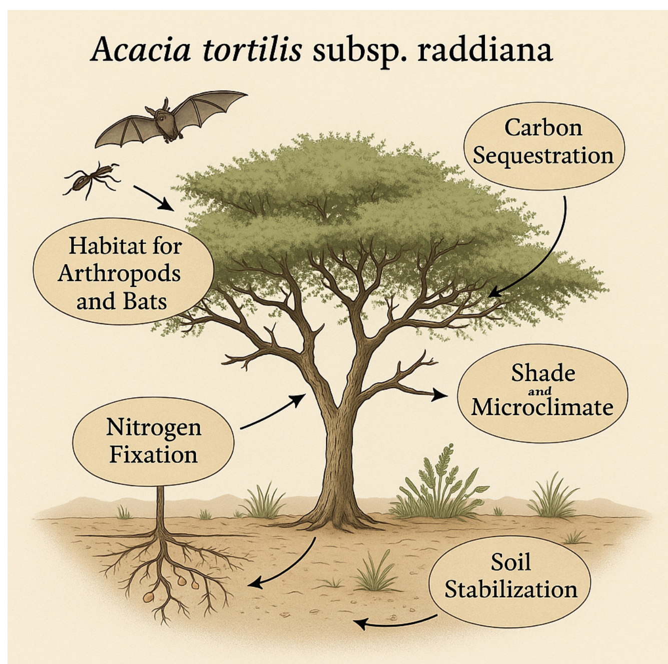

Figure 3. Ecological functions of *Acacia tortilis* ssp. *raddiana* in arid ecosystems. This keystone species enhances ecosystem services through nitrogen fixation, soil stabilization, shade and microclimate regulation, carbon sequestration, and habitat provision for arthropods and insectivorous bats. Illustration generated using ChatGPT (OpenAI) for conceptual visualization.

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2013). These creatures are not only integral to the ecological food web due to their roles in pest control and pollination but also serve as indicators of environmental health. The relationship between *Acacia tortilis* ssp. *raddiana* and these species underscores a complex interdependence, where Acacias offer vital habitats for foraging and roosting, thereby sustaining populations of these important animals. The dense canopies and rich floral resources of *Acacia* stands create microhabitats that are teeming with insect life, attracting bats and other insectivores in search of food (Coe and Coe, 1987; Benda et al., 2010; Hackett et al., 2013).

However, the resilience of this relationship is tested by environmental stressors such as water scarcity and habitat change, which threaten *Acacia* populations and, by extension, the biodiversity they support. The declining health of *Acacia tortilis* ssp. *raddiana* due to these stressors not only diminishes its capacity to provide essential services but also signals a broader ecological imbalance that could lead to a significant loss of biodiversity. The intricate ecological networks that Acacias support—spanning from the microscopic fungi that thrive in their root systems to the wide array of insects that feed on their leaves and flowers, and the bats that prey on these insects—highlight the trees' role as ecosystem engineers (Benda et al., 2010; Hackett et al., 2013; Hobbs et al., 2014; Mosbah et al., 2017).

Research has illuminated the correlation between dense *Acacia* stands and heightened levels of bat activity and arthropod richness, suggesting that the preservation of *Acacia* populations is crucial for maintaining the health and diversity of these communities. Such findings advocate for the conservation of *Acacia tortilis* ssp. *raddiana* to protect and bolster ecosystem services, emphasizing the need for strategies that mitigate environmental pressures on these trees. Efforts to conserve *Acacia* habitats not only aid in the preservation of insectivorous bats and arthropods but also contribute to the broader goals of ecological restoration and biodiversity conservation, ensuring the stability and resilience of ecosystems in the face of changing environmental conditions (Coe and Coe, 1987; Benda et al., 2010; Hackett et al., 2013; Hobbs et al., 2014).

2.2. Habitat Creation and Biodiversity

Acacia tortilis ssp. *raddiana*'s role in ecosystem dynamics is multi-faceted and critical, extending far beyond its mere presence in the landscape. By fostering a conducive habitat, it not only offers shelter but also provides a rich source of food for a diverse array of organisms. This, in turn, catalyzes a series of ecological interactions that are foundational to the health and diversity of ecosystems, particularly in arid and semi-arid regions like the Middle East. The tree's decline, therefore, poses a substantial threat to biodiversity, potentially unraveling the complex ecological tapestries where *Acacia tortilis* ssp. *raddiana* is a key thread (Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; Souza-Alonso et al., 2017).

The intricate relationships that *Acacia tortilis* ssp. *raddiana* nurtures with the surrounding flora and fauna are emblematic of its role as an ecological cornerstone. For instance, its foliage and flowers serve as a food source for numerous arthropod species, which, in turn, attract a variety of insectivorous bats, contributing to a dynamic food web. These interactions are not just limited to bats and arthropods; they extend to birds, small mammals, and even soil microorganisms, all of which benefit from the tree's presence. *Acacia tortilis* ssp. *raddiana* supports a wide array of desert biodiversity, including birds such as the desert sparrow (*Passer simplex*), mammals like the dorcas gazelle (*Gazella dorcas*), and symbiotic microorganisms such as arbuscular mycorrhizal fungi (AMF), all of which depend on the tree for shelter, food, or root associations (Kirwan et al., 2009; Segura and Moreno, 2024; Mosbah et al., 2017). The tree's ability to enhance soil fertility through nitrogen fixation further exemplifies its role in ecosystem productivity and resilience, fostering plant diversity beneath its canopy (Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; De Boever et al., 2015; Souza-Alonso et al., 2017).

Moreover, *Acacia tortilis* ssp. *raddiana*'s significance is magnified in regions like the Middle East, where environmental conditions are harsh and unforgiving. In these landscapes, the tree not only combats desertification but also acts as a bulwark against biodiversity loss, providing essential ecosystem services such as erosion control, microclimate regulation, and carbon sequestration. Its potential decline due to factors like overgrazing, land use change, and climate change underscores the urgent need for conservation strategies that protect and restore these vital trees. Safeguarding *Acacia tortilis* ssp. *raddiana* populations is not merely about preserving a single species; it's about maintaining ecological balance, promoting biodiversity, and ensuring the sustainability of these critical habitats for future generations (Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; Souza-Alonso et al., 2017).

2.3. Impact on Ecosystem Services

Acacia tortilis ssp. *raddiana*, through its array of ecological roles, significantly impacts the provision of crucial ecosystem services which are foundational to environmental health, agricultural sustainability, and human well-being. Its ability to stabilize soil not only prevents erosion but also improves soil structure and fertility, thereby enhancing agricultural productivity in arid and semi-arid regions. This soil stabilization capability is particularly critical in areas prone to desertification, where *Acacia tortilis* ssp. *raddiana* acts as a natural bulwark against the loss of arable land (Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; De Boever et al., 2015; Souza-Alonso et al., 2017).

Moreover, the role of *Acacia tortilis* ssp. *raddiana* in carbon sequestration cannot be overstated. By capturing carbon dioxide from the atmosphere and storing it in biomass and soil, it contributes to climate change mitigation efforts. This process is vital for reducing the global carbon footprint and addressing the adverse effects of climate change. In addition to its direct climate benefits, carbon sequestration by *Acacia tortilis* ssp. *raddiana* supports biodiversity by maintaining habitat quality and reducing the pressure on more vulnerable ecosystems (Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; De Boever et al., 2015; Souza-Alonso et al., 2017).

Water cycle regulation is another essential ecosystem service provided by *Acacia tortilis* ssp. *raddiana*. Through transpiration, it contributes to the atmospheric moisture balance and can influence local precipitation patterns. This function is crucial for maintaining the hydrological cycle in dry regions, ensuring the availability of water for agriculture, wildlife, and human consumption. The tree's deep root system also plays a part in enhancing groundwater recharge, further underlining its significance in water conservation and management strategies (Le Maitre et al., 2011; Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; Souza-Alonso et al., 2017; Briedman et al., 2017).

The preservation and deeper understanding of *Acacia tortilis* ssp. *raddiana*'s multifaceted contributions to ecosystem services are imperative for the development of sustainable ecosystem management and conservation strategies. Recognizing its value beyond the immediate biological interactions, it's clear that *Acacia tortilis* ssp. *raddiana* plays a critical role in supporting biodiversity, provisioning ecosystem services, and maintaining ecological balance. Consequently, there is a pressing need for its conservation and a more detailed study of its ecological interactions. Future research should delve into the mechanisms by which *Acacia tortilis* ssp. *raddiana* contributes to combating climate change and promoting sustainable ecosystems, focusing on conservation strategies that can preserve and enhance these benefits. This research is essential for formulating policies and practices that ensure the long-term sustainability of ecosystems where *Acacia tortilis* ssp. *raddiana* is a key species, supporting not only the environmental health but also the economies and communities dependent on these landscapes (Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; Souza-Alonso et al., 2017; Briedman et al., 2017).

3. Genetic Diversity and Adaptation

The genetic diversity within the *Acacia* genus, composed of 1,350 species (Maslin, 2003), is a testament to the adaptability and resilience of these species across various environments such as Africa, Hawaii, Southeast Asia, Australia, and the Mascarene Islands. This section delves into the significance of genetic diversity for the genus *Acacia*, highlighting findings from genetic studies and their implications for conservation and agricultural applications (Robinson and Harris, 2000; Barnes, 2001; Abdelsalam et al., 2020).

3.1. Significance of Genetic Diversity

The genetic diversity within the genus *Acacia* is a testament to the evolutionary resilience and adaptability that have enabled these plants to thrive across varied and often harsh environments (Robinson and Harris, 2000). This diversity is not just about survival; it's a crucial factor that allows species to respond to environmental changes, resist diseases, and adapt to new challenges. The study of genetic variations within the *Acacia* genus, including the detailed examination of the *Acacia ligulata* chloroplast genome, illuminates the depth and breadth of genetic strategies these plants employ to navigate ecological pressures (Robinson and Harris, 2000; Williams et al., 2015).

For instance, the discovery of a highly divergent clpP1 gene within the *Acacia ligulata* chloroplast genome opens a window into the genetic mechanisms that underpin ecological adaptability and success across the *Acacia* genus. This gene, among others (Table 1), is indicative of the unique evolutionary paths that different *Acacia* species have taken, adapting to their specific ecological niches. Such genetic markers are invaluable for understanding the complex interplay between genetic variation and ecological adaptability (Williams et al., 2015). For example, several genes including 18S ribosomal RNA (Korol et al., 2013), choloroplastic voucher CN20425 trnL-trnF intergenic spacer region (Pinho et al., 2023a), voucher CN20425 tRNA-Leu (trnL-UAA) gene (Pinho et al., 2023b), chloroplastic trnK, matK genes for tRNA-Lys intron (Abdel-Hamid et al., 2020a,b), clone ACAO13sp small subunit ribosomal RNA gene, clone ACAM16sp small subunit ribosomal RNA gene, clone ACAM6sp small subunit ribosomal RNA gene (Abdedaiem,

Table 1. Published DNA sequence data for *Acacia tortilis* ssp. *raddiana* and its synonymous classification (*Vachellia tortilis* ssp. *raddiana*) across various nuclear and chloroplast loci. This includes ribosomal RNA genes, chloroplast intergenic spacer regions, and tRNA intron/exon sequences submitted to GenBank, reflecting the increasing molecular focus on phylogenetics, population structure, and species-level identification.

Species	Locus	Sequence (bp)	Reference
Acacia tortilis ssp. raddiana	18S ribosomal RNA	646	Korol et al. (2013)
Vachellia tortilis ssp. raddiana	voucher CN20425 trnL-trnF intergenic spacer region, chloroplast	428	Pinho et al. (2023a)
Vachellia tortilis ssp. raddiana	voucher CN20425 tRNA-Leu (trnL-UAA) gene	568	Pinho et al. (2023b)
Vachellia tortilis ssp. raddiana	chloroplast trnK, matK genes for tRNA-Lys intron	980	Abdel-Hamid et al. (2020)
Vachellia tortilis ssp. raddiana	chloroplast rbcL gene	584	Abdel-Hamid et al. (2020)
Vachellia tortilis ssp. raddiana	clone ACAO13sp small subunit ribosomal RNA gene	548	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAM16sp small subunit ribosomal RNA gene	549	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAM6sp small subunit ribosomal RNA gene	549	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAB5sp small subunit ribosomal RNA gene	549	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAC32sp small subunit ribosomal RNA gene	549	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAC13sp small subunit ribosomal RNA gene	546	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAM21sp small subunit ribosomal RNA gene	546	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAM41sp small subunit ribosomal RNA gene	546	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAO15sp small subunit ribosomal RNA gene	554	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAO03sp small subunit ribosomal RNA gene	554	Abdedaiem (2019)
Vachellia tortilis ssp. raddiana	clone ACAO06sp small subunit ribosomal RNA gene	554	Abdedaiem (2019)

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2019), and many others have been sequenced and available in GenBank database (Table 1).

The implications of this genetic diversity are far-reaching. They not only enhance our understanding of the evolutionary dynamics within the *Acacia* genus but also offer insights into how these plants might respond to future environmental challenges. In the face of climate change, habitat destruction, and the increasing spread of diseases, the genetic resilience found in species like *Acacia tortilis* ssp. *raddiana* could provide crucial clues for conservation strategies. By leveraging this genetic knowledge, conservationists and ecologists can better predict which species or even which genetic variants within a species are most likely to withstand environmental pressures, guiding targeted conservation and reforestation efforts (Scanlon et al., 2005; Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; Souza-Alonso et al., 2017).

Moreover, the genetic diversity within *Acacia* species underscores the importance of preserving genetic resources, not only for the sake of the species themselves but also for the broader ecological communities that depend on them. As genetic studies continue to unravel the complexities of the *Acacia* genus, they enrich our understanding of biodiversity, ecosystem function, and the potential for sustainable management of natural resources in the face of global environmental change (Robinson and Harris, 2000; Williams et al., 2015).

3.2. Genetic Research and Conservation Efforts

The genetic research into *Acacia* species, particularly *Acacia tortilis* ssp. *raddiana*, plays a pivotal role in shaping the future of conservation strategies, especially in our rapidly changing world. As climate change accelerates and habitats face increasing degradation, understanding the genetic underpinnings of species adaptability and resilience becomes more than an academic pursuit—it transforms into a practical guide for action. This body of research unveils the genetic diversity that enables *Acacia tortilis* ssp. *raddiana* to withstand environmental stressors, offering a blueprint for conservationists aiming to preserve this diversity (Djibo et al., 2017; Blyth et al., 2020; Encinas-Viso et al., 2020; McLay et al., 2020).

Genetic diversity is not just a measure of genetic variance; it's a reflection of a species' evolutionary history, its past responses to environmental change, and its potential future adaptability. By identifying genetic markers associated with resilience—such as drought tolerance, disease resistance, or adaptability to varying temperatures—conservationists can pinpoint which populations of *Acacia tortilis* ssp. *raddiana* are most likely to survive in changing climates and which genetic traits are crucial for their survival. This knowledge facilitates targeted conservation efforts, such as the establishment of genetic reserves, the prioritization of genetically diverse populations for protection, and the development of reforestation projects that enhance genetic diversity (Djibo et al., 2017; Blyth et al., 2020; Encinas-Viso et al., 2020; McLay et al., 2020).

Moreover, preserving the genetic diversity of *Acacia tortilis* ssp. *raddiana* contributes directly to ecosystem stability. Diverse genetic profiles within species ensure a broader range of functional roles within ecosystems, enhancing overall resilience. For instance, certain genetic variants might be better suited for specific ecological functions like nitrogen fixation or providing habitat for wildlife species (Ndoye et al., 1995; Raddad et al., 2005, 2006). By maintaining a wide array of genetic variants, ecosystems can better withstand and recover from disturbances, whether they be natural disasters or human-induced changes (Petit and Hampe, 2006; Hughes et al., 2008).

In essence, the genetic research on *Acacia* species like *Acacia tortilis* ssp. *raddiana* offers a cornerstone for developing forward-thinking conservation strategies. It underscores the need for a conservation paradigm that not only seeks to protect species from extinction but also to preserve the genetic diversity that underlies their ecological importance and adaptability. As the challenges posed by climate change and habitat degradation grow more complex, integrating genetic insights into conservation planning will be crucial for sustaining both biodiversity and the health of ecosystems upon which human societies depend (Jump and Penuelas, 2005; Pejchar and Press, 2006; Tilman et al., 2006).

3.3. Implications for Agriculture and Forestry

The genetic insights gleaned from *Acacia* species research hold profound implications for both agriculture and forestry, providing a pathway towards more resilient and sustainable practices.

Figure 4. Socioeconomic and ecological roles of Acacia tortilis subsp. raddiana in arid landscapes of Southeastern Morocco. Top-left: Close-up of seed pods illustrating the tree's reproductive structures and potential as a fodder and gum source. Top-right: A mature tree with the characteristic umbrella-shaped canopy, providing shade, wind protection, and habitat for desert fauna. Bottom-left: A local woman collecting firewood from the tree, reflecting its importance in rural livelihoods for fuel, fencing, and traditional practices. Bottom-right: A camel browsing on Acacia foliage, demonstrating its role as a vital dry-season fodder source for livestock in nomadic and agro-pastoral systems. Photos capture the interwoven ecological, cultural, and economic value of A. tortilis subsp. raddiana in sustaining both ecosystems and communities. Illustration generated using ChatGPT (OpenAI) for conceptual visualization purposes.

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Understanding the genetic underpinnings of traits like drought and pest resistance in *Acacia tortilis* ssp. *raddiana* and its relatives can revolutionize how we approach agricultural resilience and environmental conservation. For instance, identifying specific genetic markers associated with these adaptive traits allows for the strategic breeding of *Acacia* varieties that are better suited to withstand the stresses of climate change (Jump and Penuelas, 2005; Pejchar and Press, 2006; Tilman et al., 2006). This knowledge has the potential to significantly enhance the viability of *Acacia tortilis* ssp. *raddiana* in agroforestry systems, where its integration can yield multiple benefits (Fagg and Stewart, 1994; Jump and Penuelas, 2005; Pejchar and Press, 2006; Tilman et al., 2006; Nirsatmanto and Sunarti, 2019).

Incorporating *Acacia tortilis* ssp. *raddiana* into agroforestry systems can lead to substantial soil improvements due to its nitrogen-fixing capabilities, enriching the soil and reducing the need for synthetic fertilizers. Moreover, its role in carbon sequestration aligns with global efforts to mitigate climate change, providing a natural method for capturing atmospheric carbon.

The diversification of agricultural landscapes with species like *Acacia tortilis* ssp. *raddiana* also promotes biodiversity, enhances ecosystem services, and can improve farm productivity and resilience against pests and diseases (Fagg and Stewart, 1994; Jump and Penuelas, 2005; Pejchar and Press, 2006; Tilman et al., 2002, 2006; Raddad et al., 2006; Garrity et al., 2010; De Boever et al., 2015; Nirsatmanto and Sunarti, 2019).

The broader implications of genetic research on *Acacia* species underscore their ecological and economic significance (Figure 4). By deepening our understanding of their evolutionary history and ecological adaptation, we pave the way for informed conservation strategies that safeguard these species and their habitats. Additionally, leveraging this genetic knowledge in agriculture and forestry not only supports sustainable practices but also contributes to the resilience of these systems in the face of environmental challenges (Burley et al., 1986; Tilman et al., 2002, 2006; Raddad et al., 2006; Broadhurst and Young, 2006; Garrity et al., 2010; Omondi et al., 2010; Adamski et al., 2012).

Future research should aim at expanding our genomic knowledge of the *Acacia* genus, focusing on comprehensive studies that map the genome-wide distribution of adaptive traits. Identifying these genetic traits and understanding their expression and interaction with environmental factors will be key to unlocking their potential applications in conservation, sustainable agriculture, and forestry. This forward-looking research agenda promises to enhance our ability to harness the natural resilience and utility of *Acacia* species, ensuring their preservation and beneficial use for generations to come (Hudson, 2008; Neale and Kremer, 2011; Nair et al., 2021).

4. Socioeconomic Importance

Acacia tortilis ssp. *raddiana*, along with other species in the *Acacia* genus, holds significant economic value and potential for sustainable agriculture. This section outlines the economic benefits derived from *Acacia tortilis* ssp. *raddiana*, its role in sustainable agricultural practices, and the broader implications for food security and environmental sustainability (Seigler, 2002; Midgley and Turnbull, 2003; Griffin et al., 2011; Koutika and Richardson, 2019; Griffin et al., 2023). Several studies of various aspects of *Acacia tortilis* ssp. *raddiana*, including its physiological responses, ecological significance, chemical properties, and other benefits summarized in Table 2.

Table 2. Summary of recent experimental and applied studies on *Acacia tortilis* subsp. *raddiana* (including synonymous classification as *Acacia raddiana*). The studies span diverse research domains, including environmental stress physiology, pharmaceutical potential, seed and gum chemistry, protein extraction, microbiome interactions, and ecological adaptability under hyper-arid conditions. This highlights the species' growing relevance in ecological, biomedical, and biotechnological research.

Title	Summary	Reference
Germination, physiological and biochemical responses of *Acacia* seedlings to petroleum contaminated soils	This study examines the impact of petroleum contamination on the germination and early growth stages of *Acacia raddiana* and Acacia tortilis.	Tran et al. (2018)
Green synthesis of silver nanoparticles and its environmental sensor ability to some heavy metals	Highlights the effectiveness of *Acacia raddiana* extract in the green synthesis of silver nanoparticles and their application in detecting heavy metals.	Ibrahim et al. (2024)
Antidiabetic activity of *Acacia tortilis* (Forsk.) Hayne ssp. *raddiana* polysaccharide on streptozotocin-nicotinamide induced diabetic rats	Investigates the antidiabetic properties of polysaccharide from *Acacia raddiana* gum exudates in diabetic rats.	Bhateja and Singh (2014)
Temporal and Spatial Changes in Phyllosphere Microbiome of *Acacia* Trees Growing in Arid Environments	Studies the changes in the phyllosphere microbiome of *Acacia raddiana* in response to environmental conditions.	Al Ashhab et al. (2021)
Preparation and physicochemical properties of protein concentrate, and isolate produced from *Acacia tortilis* (Forssk.) Hayne ssp. *raddiana*	Evaluates the composition and properties of protein products derived from *Acacia raddiana* seeds.	Embaby et al. (2018)
Chemical composition and nutritional evaluation of the seeds of *Acacia tortilis* (Forssk.) Hayne ssp. *raddiana*	Studies the nutritional value and chemical composition of *Acacia raddiana* seeds.	Embaby et al. (2016)
Tree growth and water-use in hyper-arid *Acacia* occurs during the hottest and driest season	Explores the growth dynamics and water use of *Acacia raddiana* under extreme arid conditions.	Winters et al. (2018)
Monosaccharide composition of acidic gum exudates from Indian *Acacia tortilis* ssp. *raddiana* (Savi) Brenan	Analyzes the monosaccharide composition of gum exudates from *Acacia raddiana*.	Lakhera and Kumar (2017)
Evolution and ecology meet molecular genetics: adaptive phenotypic plasticity in two isolated Negev desert populations of *Acacia raddiana*	Compares growth and defense traits in *Acacia raddiana* populations across an environmental gradient.	Ward et al. (2012)
Pharmacological assessment of the heartwood of *Acacia raddiana* Willd for antifungal potential	Assesses the antifungal activity of *Acacia raddiana* heartwood extracts.	Singh et al. (2022)

4.1. Economic Benefits of *Acacia tortilis* ssp. *raddiana*

Acacia species, with their remarkable versatility and resilience, have carved out a significant niche in the global economy, providing raw materials for various industries ranging from timber production to pharmaceuticals, and increasingly, sustainable agriculture (Lopez-Hortas et al., 2021). The wood of *Acacia tortilis* ssp. *raddiana*, known for its exceptional durability and natural resistance to pests, is highly sought after (Aref et al., 2013). This makes it an ideal material for crafting furniture that withstands the test of time, fuel that burns efficiently (Figure 4), and construction materials that offer structural integrity and longevity. The economic value derived from the timber alone underscores the species' contribution to local and global markets (Seigler, 2002; Midgley and Turnbull, 2003; Griffin et al., 2011; Koutika and Richardson, 2019; Griffin et al., 2023).

Beyond its structural applications, *Acacia tortilis* ssp. *raddiana* harbors a wealth of medicinal properties that have been tapped into for centuries by indigenous communities and are now being recognized by modern medicine. Compounds extracted from various parts of the plant, including its bark, leaves, and gum, have been found to possess therapeutic properties, ranging from antimicrobial to anti-inflammatory effects. This pharmacological potential opens lucrative opportunities for the pharmaceutical industry to develop new treatments and health supplements based on these natural compounds. The exploration of *Acacia tortilis* ssp. *raddiana* in pharmaceutical applications not only has the potential to generate significant revenue but also contributes to the health and well-being of populations worldwide (Seigler, 2002; Midgley and Turnbull, 2003; Griffin et al., 2011; Koutika and Richardson, 2019; Griffin et al., 2023).

Moreover, the push towards sustainable agricultural practices has spotlighted the role of *Acacia tortilis* ssp. *raddiana* as a source of organic fertilizer. Research into the use of *Acacia* as green manure or in composting processes highlights its ability to enrich soil with organic matter and essential nutrients, promoting healthier crop growth without the environmental downsides associated with synthetic fertilizers. This attribute positions *Acacia tortilis* ssp. *raddiana* as a key player in the organic agriculture sector, supporting the production of healthier foods and fostering more sustainable farming practices. As demand for organic products continues to rise, the contribution of *Acacia tortilis* ssp. *raddiana* to this sector could see significant growth, benefiting not only the environment but also farmers and consumers looking for eco-friendly agricultural solutions (Seigler, 2002; Midgley and Turnbull, 2003; Griffin et al., 2011; Koutika and Richardson, 2019; Griffin et al., 2023).

In summary, the economic contributions of *Acacia* species, particularly *Acacia tortilis* ssp. *raddiana*, span across diverse sectors, offering valuable resources for timber, medicinal, and agricultural applications (Abdallah et al., 2008; Aref et al., 2013; Lopez-Hortas et al., 2021). Their role in these industries not only underscores their economic importance but also highlights the potential for sustainable utilization and conservation of natural resources. As research and development in these areas continue to advance, the value of *Acacia tortilis* ssp. *raddiana* is expected to increase, further solidifying its status as a crucial resource for economic development and environmental sustainability (Seigler, 2002; Midgley and Turnbull, 2003; Griffin et al., 2011; Koutika and Richardson, 2019; Griffin et al., 2023).

4.2. Sustainable Agricultural Practices

The integration of *Acacia tortilis* ssp. *raddiana* into agricultural systems can enhance sustainability by improving soil health, increasing biodiversity, and reducing the reliance on chemical inputs. The species' nitrogen-fixing ability enriches soil fertility, making it beneficial for intercropping and agroforestry systems. Furthermore, the use of *Acacia tortilis* ssp. *raddiana* in organic fertilizers supports sustainable crop production by providing essential nutrients in a more environmentally friendly manner compared to synthetic fertilizers (Buresh and Tian, 1998; Raddad et al., 2005, 2006; Noumi et al., 2011).

4.3. Implications for Food Security and Environmental Sustainability

The cultivation and utilization of *Acacia tortilis* ssp. *raddiana* in sustainable agriculture have broader implications for food security and environmental sustainability. By enhancing soil health and ecosystem services, *Acacia tortilis* ssp. *raddiana* can contribute to increased agricultural productivity and resilience to climate change. This, in turn, supports food security by ensuring a stable supply of food crops. Additionally, the adoption of *Acacia*-based sustainable practices can mitigate environmental degradation, preserving biodiversity and natural resources for future generations (Figure 4) (El-Sayed et al., 2013; Blanco et al., 2015; Zabre et al., 2017; Hnini et al., 2023).

In summary, *Acacia tortilis* ssp. *raddiana* presents numerous economic benefits and opportunities for sustainable agriculture. Its contribution to timber production, medicinal uses, and organic fertilization underscores its economic value. Furthermore, the integration of *Acacia tortilis* ssp. *raddiana* into sustainable agricultural practices offers a pathway towards enhanced food security and environmental sustainability. Future research should explore the optimization of *Acacia tortilis* ssp. *raddiana*'s economic potential and its integration into sustainable agricultural systems (El-Sayed et al., 2013; Blanco et al., 2015; Zabre et al., 2017; Hnini et al., 2023).

5. Threats and Conservation Strategies

The conservation of *Acacia tortilis* ssp. *raddiana*, and other *Acacia* species, is vital for maintaining ecological balance, supporting biodiversity, and ensuring the continued availability of its economic benefits. This section outlines key strategies for the conservation of *Acacia tortilis* ssp. *raddiana*, emphasizing habitat preservation, genetic diversity, and sustainable use (Lal, 2004; Zaghloul et al., 2007; Noumi and Chaieb, 2012; Alatar et al., 2015; Alshahrani, 2021).

5.1. Habitat Preservation

The primary strategy for conserving *Acacia tortilis* ssp. *raddiana*

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involves the preservation of its natural habitats. Protecting these areas from deforestation, land conversion, and degradation is crucial for maintaining healthy populations. Establishing protected areas and implementing land management practices that safeguard *Acacia* habitats can help mitigate the impact of human activities. Additionally, restoring degraded *Acacia* habitats through reforestation and rehabilitation projects can enhance their resilience to environmental stressors (Dawson et al., 2014; Orr et al., 2017; Meybeck et al., 2021).

5.2. Maintaining Genetic Diversity

Conservation efforts must also focus on maintaining the genetic diversity of *Acacia tortilis* ssp. *raddiana*. This involves the conservation of a wide range of genetic material through in-situ and ex-situ conservation methods. In-situ conservation, or the protection of species within their natural habitats, ensures the ongoing evolution and adaptation of *Acacia tortilis* ssp. *raddiana*. Ex-situ conservation strategies, such as seed banks and botanical gardens, provide a backup for preserving genetic material and facilitate research on the species' genetic diversity and adaptability (Maxted et al., 2006; Broadhurst and Young, 2006).

5.3 Sustainable Use and Community Involvement

Sustainable use practices are essential for the long-term conservation of *Acacia tortilis* ssp. *raddiana*. This includes promoting sustainable harvesting methods, encouraging the use of *Acacia* products in a way that does not deplete natural populations, and integrating *Acacia tortilis* ssp. *raddiana* into sustainable agricultural systems. Engaging local communities in conservation efforts is also crucial, as it fosters a sense of stewardship and provides economic incentives for the preservation of *Acacia* habitats (Zaghloul et al., 2007; Sanon et al., 2009; Bellefontaine et al., 2011; Hackett et al., 2013; Hobbs et al., 2014; Alatar et al., 2015; Souza-Alonso et al., 2017; Briedman et al., 2017; Alshahrani et al., 2021).

5.4. Research and Monitoring

Ongoing research and monitoring are vital components of *Acacia tortilis* ssp. *raddiana* conservation. Studies on its ecology, genetic diversity, and responses to environmental changes can inform conservation strategies and adaptive management practices. Monitoring programs can help track the status of *Acacia tortilis* ssp. *raddiana* populations, assess the effectiveness of conservation strategies, and identify emerging threats (Lal, 2004; Oldfield, 2009; Orr et al., 2017).

In conclusion, the conservation of *Acacia tortilis* ssp. *raddiana* requires a multifaceted approach that combines habitat preservation, genetic diversity maintenance, sustainable use, community involvement, and continuous research and monitoring. By implementing these strategies, we can ensure the survival of *Acacia tortilis* ssp. *raddiana* and its continued role in ecosystems, agriculture, and the economy (Lal, 2004; Oldfield, 2009; Orr et al., 2017).

6. Conclusion & Future Research Directions

6.1. Conclusion

Acacia tortilis subsp. *raddiana* represents a model species for understanding ecological resilience and sustainable land use in arid and semi-arid ecosystems. Its capacity to improve soil fertility through nitrogen fixation, enhance biodiversity, provide habitat for a wide array of species, and serve multiple socio-economic roles underscores its ecological and developmental significance.

This review highlights how *A. tortilis* ssp. *raddiana* contributes to ecosystem services such as carbon sequestration, erosion control, and microclimate regulation. It also emphasizes the species' genetic diversity, which is key to its adaptability and potential use in agroecological restoration. However, despite its importance, the species is threatened by overgrazing, climate change, and land-use conversion, necessitating integrated conservation strategies that involve habitat protection, community engagement, and scientific monitoring.

A coordinated effort combining ecological management, genetic conservation, and sustainable development is essential to preserve this species and the services it provides. *A. tortilis* ssp. *raddiana* is not just a survivor of harsh environments—it is a critical ally in building resilient landscapes and supporting livelihoods in the face of accelerating environmental change.

6.2. Future Research Directions

To strengthen the conservation and sustainable use of *A. tortilis* ssp. *raddiana*, future research should prioritize the following areas, as summarized in Figure 5.

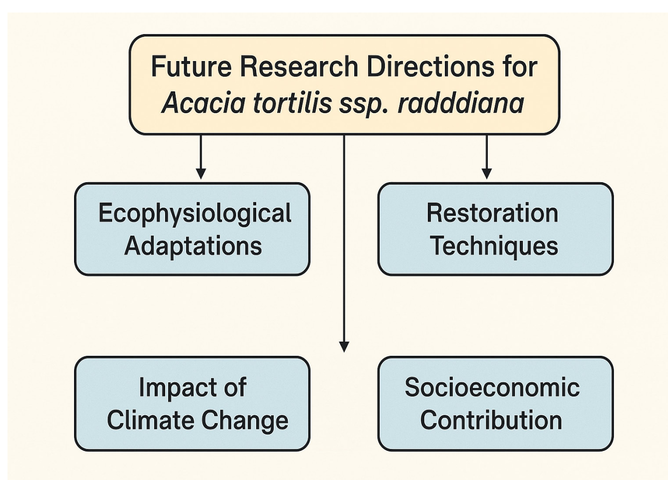

Figure 5. Future research directions for Acacia tortilis subsp. raddiana, highlighting four priority areas: (1) Ecophysiological adaptations, including drought resistance, phenotypic plasticity, and root–microbe interactions; (2) Restoration techniques, such as seedling propagation, afforestation strategies, and assisted natural regeneration; (3) Impact of climate change, examining range shifts, stress physiology, and resilience modeling; and (4) Socioeconomic contribution, focusing on community-based conservation, local knowledge, and sustainable use. Illustration generated using ChatGPT (OpenAI) for conceptual visualization.

6.2.1. Genomic and Phenotypic Adaptation Studies

- Conduct genome-wide association studies (GWAS) to identify genetic markers linked to drought resistance, phenotypic plasticity, and salinity tolerance.
- nvestigate local adaptation along environmental gradients using next-generation sequencing.

6.2.2. Microbiome and Soil Interactions

- Explore the root-associated microbiota (rhizobiome) and its role in nutrient uptake, drought mitigation, and pathogen resistance.
- Examine how soil microbial diversity varies under different *Acacia* population densities or degradation levels.

6.2.3. Remote Sensing and Spatial Ecology

- Apply satellite and UAV-based tools to monitor population dynamics, canopy structure, and regeneration trends over time.
- Use habitat suitability models to predict future distribution under climate change scenarios.

6.2.4. Ecosystem Service Quantification

- Quantitatively assess A. tortilis subsp. raddiana's role in nitrogen input (kg N/ha/year), carbon storage (Mg C/ha), and biodiversity indices compared to adjacent land covers.

6.2.5. Socioecological Systems and Community-Based Conservation

- Evaluate community-based conservation models, traditional ecological knowledge (TEK), and their integration into formal land management.
- Analyze economic trade-offs and incentives for local participaion in restoration programs.

6.2.6. Comparative Acacia Ecology

- Conduct cross-species comparisons within the *Acacia* genus to identify generalizable traits and context-specific advantages of *A. tortilis* ssp. *raddiana*.

Positioned at the intersection of ecological function and socioeconomic utility, *Acacia tortilis* ssp. *raddiana* offers a compelling case for interdisciplinary conservation. Unlocking its full potential requires bridging molecular biology, landscape ecology, and local knowledge—ensuring that this iconic desert tree continues to thrive against the odds.

Acknowledgements

I would like to thank My Abdelhamid Kassem and Ait Si Alla El Hassan for providing me with the photos of *Acacia tortilis* ssp. *raddiana* taken from Agdz, Zagora, Southeast Morocco.

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Atlas Journal of Plant Biology - ISSN 1949-1379. Published By Atlas Publishing, LP (www.atlas-publishing.org)