Bangladesh J. Plant Taxon. **31**(2): 329-347, 2024 (December) **- Review paper**
 DOI: https://doi.org/10.3329/bjpt.v31i2.78761

UNLOCKING THE POTENTIAL OF *ALBIZIA PROCERA*: A MULTIFUNCTIONAL TREE FOR SUSTAINABLE DEVELOPMENT AND CLIMATE RESILIENCE

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Keywords: *Albizia procera*; Sustainable development; Climate resilience; Agroforestry; Carbon sequestration.

Abstract

Albizia procera (Roxb.) Benth., a versatile and fast-growing tree species under the family Fabaceae, holds substantial potential for advancing sustainable development and climate resilience. This review highlights the taxonomy, ecological benefits, and diverse applications and ecological benefits of *A. procera*, emphasizing its role in reforestation, agroforestry, and sustainable forestry practices. *A. procera* is also valued for its high-quality timber, contributing to traditional woodworking and modern engineered products like Glulam beams, demonstrating its economic value. Additionally, *A. procera* contributes to its carbon sequestration, aligning with climate action goals due to its high biomass productivity. While acknowledging the need for careful management to mitigate risks such as invasiveness, this review underscores the significance of *A. procera* in fostering ecological restoration, sustainable livelihoods, and climate adaptation strategies. Its multifaceted benefits position *A. procera* as a critical asset in pursuing a sustainable and resilient future.

Introduction

The intensifying challenges of climate change, environmental degradation, and the need for sustainable development have placed unprecedented pressure on ecosystems and natural resources. Pursuing sustainable and climate-resilient strategies has become a global priority, calling for innovative solutions that balance ecological integrity with socioeconomic growth (Nuţă *et al.*, 2024; Neira *et al.*, 2023). Among the diverse plant species contributing to these efforts, *Albizia procera* (Roxb.) Benth., a versatile and fast-growing deciduous tree, stands out because of its multifaceted applications and ecological benefits. Native to the tropical and subtropical regions of

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Asia and Australia, *A. procera* holds promise in various sectors, from reforestation and afforestation to sustainable forestry practices and bio-based industrial applications. This review delves into the wide-ranging potential of *A. procera* as a cornerstone species in sustainable development and climate resilience, emphasizing its ecological adaptability, economic uses, and contributions to environmental conservation.

A. procera, commonly known as White Siris, is a member of the Fabaceae family, taxonomically placed under the class Magnoliopsida, and is renowned for its adaptability to diverse ecological conditions (Kumar *et al.*, 1998). This species exhibits a robust growth rate (Khurana and Singh, 2000), making it particularly suitable for reforestation and afforestation initiatives to restore degraded land and enhance carbon sequestration (Das and Maiti, 2016). Its ability to thrive in varying soil types, including poor, sandy, and alkaline soils, further underscores its potential for addressing land degradation challenges (Hossen and Kato-Noguchi, 2022). This adaptability is not limited to specific climatic conditions. *A. procera* has demonstrated resilience in tropical monsoon climates and arid regions, making it a valuable candidate for ecological restoration projects in diverse environments, including the challenging terrains of the Middle East. Consequently, it aligns well with large-scale environmental initiatives such as Saudi Arabia's Vision 2030, which emphasizes afforestation and sustainable land management as key strategies for combating desertification and mitigating climate change. One of the primary ecological functions of *A. procera* lies in its ability to improve soil quality through nitrogen fixation (Ghabru and Rana, 2023), a crucial process for enhancing soil fertility and promoting sustainable agriculture. By enriching soil nutrients, trees support the cultivation of various crops in agroforestry systems, thereby contributing to food security and sustainable farming practices (Newaj *et al.*, 2005). Integrating *A. procera* into agroforestry systems also aids in increasing biodiversity (Singh *et al.*, 2004), offering habitat and shade for other plant and animal species. Its rapid growth and dense canopy provide additional environmental benefits, such as reducing soil erosion and offering a green cover that enhances local microclimates (Pachuau *et al.*, 2012). These attributes position *A. procera* as a key player in combating soil degradation, promoting land reclamation, and fostering ecological resilience.

Beyond its ecological contributions, *A. procera* also holds significant economic importance (Alam *et al.*, 2005). The tree is widely recognized for its high-quality timber due to its strength, durability, and aesthetic appeal (Das *et al.*, 2023). This makes it a sought-after material for various woodworking applications, including furniture, cabinetries, and construction. The mechanical properties of *A. procera* wood, such as high bending strength and resistance to termite damage, further extend its utility in structural applications, particularly in regions where sustainable timber alternatives are needed (Pachuau and Mazumder, 2013). The production of Glulam beams from *A. procera* has shown promise as a structural timber product that exhibits superior mechanical properties compared with solid timber (Das *et al.*, 2023). This diversification in timber products emphasizes the potential of *A. procera* to support both traditional and modern industries, providing a sustainable alternative to more vulnerable hardwood species.

The versatility of *A. procera* extends to its role in supporting the livelihoods of communities in rural and urban areas. Leaves of the species are rich in essential nutrients, and used as fodder, contributing to the sustenance of pastoral economies. Moreover, it has a nurse tree role in agroforestry systems, providing shade, improving soil conditions, and enhancing the productivity of tea, coffee, and other crop plantations. Its adaptability to diverse environmental conditions makes it a reliable choice for boundary planting, shade provision, and land stabilization, supporting community-based conservation efforts and improving local resilience to climate change. Despite its numerous benefits, *A. procera* presents challenges that warrant careful consideration. Additionally, toxic compounds in certain parts of the tree, such as those used as fish poisons, call for careful application and management to avoid negative effects on aquatic ecosystems. These aspects highlight the importance of balancing the beneficial applications of *A. procera* with measures that mitigate potential risks, ensuring that its use remains sustainable across different ecological contexts. One of the primary applications of *A. procera* is in agroforestry systems. It is recognized for its rapid growth and ability to fix nitrogen, which enhances soil fertility and supports the growth of companion crops (Tiwari and Dhuria, 2018; Shukla *et al.*, 2009). The tree leaves are rich in protein and serve as fodder for livestock, making them an integral part of rural agricultural practices. Studies have demonstrated that incorporating *A. procera* into agroforestry systems can improve soil quality and increase crop yields, particularly in semi-arid regions, for instance, the pruned biomass of *A. procera* contributes significantly to nitrogen dynamics in the soil, promoting healthier crop growth (Gupta *et al.*, 2017; Prasad *et al.*, 2016). Environmental sustainability is another critical aspect of *A. procera*'s significance. This species plays a vital role in restoring degraded ecosystems through its ability to improve soil structure and fertility, making it suitable for land restoration projects (Edrisi and Abhilash, 2021). Its use in agroforestry not only aids carbon sequestration but also enhances biodiversity by providing habitats for various organisms (Brandt *et al.*, 2024). Moreover, the tree's adaptability to different soil types, including saline conditions, makes it a valuable species for reforestation and afforestation efforts in challenging environments (Paudel and Sun, 2022). As research continues to uncover its benefits, *A. procera* is poised to play an even more significant role in addressing contemporary environmental challenges. The significance of *A. procera* in sustainable development is particularly evident in its contribution to climate change mitigation efforts. As a fast-growing tree with high biomass productivity, *A. procera* plays a pivotal role in carbon sequestration, capturing atmospheric carbon dioxide and storing it in its biomass and soil. Studies have shown that *A. procera*-based agroforestry systems can significantly increase biomass and carbon storage, creating carbon sinks in semi-arid and tropical regions (Hanif *et al.*, 2023; Ahirwal *et al.*, 2020; Shah and Aziz, 2020; Mohamedkhair *et al.*, 2020; Aziz *et al.*, 2021; Shah *et al.*, 2019; Buliyaminu *et al.*, 2020). This characteristic aligns with global climate targets and underscores the potential of this tree to contribute to national and international climate action frameworks. Additionally, its use in afforestation projects in regions such as Saudi Arabia offers a strategic approach to enhancing local carbon stocks and improving soil health in arid landscapes.

The diverse applications and benefits of *A. procera* position it as a valuable species in the quest for sustainable development and climate resilience. Its ecological adaptability, economic potential, and contributions to soil fertility, biodiversity, and carbon sequestration make it an asset for efforts to restore degraded ecosystems and support sustainable livelihoods. This review aims to provide a comprehensive overview of the multiple functionalities of *A. procera*, exploring its role in ecological restoration, industrial applications, and community resilience. By highlighting the species' versatility and resilience, this study seeks to inform future research, policy-making, and practical applications that leverage the full potential of *A. procera* in advancing sustainable development goals and addressing the pressing challenges of climate change.

***A. procera* and its various functionalities**

With reference to nomenclature, *A. procera* is known by various synonyms *viz*., *Acacia procera* (Roxb.) Willd., *Mimosa elata* Roxb., and *M. procera* Roxb. In English, it is commonly known as White Siris. Still, it also goes by several other names, including Forest Siris, Safed Siris, Sil-koroi, each highlighting a particular aspect of its identity or habitat. These diverse names signify the tree's widespread ecological presence and importance in different cultural contexts.

The genus *Albizia* consists of over 160 species thriving in tropical and subtropical regions. Among the species, *A. procera* stands out as a significant species within the Fabaceae family and

Mimosoideae subfamily, as classified under the APG II (2003) and APG IV (2016) systems (Group *et al.*, 2016; Group, 2003). Earlier taxonomic systems, including those proposed by Cronquist and Dahlgren, categorized *A. procera* under the family Mimosaceae. *A. procera* is adorned with a lush canopy of green leaves, signifying its healthy and vigorous state (Fig. 1). Dense and vibrant foliage offers a refreshing verdure often sought in urban landscapes for aesthetic and ecological benefits. Beneath the verdant umbrella, the tree trunk is robust and sturdy, displaying the characteristic solidity and hardness of the species. This hardy trunk supports an extensive canopy, indicating the maturity and resilience of the tree.

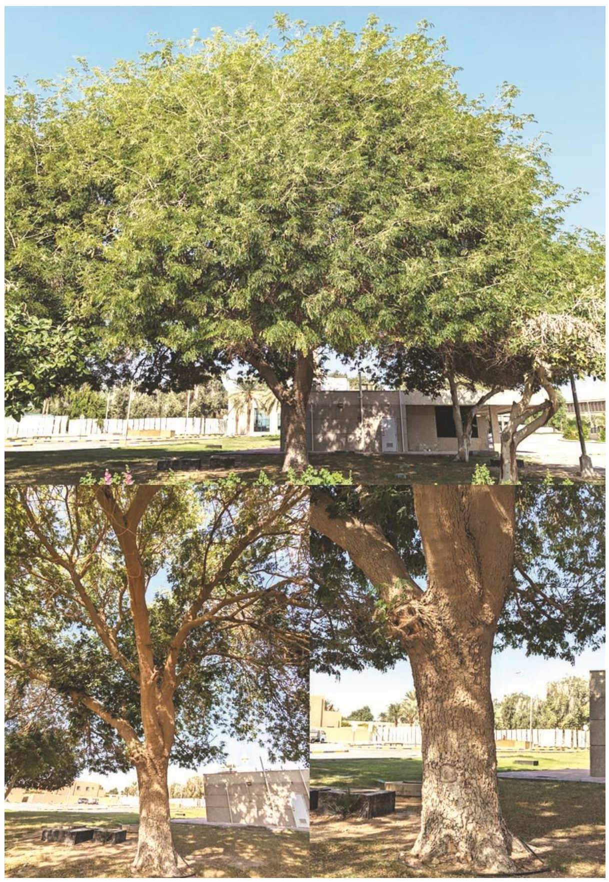

Fig. 1. Habit of *A. procera* tree as observed on the King Fahd University of Petroleum & Minerals (KFUPM) campus.

Taxonomy, distribution, and ecological significance

A. procera is a deciduous tree, attaining 10-40 m tall, characterized by a straight, unbuttressed trunk and a smooth bark that varies in color from pale grey to brownish grey. It has unbuttressed bole that can be straight or crooked, nearly smooth, bark pale grey to brownish grey, distinctly visible from a distance, as shiny brown, exfoliating in thin flakes, many reddish-brown lenticels present in branchlets. The young shoots were white and silky pubescent. Leaves bipinnately compound, stipulate, stipule minute, 0.8 mm long, caducous, rachis about 8-27 cm long, triangular, glabrous, channeled on the upper side, elongated or oval shaped, sessile, c. 5-8×2-2.5 mm, exist 1.0-3.0 cm above the base of petioles, pinnae 1-6 pairs, c. 11-27 cm long, glabrous, triangular, often with 1-3 small, oblong glands between the bases of upper leaflets pair, leaflets c. 3-10 pairs, opposite to sub-opposite, c. 1.5-5.8 ×1-2.5 cm, shortly stalked, obliquely oblong, ovate to rhomboid-oblong or trapezoid, obtuse or retuse, entire, rigidly chartaceous, midrib diagonal. Extended canopy is evergreen, but in the dry season, it is leafless for a short period. Inflorescence large, terminal, copious panicles and pedunculate heads, peduncles usually in bunches of 2-5 together or often solitary, c. 0.6-3.0 cm long, each head c. 1.5 cm across, consisting of 16-30 flowers. Flowers yellowish-white and sessile. Calyx pale green, c. 1.5-2.7 mm long, tubular, teeth 5, small, triangular, acute, unequal, and glabrous outside. Corolla c. 4.5-6.8 mm long, funnel-shaped, greenish-white, lobes 5, c. 1.2-2.5 mm long, elliptic, acute. Stamens extended numerous large, yellow, bilobed, staminal tubes longer than the corolla tube. The ovary is nearly sessile, c. 1.8 mm long, glabrous, has a filiform style, and has stigmas minute. The fruit is a pod, c. 10-19×1.3-3.0 cm, linear-oblong, smooth, flattened, shiny reddish-brown with distinct marks over the seeds, dehiscent along lower suture only, fruits long persisting on the tree. Seeds 7-13 per pod, c. 6.5×5.0 mm, obovate-elliptic, flattened, c. 2.0 mm thick with areole c. 4.0×3.5 mm (Taylor, 2000). The flowering and fruiting period of *A. procera* spans from May to January, showcasing its extended seasonal cycle.

A. procera is a species of remarkable ecological and geographical significance with broad distribution and distinct morphological features. This species predominantly flourishes in Bangladesh, especially in the forested regions of the Chittagong, Chittagong Hill Tracts, Cox's Bazar, and Dhaka-Mymensingh Sal forests. It extends its presence to community and village forest areas across the country, but its cultivation is not limited to natural habitats. *A. procera* is also a prominent component of afforestation initiatives in residential and roadside areas in Bangladesh, driven by both public and private entities. Globally, *A. procera* is indigenous to many regions, demonstrating its adaptability and ecological resilience. Its native range spans central India across the tropical expanses of Asia, including Bhutan, Myanmar, Nepal, Pakistan, Thailand, and New Guinea, and throughout Indo-China, Taiwan, South China, Indonesia, Malaysia, Laos, Cambodia, Vietnam, Australia, Brunei, and the Philippines, excluding the Malaya Peninsula. The species has also been introduced and thrives in various countries such as Antigua and Barbuda, Bahamas, Barbados, Cuba, Dominica, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Netherlands Antilles, Panama, Puerto Rico, St Kitts and Nevis, St Lucia, St Vincent and the Grenadines, Sudan, Tanzania, Trinidad and Tobago, the Virgin Islands (US), and Zimbabwe. This wide-ranging distribution underscores the adaptability of *A. procera* to diverse ecological environments and highlights its importance in regional ecosystems (Rahman and Keya, 2015).

A. procera (Sil Koroi) is notable for its wide distribution, distinct morphology, and ability to adapt to various climatic conditions. This species contributes significantly to the ecological diversity of the regions it inhabits and offers extensive potential for sustainable forestry practices and environmental conservation.

Habitat and propagation

A. procera flourishes in environments ranging from lowland rainforests and monsoon forests to more challenging terrains, such as fire-induced grasslands, pyrogenic lands, and stunted and seasonal swamp forests. Additionally, it is found in mixed deciduous forests, savannah woodlands, alongside roadsides, dry gullies, and commonly in open secondary forests, demonstrating its ability to adapt to a variety of ecological niches (He *et al.*, 2020). Propagation of *A. procera* is predominantly through its seeds, which exhibit a high germination rate of 90-100% (Parvin, 2005). These seeds maintain viability for 4–5 months and are potentially longer under optimal conditions. To enhance germination, a recommended practice involves briefly soaking the seeds in boiling water for five seconds, followed by overnight soaking in cool water before immediate sowing. This treatment doubled the germination rate. Additionally, scarifying the seed coat before boiling can further improve germination efficiency. Direct sowing in the field is preferable to planting in the nursery for healthy seedling development. During the seedling stage, maintaining soil moisture and regular weeding is crucial to minimize soil particle loosening and promote healthy growth. Line sowing is effective in facilitating weeding and ensuring optimal growth conditions. The seedlings of *A. procera* are characterized by the development of thick and long taproots, indicative of their robust nature. Regarding seed storage, the species exhibits orthodox behaviour, allowing fresh seeds to remain viable at room temperature for up to 10 months. However, without proper management, the germination rate can decrease to 50% after storage (Abdullah *et al.*, 2019). Seeds can remain viable for over ten years at room temperature, and airtight storage can preserve seed viability for over three years with a moisture content of approximately 13 ± 2%. Apart from seed propagation, *A. procera* can also be propagated vegetatively through stem or root cuttings, although this is less advisable during the peak of the rainy or dry seasons. Layering is another effective method of vegetative propagation, and root suckers can be produced from exposed roots, offering alternative propagation strategies for this species. This adaptability in both habitat preference and propagation methods underscores the versatility and resilience of *A. procera*, making it a valuable species for ecological restoration and sustainable forestry practices.

Cultivation techniques

A. procera successfully grows at elevations from sea level up to 1,500 m, encompassing tropical, subtropical, and warm temperate zones. The species demonstrates a wide temperature tolerance, ranging from 1-20 °C to 36-48 °C, and is well suited to areas with annual average rainfall between 90 and 5500 mm (Tsukada, 1983). *A. procera* can withstand frost and desert conditions, underscoring its resilience. In terms of soil adaptability, this species is well suited to various soil types, including shallow, fertile, alkaline or acidic, sandy, dry, and stony soils. Young plants prefer growth in shaded areas, whereas mature plants are drought-tolerant (Park *et al.*, 2006). This species is known for its aggressive growth rate, which can lead to it behaving as a weed in some environments. The annual growth rate in diameter ranges from 1-4.5 cm, enabling the plant to achieve a diameter at breast height (dbh) of 40-65 cm within 30-40 years. In unburned areas, *A. procera* colonizes alongside the Alang-Alang (*Imperata cylindrica*) grasslands. This results in canopy closure with a 2.5-3.5 × 0.5 meters spacing in pure stands within approximately three years. Owing to its dense canopy, regular weeding is necessary to manage undergrowth. The species can be mixed with other plant species, and for optimal growth, it is recommended to plant at a spacing of 3.25 × 1.25 meters. Such mixed planting and pruning in the upper canopy promote plant growth and bushy crown development (Potter *et al.*, 2000).

Thinning practices are advised every alternate nine years. Phosphorus has been noted to enhance nodulation and nitrogen fixation, particularly in infertile soils. For timber production, a rotation period of at least 40 years is required, involving the coppicing of the plant. In contrast, a shorter rotation period of approximately 20 years is sufficient for fuelwood production. The cultivation process necessitates weeding twice in the first year and once in the second year, with care not to disturb the deeper soil layers but to focus on eradicating weeds close to the seedlings. As an ornamental plant, *A. procera* is also planted along avenues and in gardens, adding aesthetic value to these environments. The cultivation status of *A. procera* varies, including cultivated, ornamental, semi-cultivated, and wild categories, reflecting its versatility and adaptability to different cultivation practices and environmental conditions (Mali and Panchal, 2017).

Economic uses and harmful aspects

A. procera is renowned for its diverse economic uses, values, and certain harmful aspects. Primarily, this plant serves crucial ecological functions, such as erosion control, providing shade and shelter, and land reclamation. Additionally, its ornamental value is recognized, with its use in landscaping for boundary marking, barriers, or support structures. One of the standout economic uses of *A. procera* is in timber production. In Bangladesh, it is celebrated as one of the best-known timber trees owing to its hard, strong, and durable wood. This quality suits various applications, including furniture, cabinet works, pillars, wheels, house buildings, and agricultural implements. It is also used in constructing railway sleepers, sugarcane crushers, bridges, rice pounders, and tea boxes, highlighting its versatility. The leaves of *A. procera* possess insecticidal properties, adding to its economic value. Traditionally, the paste made from its leaves has been applied as a poultice to treat ulcers, indicating its medicinal potential. However, it is important to note that *A. procera* has been recorded as a fish-poisoning plant in Australia. This suggests the need for careful management and consideration of its use in different ecological contexts to prevent unintended harmful impacts on local fauna. *A. procera* has many economic uses and values, from its robust and versatile timber to its ecological benefits. However, its potentially harmful effects, such as its use as a fish poison, warrant careful utilization and management in various environments (Ahlawat and Sharma, 1997; Halliday, 1984; Matin and Rashid, 1992; Abraham *et al.*, 1995).

Physical properties

An in-depth analysis of its physical properties is essential for understanding the comprehensive profile of *A. procera*. These properties, crucial for application in various species, have been meticulously documented in the International Tropical Timber Organization (ITTO) report (ITTO, 2024). Table 1 presents a detailed enumeration of these physical properties, offering valuable insights into the structural characteristics of the species and their potential utility in various industrial and environmental applications. These data enhance our understanding of *A. procera's* physical attributes and aid in determining its suitability for specific uses, ranging from timber production to ecological restoration projects.

Table 1. Physical properties of *A. procera* (ITTO, 2024).

Properties	Estimates
Basic density or specific gravity (O.D. weight/vol. Green) (g/cm^3)	0.64
Air-dry density (weight and volume at 12%mc) (g/cm^3)	0.71
Total shrinkage tangential (saturated to 0% mc) (%)	6.2
Total shrinkage radial (saturated to 0% mc) (%)	3.0
Drying defects	Ease of Drying Shrinkage during air drying is moderate
Recommended dry kiln schedule	JP-24
Dimensional stability ratio (total tangential shrinkage %/total radial shrinkage %)	2.1

Mechanical properties

A. procera stands out for its exceptional mechanical properties and versatile wood composition. The sapwood, with its yellowish-white hue, contrasts sharply with the heartwood, which is robust, dense, and varies from light to dark brown, often adorned with walnut-like alternating bands. Its straight grain pattern enhances its visual appeal and mechanical performance, while its high propensity for splitting is advantageous for specific woodworking applications. The wood seasons well, further improving its workability and durability, making it a preferred material across various industries.

Renowned for its strength, elasticity, toughness, and hardness, *A. procera* wood is extensively used in crafting high-quality cabinets and furniture, as well as construction materials, agricultural tools, and household products (Rojas-Sandoval, 2016). Its adaptability extends to specialized applications such as poles, house posts, truck and bus bodies, packing cases, mouldings, carts, cane crushers, carvings, boats, oars, oil presses, and rice pounders. The wood's resistance to termites-including *Bifiditermes beesoni*, *Cryptotermes cynocephalus*, and *Coptotermes curvignathus*-further enhances its suitability for use in termite-prone regions. However, *Coptotermes curvignathus* is also recognized as a pest of the tree in India, necessitating careful consideration in its cultivation and utilization (Abraham *et al.*, 1995). This combination of durability, versatility, and resistance underpins the widespread use and economic importance of *A. procera*.

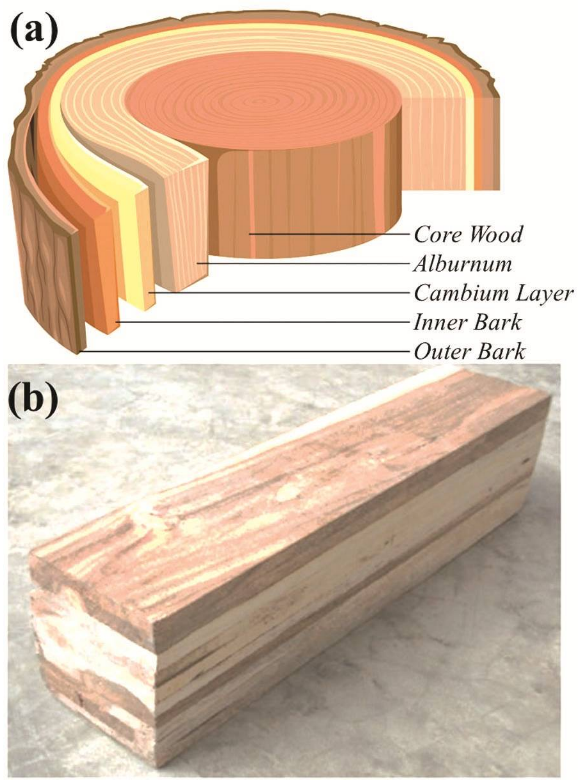

Fig. 2. (a) Cross-sectional anatomy of tree wood, highlighting the distinctive layers from the periphery to the core. (b) *A. procera* Glulam beam. Reproduced with permission (Das *et al.*, 2023). Reproduced under the term CC BY 4.0.

Fig. 2a presents a generalized cross-section of plant wood, detailing the internal structure with distinct layers, including the outer cork, living phloem, vascular cambium, sapwood, and central heartwood, a structure with which *A. procera* shares more or less. Table 2 shows the mechanical properties of *A. procera* based on the findings of the ITTO report (ITTO, 2024). The mechanical properties of *A. procera* wood, including its strength, elasticity, durability, and resistance to pests, underline its significance as a valuable resource in various industries. Its ease of operation and aesthetic and functional qualities make it an ideal choice for a wide range of products, from fine furniture to structural materials. *A. procera* Glulam beams demonstrate superior physical and mechanical properties than solid *A. procera* timber (Das *et al.*, 2023). It exhibited a significant increase in density with a notable decrease in water absorption, linear expansion, and thickness swelling. The mechanical properties, including the modulus of rupture and modulus of elasticity, were also markedly enhanced in the Glulam beams, underscoring their potential as reliable structural timber products. Fig. 2b illustrates the *A. procera* Glulam beam, offering insights into its structural composition.

Table 2. Mechanical properties of *A. procera*.

Properties	Estimates
Bending strength (MOR),12%MC (kgf/cm²)	1135
Stiffness (MOR) 12% MC (kgf/cm²)	126781
Compression parallel to fibre 12% MC (kgf/cm²)	621
Shear strength radial 12%mc (kgf/cm²)	121
Janka hardness (side) 12%mc (kgf)	817
Janka hardness (end grain) 12%mc (kgf)	677

Chemical properties

The chemical composition of *A. procera*, particularly its wood, plays a pivotal role in determining its utility in various industries, notably in producing pulp, paper, boards, and furniture. Understanding the chemical properties of this wood is crucial for evaluating its suitability as a raw material in biorefineries and for devising efficient conversion methodologies. A comprehensive analysis of *A. procera* wood revealed significant contents of primary chemical components essential for industrial applications. The α-cellulose content, a key element influencing the strength and quality of paper and textile fibres, is approximately 37% (Alam *et al.*, 2007). This relatively high percentage of α-cellulose indicates the potential of *A. procera* wood in producing high-grade pulp and paper products. In addition to α-cellulose, the wood of *A. procera* contains approximately 64% hemicellulose, encompassing the total cellulose and hemicellulose content. This hemicellulose component is instrumental in providing structural integrity and flexibility to wood, making it suitable for various applications in the paper and board industries. The lignin content in *A. procera* wood is estimated to be approximately 27% (Alam *et al.*, 2007). Lignin, a complex organic polymer, contributes to the rigidity and resistance to rotting of the wood. This substantial lignin content enhances the durability and longevity of products made from this wood, making it a valuable material for furniture and construction (Hossain *et al.*, 2023). Furthermore, the solubility of *A. procera* wood in various solvents has been studied to understand its reactivity and processability. The solubility in cold water is approximately 5%, that in hot water is approximately 8%, and notably higher at 24% in a 1% caustic soda (NaOH) solution. These solubility metrics are critical for processing wood in different industrial contexts, especially treatments and finishes. Additionally, the benzene-ethanol extractive content of *A. procera* wood is approximately 6.5%. Extractives contribute to wood's colour, odor, and resistance to biological degradation. This relatively high extractive content could influence the properties of wood and its processing in various industrial applications (Hossain *et al.*, 2023). The chemical composition of *A. procera* wood, characterized by significant contents of α-cellulose, hemicellulose, lignin, and extractives, along with its solubility profile, underscores its potential as a versatile and valuable raw material for diverse industrial applications. This detailed understanding of its chemical properties is essential for optimizing its use in biorefinery processes and other fields.

***A. procera* in green synthesis of metal oxide nanoparticles**

Because of their incredibly small size and attractive physicochemical properties, nanoparticles are well-suited for various biomedical applications. Researchers have examined various possible applications of these special compounds, such as biocatalysis, antiviral therapies, targeted drug delivery, medical imaging contrast agents, biomarkers, and antimicrobial and antibacterial properties (Chandni *et al.*, 2013; Bindhu and Umadevi, 2013). Nanoscale antimicrobial materials have potential use in various fields, such as food processing, water treatment, and biodevices, where microbial contamination is common (Zada *et al.*, 2024). As a result, the demand for metal oxide nanoparticles (MNPs) is rising, leading researchers to investigate novel fabrication techniques to produce MNPs with precise structural control (Pal *et al.*, 2007; Hasan *et al.*, 2022). However, it has been discovered that chemical processes may be hazardous to people because they increase the toxicity and reactivity of particles. Utilizing plant extracts is one environmentally responsible way to produce MNPs; this process has recently gained favor because it can guarantee a high output while being non-toxic and ecologically beneficial (Kuppusamy *et al.*, 2016; Nayak *et al.*, 2016; Kirankumar and Sumathi, 2017). The leaf extract of *A. procera* contains proteins, glycosides, alkaloids, reducing sugars, phenols, and carbohydrates. (khatoon *et al.*, 2013). Fig. 3 illustrates the biosynthesis of Ag-NPs through reduction by biological sources, followed by nanoparticle growth, and stabilization and capping mediated by bio-compounds from plants, fungi, or bacteria (Mikhailova, 2025). A similar procedure was adopted to explore the potential use of alkaloids, particularly phenols, as capping and reducing agents in the synthesis of Ag-NPs. It was reported that spherical Ag-NPs, approximately 6.18 nm in size, were capable of eliminating the organic pollutant dye methylene blue (MB) (Rafique *et al.*, 2019). They also demonstrated strong antibacterial properties against *Escherichia coli* and *Staphylococcus aureus*.

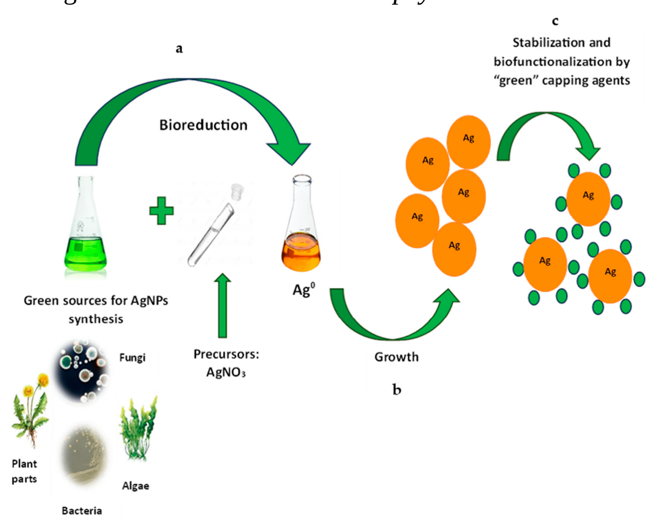

Fig. 3. Schematic representation of Ag-NPs biosynthesis. (a) Reduction process facilitated by various biological sources; (b) growth and formation of nanoparticles; (c) stabilization and capping involving compounds derived from plants, fungi, or bacteria. Reproduced with permission (Mikhailova, 2025). Reproduced under the term CC BY 4.0.

***A. procera* for the modern household furniture application**

According to a report by the ITTO, it has been determined that *A. procera* can be successfully laminated using both rotary veneer cutting and sliced veneer methods (ITTO, 2024). Moreover, it has been noted that the workability of this particular species ranges from fair to difficult. In planning and moulding, limiting the cutting angle to a maximum of 20° is advisable to minimize the wood's tendency to pick up. The hand tools perform satisfactorily, whereas the finishing process yields commendable results. Hence, it can be inferred that *A. procera* can produce plywood and particleboard. Nanomaterials possess diverse potential uses, including their utilization in composite materials and their efficacy as reinforcing agents. The synthesis of nanomaterials from wood entails the fragmentation of wood into constituent components at the nanoscale level. Although not a conventional use for *A. procera*, it is theoretically feasible to extract cellulose nanofibers or other nanoscale constituents from its wood owing to its α-cellulose content of approximately 37% (Alam *et al.*, 2007).

Contribution of A. procera as an organic fertilizer

In the agricultural initiative, we ventured to the small village of Harriaghop in Jashore, Bangladesh, to collect leaves from the *A. procera* plant. To ensure the leaves were impurity-free, they were meticulously washed with clean, drinkable water, removing any mud or unwanted particles. The next step involved transforming these leaves into compost fertilizer. Where the leaves were mixed with a small amount of soil and placed in a cave. After patiently waiting for approximately 25 days, our composite fertilizer was successfully produced (Fig. 4). Using the fertilizer we obtained, we conducted a cultivation experiment involving *Amaranthus dubius*, commonly known as Lal Shak. We compared *Amaranthus dubius's* growth with applying our composite fertilizer against a control group without any additional fertilizer. The results were striking, revealing the outstanding growth-promoting qualities of our compound fertilizer (Fig. 5a & 5b), as opposed to the comparatively minor growth observed in *Amaranthus dubius* without the benefit of our specialized fertilizer (Fig. 5a). This experiment highlights the potential of our locally sourced compost to enhance agricultural productivity.

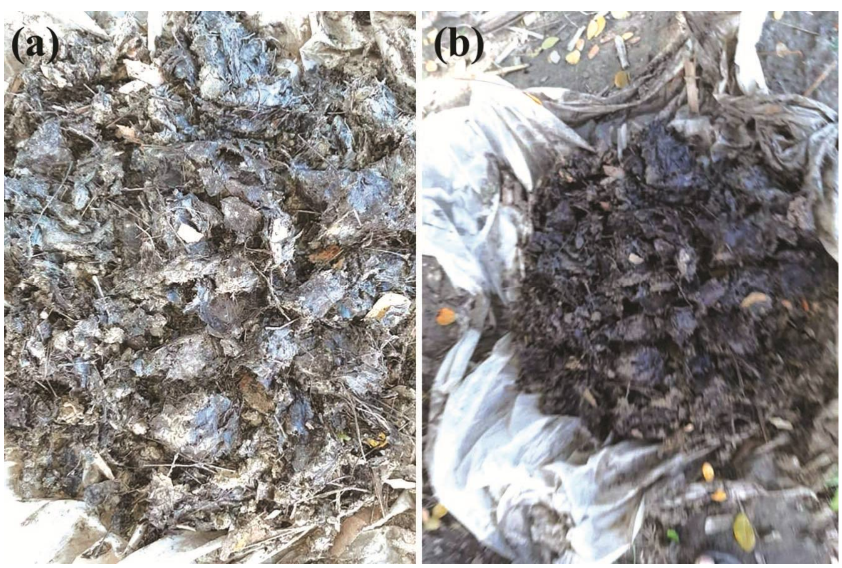

Fig. 4. Preparation of fertilizers using *A. procera* leaves.

Fig. 5. Cultivation of *Amaranthus dubius* using prepared fertilizer (a, b) and without using prepared fertilizer (b).

The prospect of reforestation in the vast unused land in Saudi Arabia as an initiative for the 2030 vision

A. procera can grow in a variety of soils. It grows best on moist alluvial soils, well-drained loams, or clay soils. Its ability to grow in dry, sandy, stony, and shallow soils makes it a useful species for afforestation of difficult sites. Good survival and rapid early growth have been reported in afforestation trials in saline and alkaline soils. *A. procera* can tolerate a pH of 5.5–7.5 and is moderately tolerant of acid to alkaline soils. *A. procera* can tolerate annual temperatures ranging from 1 to 18°C to 37–46°C and yearly rainfall of 100–5,000 mm. Established plants are drought-tolerant. Adult plants succeed in full sun and light shade, although young trees require more shade. Phosphorus fertilizer can improve nodulation and nitrogen fixation, particularly in infertile soils.

The data on soil samples from different locations in the Empty Quarter (20°N 50°E? / ?20°N 50°E), also known as the no man's land, of Saudi Arabia, are presented in Table 3. These areas are dominated by fine sand, and highly challenging weather prevails throughout the year, mainly in summer, because of the high heat. As *A. procera* can grow on dry, sandy, stony, and shallow soils, it has the potential to grow in the Empty Quarter (Rub' al Khali) of Saudi Arabia. However, young

Table 3. Results of soil samples from different locations in the Empty Quarter of Saudi Arabia (Alsabhan *et al.*, 2022; Laik *et al.*, 2009).]

Sample location	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt/clay (%)	pH	Electrical conductivity (mmhos/cm)
Tukhman area	14.17	21.17	27.48	31.9	5.28	7.46	13.22
Mushayeb area	29.93	27.49	14.13	25.64	2.81	7.57	19.01
Faydah area	19.25	26.41	17.69	32.67	3.97	8.02	13.33
Mulayhah area	13.96	13.33	26.1	43.23	3.38	7.53	30.11
Kharif area	18.42	24.58	23.6	31.95	1.44	7.63	4.30

trees require shade. Moreover, the pH value of the soil samples tested in the Empty Quarter of Saudi Arabia was neutral to moderately alkaline (range 7.5-8.2). According to the literature, *A. procera* can tolerate a pH of 7.5. Thus, it is crucial to experiment with the soil pH suitability of *A. procera* in the empty quarter of Saudi Arabia.

The ideal range for soil electrical conductivity (EC) levels is between 1.1 and 5.7 millimhos per centimeter (mmhos/cm). Extreme levels of soil EC, whether too high or excessively low, can impede crop growth. Low EC levels suggest a scarcity of accessible nutrients, whereas excessive EC levels indicate an abundance of nutrients. The EC in several sample plots inside the Empty Quarter of Saudi Arabia had a wider range of values, with greater EC levels observed. Alsabhan *et al*. reported that the soil EC in Saudi Arabia varies between 2.5 and 37.4 mmhos/cm (Alsabhan *et al*., 2022). Elevated EC levels can result in salt stress, disrupting the water balance in plants and impeding nutrient absorption. *A. procera* can enhance soil quality by decreasing soil EC. Laik *et al*. discovered a notable reduction in soil EC in the afforested areas where *A. procera* was planted (Laik *et al.*, 2009). The breakdown of organic matter, accompanied by the production of organic acids, has reduced the soil conductivity of afforested areas with *A. procera*. The efficacy of *A. procera* in enhancing soil quality by reducing its electrical conductivity may be attributed to its inherent resilience to unfavorable soil conditions (Laik *et al.*, 2009). Investigating climatic conditions is also crucial for assessing the viability of afforestation through *A. procera* in the Empty Quarter.

The monthly air temperature and precipitation in Saudi Arabia are shown in Fig. 6. The average temperatures in Saudi Arabia for the coolest months, December through February, are 23°C at Jeddah, 14°C at Riyadh, and 17°C at Al-Dammām. From June to August, summers are fiercely hot, with daytime temperatures in the shade exceeding 38° C in almost the entire country. As *A. procera* can tolerate annual temperatures of up to 37–46° C, it has the potential to grow in the Empty Quarter of Saudi Arabia. Moreover, the average yearly rainfall in most parts of Saudi Arabia is below 150 mm throughout the year, except in the southwestern part, where rainfall occurs between 400 and 600 mm annually. As *A. procera* can survive with a minimum annual rainfall of 100 mm, it has the potential to grow in the Empty Quarter of Saudi Arabia.

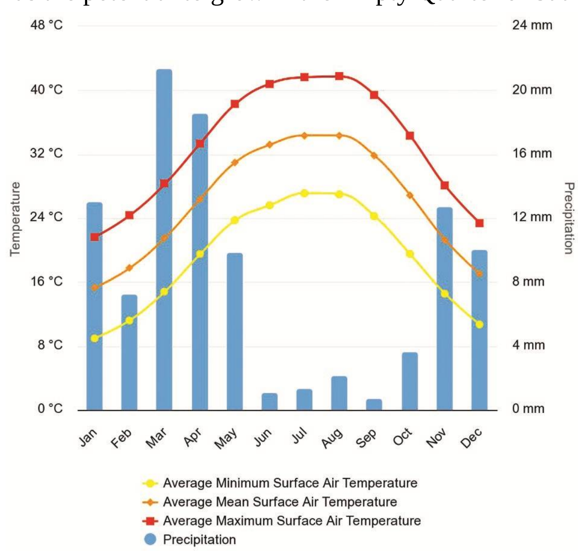

Fig. 6. The monthly air temperature and precipitation in Saudi Arabia are based on data from the years between 1991 and 2022 (Bank, 2023).

***A. procera* and environmental sustainability: Beyond climate change mitigation**

A. procera extends its influence beyond traditional climate change mitigation and serves as a cornerstone in the broader context of environmental sustainability through its multifaceted benefits and applications. Forests play a crucial role in storing atmospheric carbon and mitigating climate change. In a forest ecosystem, carbon is stored in various components, including trees, plants on the forest floor, leaf litter, and decaying soil matter. As plants grow, they capture carbon and release oxygen, leading to carbon sequestration. The more forest biomass grows, the more carbon it holds, creating a valuable carbon stock (Keith *et al.*, 2009; Shah *et al.*, 2024). Additionally, plants on the forest floor contribute to carbon storage. Over time, fallen branches, leaves, and other organic materials accumulate on the forest floor, storing carbon until decomposition. Soil plays a role by sequestering carbon through root interactions with decomposing plant litter. Tree planting is a way to create new carbon sinks through afforestation, reforestation, or other schemes. The role of forest ecosystems as either carbon sinks or carbon sources is determined by the net ecosystem carbon exchange (Lal, 2005). This exchange balances the total carbon absorbed through gross ecosystem primary productivity with the carbon released by ecosystem respiration (Fig. 7).

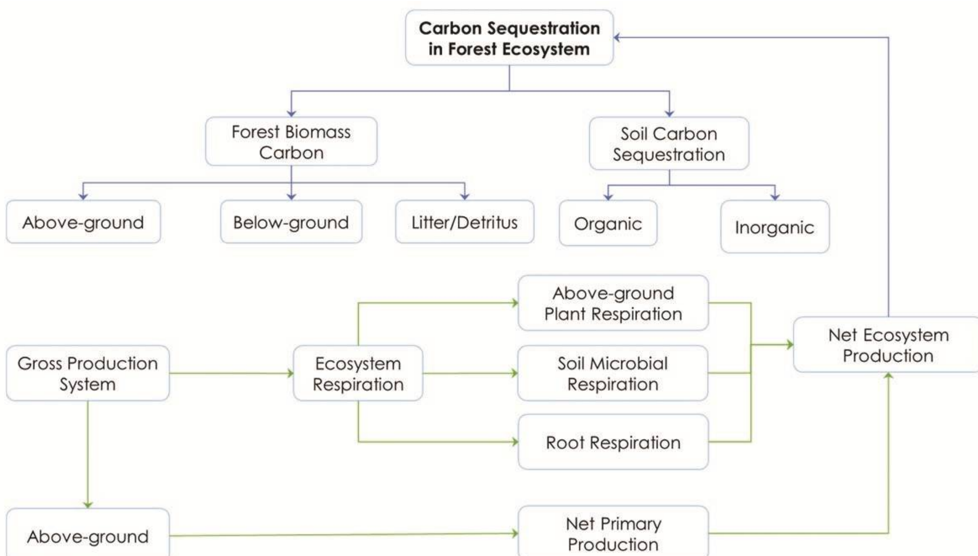

Fig. 7. The process of carbon storage in forest ecosystems.

Afforestation is crucial for reducing atmospheric carbon dioxide levels, thus mitigating the impact of climate change. Additionally, afforestation improves soil quality, prevents erosion, and enhances land fertility. It is also instrumental in reversing or preventing desertification, thereby preserving ecosystems. On the other hand, agroforestry serves as a dynamic natural resource management system. Both practices play vital roles in carbon sequestration. *A. procera* is suitable for afforestation and agroforestry. One of the most important benefits is its ability to sequester carbon from the atmosphere and store it in biomass and soil. A five-year-old agricultural system in a semi-arid region was examined. This system included combinations of *A. procera* with two different crops: *A. procera* paired with black gram mustard and *A. procera* paired with green gram wheat. The biomass measurements in these combinations were 34.77 tC/ha and 35.13 tC/ha, respectively (Reang *et al.*, 2021; Siarudin *et al.*, 2021).

The carbon sequestration potential of *A. procera* varies depending on the management system, type of shade tree, and environmental conditions. *A. procera* can be grown in different agroforestry systems, such as mixed tree-shaded, *Albizia*-shaded, *Syzygium*-shaded, and pure stands (Hossen and Kato-Noguchi, 2022). In an agroforestry study conducted in 2011, biomass and carbon storage were evaluated for *A. procera* and *Dalbergia sissoo* in irrigated environments and *Emblica officinalis* and *Hardwickia binata* in rainfed conditions. *A. procera* showed the highest biomass accumulation of 120.42 tons per hectare at 11 years, surpassing *Dalbergia sissoo*'s 84.75 tons under irrigation at 17 years. Under rainfed conditions, *Emblica officinalis* and *Hardwickia binata* recorded 14.99 and 101.34 tons of biomass per hectare at 15 and 20 years, respectively. *A. procera*, as a fast-growing tree, had a superior biomass productivity of 10.95 tons per hectare per year, followed by *Dalbergia sissoo* and *Hardwickia binata*. However, *Emblica officinalis*, a fruit-bearing plant, had the lowest biomass productivity. Carbon storage was highest in *A. procera*, followed by *Dalbergia sissoo* under irrigated conditions (Reang *et al.*, 2021; Siarudin *et al*., 2021).

Implementing afforestation programs in arid and semi-arid areas of Saudi Arabia, specifically focusing on *A. procera*, offers climate change mitigation benefits. Given its ability to grow in dry conditions and its high biomass growth, it could be a key species in Saudi Arabia's afforestation programs. This initiative aligns with the goals of the Saudi Green Initiative, Middle East Green Initiative, and other environmental strategies aimed at combating desertification and climate change. Therefore, its high carbon sequestration capacity should be exploited. Policies should support research and implement optimal planting and management practices to maximize carbon capture. Considering the adaptability of *A. procera* to different environmental conditions, afforestation projects should be tailored to local climatic and soil conditions. This includes utilizing their tolerance to saline water in areas with such soil characteristics. The integration of *A. procera* in mixed farming systems needs to be explored in local conditions. Continuous monitoring of afforestation projects is essential. Support for ongoing research into the growth patterns, carbon sequestration rates, and ecological impacts of *A. procera* will inform future policy and management decisions. Community involvement in afforestation projects can ensure sustainability and foster a sense of ownership and responsibility towards environmental conservation. Coordination with agricultural, environmental, and water resource management policies is crucial for the success of afforestation programs.

Conclusion and future prospects

Albizia procera is a multipurpose species with immense potential in sustainable development, ecological restoration, and climate resilience. Its fast growth, adaptability to degraded and saline soils, and contributions to carbon sequestration make it invaluable for afforestation and reforestation efforts, particularly in arid and semi-arid regions. The species enhances soil fertility and biodiversity in agroforestry systems, supports rural livelihoods through high-quality timber production, and aligns with global initiatives such as the Saudi Green Initiative to combat land degradation and desertification. Emerging applications, such as green nanoparticle synthesis, further highlight its role in advancing eco-friendly industrial and biomedical solutions. Despite its advantages, challenges such as its potential invasiveness and toxicity in specific contexts necessitate sustainable management and responsible applications to avoid ecological imbalances. Addressing these issues through stakeholder engagement and evidence-based strategies is critical for maximizing benefits while minimizing risks. Future research should focus on optimizing propagation methods, water-use efficiency, and soil management for *A. procera* in challenging environments. Its integration into agroforestry systems can enhance food security and promote sustainable agriculture by improving soil health and crop productivity. Exploring its pharmaceutical potential, including bioactive compounds with therapeutic properties, can lead to innovative plant-based therapies. Additionally, its use in bio-based materials such as cellulose nanofibers and green nanoparticles offers promising industrial applications aligned with the circular economy. To fully realize the potential of *A. procera*, a collaborative approach involving researchers, policymakers, and communities is essential. By integrating scientific research with sustainable practices and community participation, *A. procera* can significantly contribute to combating climate change, restoring degraded ecosystems, and achieving sustainable development goals globally.

Acknowledgements

The funding support provided by the Interdisciplinary Research Center for Hydrogen Technology and Carbon Management (IRC-HTCM), King Fahd University of Petroleum & Minerals, Saudi Arabia, through the project INHE 2311, is highly acknowledged.

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(Manuscript received on 25 July 2024; revised on 20 November 2024)