

Chapter

The Characteristics of Popular Hardwood Species in Sudan-Review

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Abstract

Sudan's diverse ecosystems support valuable hardwood species crucial for economic, environmental, and social sustainability. This review evaluates seven key species such as *Acacia nilotica*, *Anogeissus leiocarpus*, *Azadirachta indica*, *Balanites aegyptiaca*, *Sclerocarya birrea*, *Khaya senegalensis*, and *Eucalyptus camaldulensis*, emphasizing their physical, mechanical, anatomical, and chemical properties. Findings indicate *A. leiocarpus* possesses the highest density (0.94 g/cm^3) and superior strength, ideal for construction, while *S. birrea* offers better workability despite lower density. These hardwoods support timber, fuelwood (16.7 million m^3 annually), and medicinal uses, yet they face severe threats from deforestation, agricultural encroachment, and climate change. Overexploitation risks long-term sustainability, necessitating urgent conservation measures. By synthesizing published data, this study highlights species-specific applications, from structural uses to pulp production and underscores the need for science-based forest management. The review provides critical insights for policymakers to balance utilization with preservation, ensuring Sudan's hardwood resources remain viable for future generations while supporting livelihoods and ecological stability. Sustainable practices must integrate research findings to mitigate current pressures on these indispensable species.

Keywords: Sudanese hardwood species, wood properties and utilization, forest resource management, sustainable timber production, deforestation and conservation

1. Introduction

Sudan's vast and ecologically diverse landscapes harbor a rich variety of hardwood species that constitute a vital natural resource for the nation. Spanning approximately 1.86 million square kilometers, Sudan's unique geographical position between the Sahara Desert and tropical savannas creates distinct ecological zones supporting diverse forest ecosystems [1]. These forests, comprising over 3156 species from 170 plant families [2], play a crucial role in sustaining livelihoods and maintaining ecological balance. Among these, seven key hardwoods—*Acacia nilotica*, *Anogeissus leiocarpus*, *Azadirachta indica*, *Balanites aegyptiaca*, *Sclerocarya birrea*, *Khaya senegalensis*, and *Eucalyptus camaldulensis*—have emerged as particularly significant due to their multiple uses and ecological importance [3].

The economic and ecological significance of these species is profound. They serve as primary sources of timber, fuelwood, and various non-timber forest products, with wood fuel alone accounting for 94% of Sudan's total forest production in 2022 [4]. These hardwoods provide essential materials for construction, furniture manufacturing, and traditional medicine while also functioning as carbon sinks and soil stabilizers against desertification [5]. Their multipurpose nature makes them indispensable to rural communities and national industries alike, supporting everything from household energy needs to pharmaceutical applications [6].

Despite their importance, Sudan's hardwood resources face severe and growing threats. Rapid population growth, agricultural expansion, and unsustainable harvesting practices have led to alarming deforestation rates [4]. Climate change exacerbates these pressures through altered rainfall patterns and rising temperatures, affecting species distribution and growth [7]. Compounding these challenges is a critical lack of comprehensive scientific data on the properties and sustainable management of these species. Current research remains fragmented, with studies often limited to specific regions or focusing on isolated characteristics [8, 9]. This knowledge gap hinders the development of effective conservation strategies and optimal utilization practices.

The justification for this study lies in addressing these critical gaps. A systematic review of hardwood properties is urgently needed to inform sustainable management decisions and maximize their economic potential. Understanding variations in density, mechanical strength, and durability can guide appropriate industrial applications [10], while documenting chemical composition can reveal new pharmaceutical and industrial uses [3]. Furthermore, synthesizing available ecological data can enhance conservation efforts amidst climate change [11]. Without such comprehensive knowledge, Sudan risks continued overexploitation and irreversible loss of these vital resources.

This chapter aims to provide a thorough review of the physical, mechanical, anatomical, and chemical properties of Sudan's seven most important hardwood species. The objectives are threefold: (1) to systematically compile and analyze existing research on these species, identifying patterns and inconsistencies; (2) to evaluate their suitability for various applications based on documented properties; and (3) to highlight critical knowledge gaps requiring further research. By achieving these objectives, this work will serve as a valuable resource for policymakers, industries, and conservationists working to balance utilization with preservation of Sudan's precious hardwood resources.

2. Methodology

The methodology for this review involved extensive literature searches across multiple academic databases including Google Scholar, ResearchGate, and ScienceDirect [7]. Studies published between 1987 and 2023 were considered, with particular attention to peer-reviewed journal articles, theses, and technical reports. Data on wood properties were extracted, compared, and analyzed to identify trends and variations across species and geographical locations. Where multiple studies reported conflicting results, average values were calculated to provide representative estimates [12].

3. Result and discussion

3.1 Present status of wood products in Sudan

In 1994, Sudan's total firewood consumption was estimated at approximately 5.9 Mm³. A significant portion of this about 73.1% was consumed in low rainfall zones, reflecting the high dependence on wood fuel in ecologically vulnerable areas. The per capita firewood consumption was 0.36 m³, with the desert region exhibiting the highest per capita use at 0.43 m³. Moreover, low-income households accounted for 42.7% of total firewood consumption, underscoring the socioeconomic reliance on forest resources for domestic energy. Between 1999 and 2001, Sudan's annual industrial roundwood production averaged around 2.17 Mm³, while fuelwood production rose to approximately 16.7 Mm³. Charcoal demand remained consistently high during this period, largely dependent on stem wood—a practice known for substantial conversion losses [13]. By 2022, forest production in Sudan had undergone significant changes. Industrial roundwood production declined sharply to 163 m³. However, the country produced 383,000 m³ of wood chips and particles, 301,000 m³ of pulpwood (round and split), and around 360,000 m³ of sawlogs and veneer logs. Wood fuel remained the dominant forest product, with an estimated output of 15,583,393 m³—representing approximately 94% of total forest production [4]. These figures are presented in **Figure 1**.

Hardwood species are trees that have broad leaves and produce seeds with some form of covering, such as fruits or nuts, which have needle-like leaves and produce seeds without any covering [14]. Hardwood has distinct characteristics such as high density, high durability, and high tensile and compressive strength, which makes it suitable for structural applications, such as in construction and furniture manufacturing. Also, it has attractive grain patterns, rich colors, and a polished appearance. This makes it highly desirable for use in high-end furniture, cabinetry, and decorative finishes. Moreover, hardwoods are generally easier to work with when it comes to cutting, shaping, and joining. They can be finely crafted, making them a popular choice for woodworking and furniture-making projects. In addition to their versatility, hardwoods are also known for their resilience in outdoor environments and their natural resistance to pests and decay. The examination of wood characteristics is

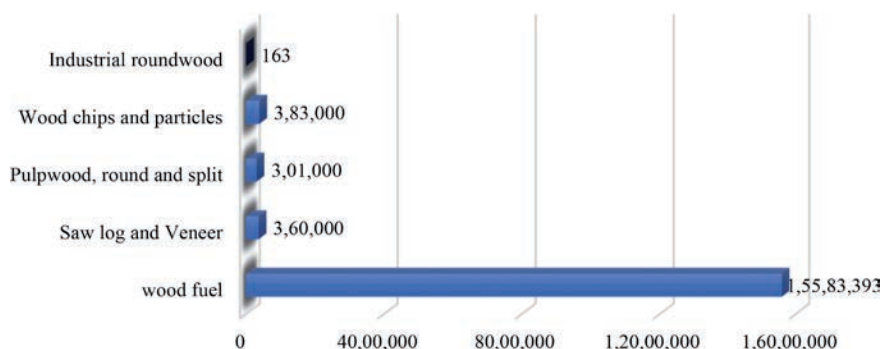


Figure 1.
 The forest wood production value (m³) in 2022.

a crucial aspect in assessing the appropriateness and utilization of wood material, which is dependent on the specific wood species [15]. To understand the behavior of wood, it is essential to conduct experiments that assess its physical and mechanical properties, in addition to examining its anatomical structure and chemical composition, both of which significantly influence its overall quality.

Hardwood species are important for Sudan for several reasons: first they provide valuable products such as timber, fuelwood, charcoal, fruits, nuts, honey, gum Arabic, and medicinal plants. These products support the livelihoods of many rural communities and contribute to the national economy. Secondly, they protect the land from desertification, erosion, and climate change by stabilizing the soil, retaining moisture, moderating temperatures, and enhancing biodiversity. Finally, they offer environmental services such as carbon sequestration, water purification, flood control, and wildlife habitat. However, hardwood species in Sudan are facing many threats, such as deforestation, overexploitation, agricultural expansion, fire, pests, diseases, and conflicts.

3.2 The most popular hardwoods used in Sudan are

- *Acacia nilotica subsp. nilotica* (Sunt) is a member of the Mimosoideae subfamily of leguminous trees, widely distributed across arid and semiarid regions worldwide. In Sudan, it grows along the banks of the Nile and in seasonal watercourses in areas like Blue Nile, Kordofan, Darfur, and Northern Bahr El Ghazal [2]. This medium-sized tree, reaching up to 17 meters in height and 50 cm in diameter, has a rounded or umbelliform crown with a straight, short cylindrical bole. Its blackish-gray, rough bark flakes in fibrous scales. The sapwood is white, while the heartwood is deep red-brown, hard, heavy, and durable. A fast-growing, drought-resistant legume, it plays a key role in biological nitrogen fixation, with a strong taproot system [16] and an extended growing season. This tree is utilized for timber, firewood, charcoal, gum Arabic, tannin, medicine, and fodder [3], with its hard, durable wood used for fuel, railway sleepers, structural components, transmission poles, and agricultural tools [17].
- *Anogeissus leiocarpus* (Sahab), a member of the Combretaceae family, can grow up to 20 meters tall. It is commonly found in South Kassala, Kordofan, South Darfur, and Blue Nile states [2]. The grayish-brown wood is hard and ring-porous and contains surface crystals and traumatic ducts [18]. It is used locally for poles, beams, and fence posts, as well as for firewood and charcoal due to its high energy content.
- *Azadirachta indica* (Neem), a fast-growing tree native to Asia, can reach heights of 15–20 meters, occasionally growing up to 35–40 meters. It is evergreen, although it sheds leaves during severe drought. The tree has a well-developed root system and produces a round or oval crown. The bark is fissured and varies in color from whitish gray to reddish-brown. Its wood is reddish and durable, making it suitable for various uses, including timber, fuel, and medicinal applications.
- *Balanites aegyptiaca* (Heglig), belonging to the Zygophyllaceae family, is a drought-resistant tree typically found in arid and semiarid regions. It can grow 8–10 meters tall and is widely distributed in Sudan. The wood is hard, compact, and resistant to insects, making it suitable for agricultural implements, furniture, and tool handles. It is also valued for its medicinal properties, with various extracts used for antioxidant, antifungal, and anticancer treatments [19, 20].

- *Sclerocarya birrea* (Humeid), a member of the *Anacardiaceae* family, grows up to 12 meters tall [19]. The wood is traditionally used for carving, furniture, and saddles. It is found in several regions of Sudan, including Kassala and Kordofan. The wood is soft, diffuse-porous, and medium-density, with a color ranging from grayish to reddish-brown. It is essential for sustaining rural livelihoods [21].
- *Khaya senegalensis* (Mahogany) is a medium-sized tree from the *Meliaceae* family, native to Africa. It can reach 15–30 meters in height with a diameter of up to 1 meter [22]. The bark is gray-brown, and the heartwood is pinkish-red. Its wood is often used in carpentry, furniture-making, and building construction, prized for its ease of use and good gluing properties [23].
- *Eucalyptus camaldulensis* (Ban), an exotic species from Australia, can grow up to 30 meters tall. It is commonly planted in Sudan along riverbanks and irrigated plantations. The wood is used for timber, firewood, charcoal, pulp, paper, oil, and medicine [3]. Its white flowers are attractive to bees, and its trunk is straight, covered in rough, fibrous bark.

The review of Sudanese hardwood properties is vital for informing sustainable forest management, industrial applications, and environmental conservation. It is crucial for decision-making, ensuring the responsible and sustainable use of these valuable resources. This paper aims to provide a comprehensive overview of the properties of seven prominent hardwood species in Sudan, highlighting their economic and ecological importance.

3.3 Studies on tree species in Sudan: A focus on indigenous and exotic species

Figure 2 indicates that *Acacia nilotica* is the most widely studied species across different regions in Sudan, which could be due to its widespread use in forestry, agriculture, and its role in agroforestry systems. Conversely, species like *Azadirachta indica* and *Khaya senegalensis* have been studied less, possibly due to their more specific or limited applications in Sudan's landscape. The distribution of studies also

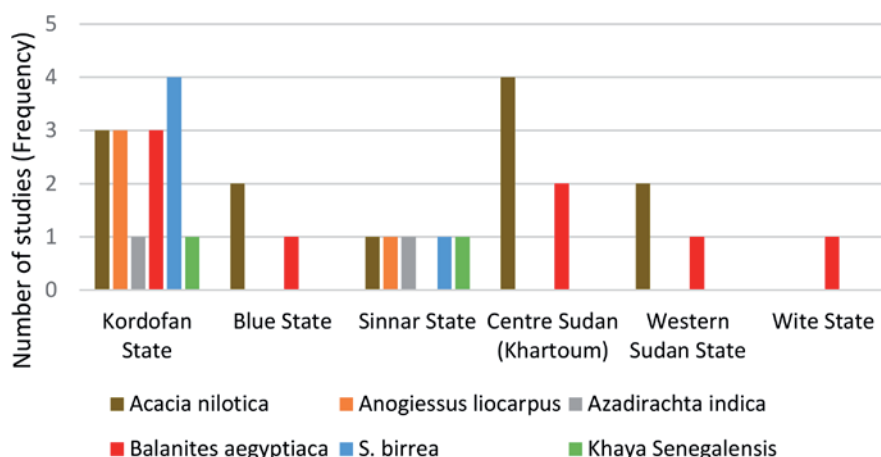


Figure 2.
 Geographical distribution of studies on tree species in Sudan.

suggests regional preferences or ecological factors influencing the selection of species for research, with more studies concentrated in central and western parts of Sudan.

3.4 Comprehensive analysis of anatomical, physical, and mechanical properties across various tree species

The research studies reviewed in this paper provide valuable insights into the wood properties of several tree species, focusing on their anatomical, physical, and mechanical characteristics. These studies, summarized in **Tables 1–7**, contribute to

Author and publication year	Study area	Title	Objective
Gamal et al. [9]	Kordofan (South) & Sinnar state	Suitability of some Acacia species grown in Sudan for paper making	The aim is to analyze the wood fiber properties of five Acacia species cultivated in Sudan and evaluate their potential for use in the pulp and paper industry.
Ahmed et al. [24]	Kordofan (North and South)	Effect of wood extractives on the equilibrium moisture content of six Sudanese hardwood species	To examine how the removal of hot-water extractives influences the desorption and adsorption equilibrium moisture content of six hardwood species.
Mohammed et al. [11]	Darfur (North)	Relationship between anatomical properties and some physical and mechanical properties for five wood species growing in North Darfur-Sudan	To evaluate the relationships between anatomical properties and selected physical and mechanical characteristics of five wood species from North Darfur, Sudan.
Elamin [25]	Blue Nile	Mechanical properties (bending and Compression stress) as a tool for grading stress of <i>Acacia nilotica</i> wood.	To assess the mechanical properties of <i>Acacia nilotica</i> (L.) Willd and classify the grades based on basic stress.
Elgailani and Ishak [26]	Centre Sudan (Khartoum)	Determination of tannins of three common Acacia species of Sudan	To analyze and compare the tannin content of three common Acacia species in Sudan, as vegetable tannins play a significant role in the leather industry.
Hagar [27]	Centre Sudan (Khartoum)	Wood and Charcoal Anatomy of Eight Charcoal-producing Wood Species in Central Sudan	To examine the wood and charcoal anatomy of charcoal-producing tree species and explore the changes in wood macrostructure caused by charring.
Mahdi et al. [6]	Centre (Khartoum) & western Sudan	Characterization of <i>Acacia nilotica</i> as an indigenous tanning material of Sudan	To examine the quantity and quality of tannins in the bark and fruits of the three subspecies of <i>A. nilotica</i> .
Mahgoub, [28]	Kordofan (South)	Variation in wood density and shrinkage of twelve species from Kordofan state	To analyze the variation in wood density and shrinkage across twelve tree species from Kordofan state.
Khristova and Karar [29]	Centre Sudan (Khartoum)	Soda-anthraquinone pulp from three <i>Acacia nilotica</i> subspecies	To investigate the wood characteristics of the three Sudanese <i>Acacia nilotica</i> subspecies and their soda-AQ pulping potentialities.
Dafaalla and Ahmed [30]	Blue Nile	Variation in the mechanical properties of sunt wood (<i>Acacia Nilotica</i> .) from different sites growing in Blue Nile Sudan	To investigate the variation on mechanical properties of sunt wood (<i>Acacia nilotica</i> L. Wild-DeI) from different sites.

Table 1.
List of research done on *A. nilotica subspecies nilotica*.

Author and publication year	Study area	Title	Objective
Abdelatif et al. [8]	Kordofan (South)	Structural characterization of three types of woods in Sudan: (<i>Anogeissus leiocarpus</i>) Sahab, (<i>Balanites aegyptiaca</i>) Heglieg, and (<i>Sclerocarya birrea</i>) Humeid	To determine structural characterization (i.e., strength classes) of some common Sudanese timber species in order to facilitate their use in structural design.
Younis et al. [31]	Kordofan (North)	Inter- and intraspecific differences in physical and mechanical properties of wood from <i>Sclerocarya birrea</i> and <i>Anogeissus leiocarpus</i>	To investigate the variability of wood along the height of a tree and horizontal positions (innerwood, middlewood, and outerwood).
Gamal et al. [12]	Kordofan (South)& Sinnar states	Variation in wood fiber characteristics among thirty-two hardwood species grown in low-rainfall woodland Savannah (Sudan)	To shed some lights on the variations in fiber characteristics of thirty-two hardwood species belonging to eighteen families grown in the low rainfall woodland savannah of Sudan
Osman [32]		Variation in density and fiber dimensions and the demarcation of juvenile and mature wood of ten trees species grown in Sudan	To identify the transition point from juvenile to mature wood by examining radial variations in these properties.

Table 2.
 List of research done on *A. leiocarpus*.

Author and publication year	Study area	Title	Objective
Gamal et al. [12]	Kordofan (South) & Sinnar states	Variation in wood fiber characteristics among thirty-two hardwood species grown in low-rainfall wood land Savannah (Sudan)	To shed some lights on the variations in fiber characteristics of thirty-two hardwood species belonging to eighteen families grown in the low rainfall woodland savannah of Sudan

Table 3.
 List of research done on *A. Indica*.

a better understanding of the variations within and between individual trees and the relationships between different wood properties. This information is crucial for both the practical utilization of the wood and the broader ecological and commercial implications of these species.

Table 1 presents studies on *Acacia nilotica* subspecies *nilotica*, which extensively investigated the anatomical properties, chemical composition, extractive content, and both physical and mechanical properties of the wood. These studies also explored the variations in these properties and their relationships with anatomical features. This comprehensive approach provides essential insights into how the anatomical structure of the wood influences its physical and mechanical properties, which are important for its potential applications.

Table 2 focuses on *Acacia leiocarpus*, where previous research investigated the physical and mechanical properties of the wood, along with their variations, as well

Author and publication year	Study area	Title	Objective
Abdelatif et al. [8]	Kordofan (South)	Structural characterization of three types of woods in Sudan: (<i>Anogeissus leiocarpus</i>) Sahab, (<i>Balanites aegyptiaca</i>) Heglieg, and (<i>Sclerocarya birrea</i>) Humeid	To determine structural characterization (i.e., strength classes) of some common Sudanese timber species in order to facilitate their use in structural design.
Gamal et al. [33]	Kordofan (North & South) Blue state & White state	<i>Balanites aegyptiaca</i> : A multipurpose tree species for forest-based industry development in Sudan	To investigate some wood properties of <i>Balanites aegyptiaca</i> and to assess its suitability for pulp and paper and flooring industries
Mohammed et al. [11]	Darfur (North)	Relationship between anatomical properties and some physical and mechanical properties for five wood species growing in North Darfur-Sudan	To conducted to assess the relationships between anatomical properties and some physical and mechanical properties of five wood species growing in North Darfur, Sudan.
Awad [34]	Centre Sudan (Khartoum)	Variation among trees, sites, and log position along the stem on physical and mechanical properties of Heglig wood (<i>Balanites aegyptica</i>) growing in central Sudan	To investigate the differences in the properties among population of <i>Balanites aegyptica</i> collected from Tozi, Elgazair, and Fraish forests
Hagar [27]	Centre Sudan (Khartoum)	Wood and charcoal anatomy of eight charcoal-producing wood species in Central Sudan	To study the wood and charcoal anatomy of charcoal-producing tree species and to investigate the alteration in wood macrostructure induced by charring.
Osman [32]	Blue Nile State, Northern Kordofan State, Southern Kordofan state and White Nile state	Variation in density and fiber dimensions and the demarcation of juvenile and mature wood of ten trees species grown in Sudan	To identify the transition point from juvenile to mature wood by examining radial variations in these properties.
Mahgoub [28]	Kordufan (South)	Variation in wood density and shrinkage of twelve species from Kordofan state	(1) To investigate the variation in wood density and shrinkage of the twelve hard wood species grows in Southern Kordofan, (2) study the relationship between shrinkage and moisture content as influenced by wood density, and (3) study the relationship between wood density, shrinkage, and anatomical characteristic.

Table 4.
List of research done on *B. aegyptiaca*.

as its anatomical structure. These studies contribute to understanding the relationships between anatomical features and the physical and mechanical properties, offering useful data for potential industrial uses of *A. leiocarpus* wood. The variation in properties across different trees also indicates that the species may exhibit a range of wood qualities, which could be important for different applications.

Author and publication year	Study area	Title	Objective
Abdelatif et al. [8]	Kordofan (South)	Structural characterization of three types of woods in Sudan: (<i>Anogeissus leiocarpus</i>) Sahab, (<i>Balanites aegyptiaca</i>) Heglieg, and (<i>Sclerocarya birrea</i>) Humeid	To determine structural characterization (i.e., strength classes) of some common Sudanese timber species in order to facilitate their use in structural design.
Younis et al. [31]	Kordofan (North)	Inter- and intraspecific differences in physical and mechanical properties of wood from <i>Sclerocarya birrea</i> and <i>Anogeissus leiocarpus</i>	To investigate the variability of wood along the height of a tree and horizontal positions (innerwood, middlewood, and outerwood).
Gamal et al. [12]	Kordofan (South) & Sinnar states	Variation in wood fiber characteristics among thirty-two hardwood species grown in low-rainfall woodland Savannah (Sudan)	To shed some lights on the variations in fiber characteristics of thirty-two hardwood species belonging to eighteen families grown in the low rainfall woodland savannah of Sudan.
Mahgoub [28]	South Kordufan	Variation in wood density and shrinkage of twelve species from Kordofan state	(1) To investigate the variation in wood density and shrinkage of the twelve hard wood species grows in Southern Kordofan, (2) study the relationship between shrinkage and moisture content as influenced by wood density, and (3) study the relationship between wood density, shrinkage, and anatomical characteristic.
Nasroun and Elzaki [10]	Sudan	The relationship between the anatomical structure and the mechanical properties of wood.	To examine the relationships between wood anatomical characteristics—quantified using stereological methods—and both the specific gravity and mechanical properties of wood in eight broad-leaved tree species cultivated in Sudan.

Table 5.
 List of research done on *S. birrea*.

Author and publication year	Study area	Title	Objective
Gamal et al. [12]	Kordofan (South) & Sinnar states	Variation in wood fiber characteristics among thirty-two hardwood species grown in low-rainfall woodland Savannah (Sudan)	To shed some lights on the variations in fiber characteristics of thirty-two hardwood species belonging to eighteen families grown in the low rainfall woodland savannah of Sudan

Table 6.
 List of research done on *K. senegalensis*.

Research on *Acacia indica*, as shown in **Table 3**, primarily focused on the anatomical properties of the wood. Although the scope of this research was limited compared to the other species, the findings provide foundational knowledge of the wood's structure. Understanding these anatomical characteristics is a crucial first step toward evaluating its suitability for various uses, even though further studies would be needed to explore its physical and mechanical properties.

Author and publication year	Study area	Title	Objective
Nasroun and Elzaki [10]	Sudan	The relationship between the anatomical structure and the mechanical properties of wood.	To examine the relationships between wood anatomical characteristics—quantified using stereological methods—and both the specific gravity and mechanical properties of wood in eight broadleaved tree species cultivated in Sudan.

Table 7.
list of research done on *E. camaldulensis*.

Table 4 highlights research on *Balanites aegyptiaca*, where both physical and mechanical properties, as well as anatomical features, were examined. Additionally, the variations in these properties both within and between trees were explored. This research helps to establish a more detailed understanding of how these properties differ among trees, which is critical for determining the species' practical applications. The study of such variations may also assist in developing better management strategies for the species.

In **Table 5**, studies on *Sclerocarya birrea* focused on the basic physical, mechanical, and anatomical properties of the wood while also exploring the variations in these properties across individual trees. This research offers valuable insights into the wood's overall quality and potential uses, providing a comprehensive view of how these properties fluctuate within the species. Understanding these variations can help optimize the use of *S. birrea* wood in various industries.

Research on *Kombo senegalensis*, presented in **Table 6**, was focused exclusively on the anatomical properties of the wood. While limited in scope, this study provides important baseline data that can serve as a foundation for future research, particularly for those interested in examining the species' physical and mechanical properties in more detail.

Finally, **Table 7** covers studies on *Eucalyptus camaldulensis*, where both anatomical and mechanical properties were examined, along with their interrelationships. The research highlights the importance of understanding how anatomical structure influences mechanical performance, which is crucial for determining the species' suitability for various industrial applications.

These findings are critical for assessing the practical uses of these woods and for developing sustainable management practices. Further research, particularly on the variations in wood properties within individual trees and between different regions, would enhance the knowledge base and improve the application of these species in various sectors.

3.4.1 The physical properties

The physical properties of the seven Sudanese hardwood species, as presented in **Table 8**, reveal notable variations in the basic density, shrinkage values, and other wood characteristics, which are crucial for understanding the suitability of these species for different uses. Among the species studied, *Acacia leiocarpus* exhibited the highest basic density, followed by *Acacia nilotica* subspecies *nilotica*. On the other hand, *Sclerocarya birrea* showed the lowest basic density value, which indicates it may be less dense and potentially more lightweight compared to the other species, impacting its mechanical strength and durability.

Physical property	Hardwood species						
	<i>A. nilotica</i> subs. <i>Nilotica</i>	<i>A. leiocarpus</i>	<i>A. indica</i>	<i>B. aegyptiaca</i>	<i>S. birrea</i>	<i>K. senegalensis</i>	<i>E. camaldulensis</i>
Basic density g/cm ³	0.623–0.95 (0.79)	0.92–0.96 (0.94)		0.66–0.78 (0.72)	0.49–0.54 (0.52)		0.58
Air dry density g/cm ³				0.789			
Oven-dry density					0.55		
Green density					1.09		
Bark to wood mass (%)	14						
Bark to wood volume (%)	12						
Tangential shrinkage %	11.62			11.53			12.15
Longitudinal shrinkage %	0.86			1.59			1.19
Radial shrinkage %	5.28			5.62			6.26

() = average value.

Table 8.
 The physical properties drawn from the literature.

The research highlighted that oven-dry density and green density values were only available for *S. birrea*, while air-dry density values were reported for *Balanites aegyptiaca*. The lack of data for some species suggests that more comprehensive studies are needed to fill these gaps and provide a complete picture of the physical properties of these hardwoods. These density values are essential in determining how the wood behaves in terms of strength, weight, and its suitability for specific applications such as construction, furniture making, or fuel. Shrinkage characteristics are also important for understanding the dimensional stability of wood as it dries. *S. birrea* showed a tangential shrinkage of 11.53%, while *Balanites aegyptiaca* exhibited a slightly higher value of 12.15%. The radial shrinkage values were also reported for *S. birrea* (5.28%) and *B. aegyptiaca* (5.62%), with both species demonstrating relatively moderate shrinkage. *Acacia nilotica* subspecies *nilotica* exhibited a tangential shrinkage of 11.62%, similar to *S. birrea*, while *K. senegalensis* and *Eucalyptus camaldulensis* demonstrated somewhat higher shrinkage percentages in the radial direction. These shrinkage values are important in assessing the wood's potential for warping or cracking as it dries, affecting its suitability for specific end uses. Furthermore, the bark-to-wood mass and volume ratios were also considered, with *Acacia nilotica* subspecies *nilotica* showing a bark-to-wood mass percentage of 14%, which is relatively high compared to other species. These ratios indicate the proportion of bark relative to the usable wood and are an important consideration for wood processing and biomass utilization (Table 8).

Overall, the physical properties presented for these species underscore the diversity in wood characteristics, which can influence their applications in different

industries. While species like *Acacia leiocarpus* and *Acacia nilotica* subspecies *nilotica* are denser and potentially stronger, species like *Sclerocarya birrea* and *Balanites aegyptiaca* may offer advantages in lightweight applications or where lower density is desired. Further research is needed to better understand the full spectrum of physical properties across these species, including the missing data for certain species, to guide their effective use in various industries.

3.4.2 The anatomical properties

The anatomical properties of the seven Sudanese hardwood species, as presented in **Table 9**, provide essential information about their fiber and vessel characteristics,

Anatomical properties	Species						
	<i>A. nilotica</i> <i>subs. Nilotica</i>	<i>A. leiocarpus</i>	<i>A. indica</i>	<i>B. aegyptiaca</i>	<i>S. birrea</i>	<i>K. senegalensis</i>	<i>E. camaldulensis</i>
Fiber							
Fiber length (mm)	1.0–2.10 (1.55)	1.007–1.01 (1.01)	0.83	1.15–1.77 (1.47)	0.97–1.033 (1.00)	1.19	0.81–2.28 (1.55)
Fiber width (µm)	16.75–18.6 (17.86)	12.4–14.2 (13.30)	19.5	12.3–14.17 (13.24)	15–28.4 (21.70)	19.3	10–14.50 (12.25)
Lumen width (µm)	7.23–7.80 (7.52)	4.78–10.5 (7.64)	10.27	6.87–10.5 (8.69)	20.01	9.85	6.17
Wall thickness (µm)	5.3	4.69	4.61		4.21	4.74	
Fiber double wall thickness (µm)	8.95–11.39 (10.17)	1.9		1.9–8.10 (5.00)	2		5–8.0 (6.50)
Vessels	0.103						
Horizontal diameter (mm)	0.120			0.083			
Vertical diameter (mm)	0.03			0.068			
Horizontal double-cell wall (mm)	0.02			0.027			
Vertical double-cell wall (mm)	0.10			0.012			
Lumen diameter (mm)	0.21			0.056			
Mean horizontal free path (mm)	0.23			0.693			
Mean vertical free path (mm)	28.54			0.844			
Volume fraction %	19			22			
() = average value.							

Table 9.
The anatomical properties drawn from the literature.

which directly influence the mechanical properties, processing efficiency, and potential applications of the wood. Variations in fiber length, fiber width, lumen width, and other anatomical features are important for determining the strength, durability, and suitability of the wood for specific uses, such as in construction, pulp production, or furniture making.

In terms of fiber length, *Acacia nilotica* subspecies *nilotica* exhibits the longest fiber, with a range of 1.0–2.10 mm and an average of 1.55 mm. This is relatively longer compared to *Acacia leiocarpus*, which has an average fiber length of 1.01 mm, and *Sclerocarya birrea*, which has fibers ranging from 0.97 to 1.033 mm. Longer fibers are generally associated with stronger and more durable wood, making *A. nilotica* subspecies *nilotica* potentially more suitable for applications requiring strength and durability. On the other hand, shorter fibers, such as those found in *A. indica* (0.83 mm), may be less mechanically robust but could be advantageous in applications where flexibility or lighter weight is desired.

Fiber width, another critical anatomical property, also shows variation across species. *A. nilotica* subspecies *nilotica* has fiber widths ranging from 16.75 to 18.6 μm , with an average of 17.86 μm . In comparison, *Balanites aegyptiaca* has a wider fiber width, with values ranging from 15 to 28.4 μm (average of 21.70 μm). Wider fibers typically contribute to higher wood density and improved mechanical strength, which may make *B. aegyptiaca* particularly useful in structural applications. *A. indica*, with a fiber width of 19.5 μm , also falls within the higher end of the range, suggesting it may have similar mechanical advantages.

Lumen width, which refers to the inner cavity of the fiber, is another important factor in determining the wood's porosity and processing characteristics. *Balanites aegyptiaca* has a particularly wide lumen diameter of 20.01 μm , much larger than the other species, such as *A. nilotica* subspecies *nilotica* (7.23–7.80 μm) or *S. birrea* (9.85 μm). A wider lumen can increase the wood's ability to absorb moisture and enhance its pulping potential, though it may reduce the wood's overall mechanical strength.

Wall thickness and double-wall thickness of fibers also vary significantly across species. For instance, the wall thickness of fibers in *A. nilotica* subspecies *nilotica* is 5.3 μm , while *A. leiocarpus* has a thinner fiber wall (4.69 μm). The thicker the fiber wall, the more robust and durable the wood, making species with thicker walls, such as *A. nilotica* subspecies *nilotica*, potentially more valuable for structural purposes. Similarly, the fiber double-wall thickness in *A. nilotica* subspecies *nilotica* ranges from 8.95 to 11.39 μm , significantly thicker than in *A. leiocarpus* (1.9 μm), which could contribute to differences in their overall wood strength and mechanical properties.

The vessel characteristics are also noteworthy. The horizontal and vertical diameters of vessels in *A. nilotica* subspecies *nilotica* are 0.120 mm and 0.03 mm, respectively, while in *Sclerocarya birrea*, the horizontal and vertical diameters are 0.083 mm and 0.068 mm, respectively. The size of the vessel elements, particularly the horizontal diameter, plays a role in the permeability and porosity of the wood, affecting its suitability for water conduction and use in applications where fluid movement is important. The larger horizontal diameter in *A. nilotica* subspecies *nilotica* may provide better conductivity compared to the smaller vessels in *S. birrea*.

Moreover, the volume fraction of fibers and vessels in the wood affects its overall composition. *A. nilotica* subspecies *nilotica* has a lower volume fraction of vessels (19%) compared to *Balanites aegyptiaca* (22%). This difference reflects the varying roles of fiber and vessel content in each species, with a higher volume fraction of fibers generally leading to denser and stronger wood. Conversely, species with a higher volume fraction of vessels may be more porous and lighter, which can

influence their suitability for different commercial and industrial uses (**Table 10**). Overall, the anatomical properties of these seven Sudanese hardwood species exhibit considerable variability, which directly influences their mechanical properties and potential applications. Species like *Acacia nilotica* subspecies *nilotica* and *Balanites aegyptiaca* appear to have stronger, more robust fibers, making them suitable for construction and heavy-duty applications, while species like *Sclerocarya birrea* with smaller fiber diameters and vessel sizes may be better suited for lighter uses such as paper production or less demanding structural applications. Understanding these anatomical features helps to tailor the use of each species for specific purposes, whether in the timber industry, pulp and paper manufacturing, or other wood-based products. Further studies are needed to explore the relationships between these anatomical characteristics and the overall mechanical performance of the wood, providing a more detailed understanding of their full potential.

3.4.3 The mechanical properties

Table 10 provides a comprehensive overview of the mechanical properties of seven Sudanese hardwood species, which include important metrics such as Modulus of Rupture (MOR), Modulus of Elasticity (MOE), Compression Strength (CS), Shear Strength (SH), and other relevant mechanical characteristics. These properties are vital for understanding the suitability of each species for various engineering and construction applications, as well as for assessing their overall structural integrity and durability.

Modulus of Rupture (MOR), which is a measure of the wood's ability to resist bending or breaking under stress, varies significantly across the species. *Acacia nilotica* subspecies *nilotica* shows the highest MOR value at 140.70 MPa, indicating that this species has superior bending strength compared to the others. This suggests that *A. nilotica* subspecies *nilotica* would be highly suitable for structural applications where high bending strength is required, such as beams and supports. In comparison, *Balanites aegyptiaca* and *Sclerocarya birrea* have lower MOR values, 51.58 MPa and 99.03 MPa, respectively, making them less suitable for heavy-duty structural applications but potentially more suitable for lighter uses where lower strength is acceptable.

Modulus of Elasticity (MOE), which indicates the stiffness or rigidity of the wood under stress, shows a wide range of values. *A. nilotica* subspecies *nilotica* again leads with a value of 17,500.51 MPa, suggesting that its wood is particularly stiff and resistant to deformation. This is an important characteristic for wood used in construction, particularly in applications requiring rigidity and minimal deflection under load, such as in flooring or heavy structural elements. *A. leiocarpus* and *A. indica* also exhibit relatively high MOE values, indicating their suitability for similar applications. On the other hand, *B. aegyptiaca*, with an MOE value of 6932.7 MPa, demonstrates lower rigidity and may be more suitable for applications where some flexibility is beneficial, such as in crafts or composite materials.

Compression Strength (CS) parallel to MOE is another crucial factor for understanding the compressive load-bearing capacity of wood. The values for CS in the longitudinal direction (CS//) range from 38.26 MPa in *Balanites aegyptiaca* to 68.47 MPa in *Acacia nilotica* subspecies *nilotica*, with the latter exhibiting the highest compressive strength. This suggests that *A. nilotica* subspecies *nilotica* is ideal for load-bearing applications, particularly in structural and construction fields where the material will be subjected to vertical loads. In contrast, the lower CS values in species such as *B. aegyptiaca* indicate that they may be better suited for less load-intensive applications or for uses in which the material will not be heavily stressed in compression.

Mechanical properties	Species						
	<i>A. nilotica subs. Nilotica</i>	<i>A. leiocarpus</i>	<i>A. indica</i>	<i>B. aegyptiaca</i>	<i>S. birrea</i>	<i>K. senegalensis</i>	<i>E. camaldulensis</i>
MOR	140.70	70.97–96.7 (83.84)		87.25–114.5 (102.38)	40.73–62.43 (51.58)		99.03
MOE	9400–25601.02 (17500.51)	8400–12,577 (10488.50)		8400–10,493 (94446.50)	6600–7265.4 (6932.70)		8503.4
CS //	58.7–68.47 (63.59)	45.77–66.57 (56.17)		47.47–60.12 (53.80)	38.26–39.51 (38.89)		57.00
SH //	32.7–34.7 (33.70)	16.52–16.64 (16.58)		19.45	13.32–16.66 (14.99)		
Tension strength				52.19	27.85		
US	234.64						
Ultimate CS	102.62						
MOC	2166.3–3446.63 (2806.47)			1959.7			1727.5
Poison ratio	0.297						
H (cross surface)				87			
H (radial surface)				46			

() = average value of the range; UBS = Ultimate strength; H = Hardness; modulus of elasticity from the compression.

Table 10.
 The mechanical properties drown from the literature.

Shear Strength (SH), which measures the wood's resistance to forces that can cause sliding along the grain, is an essential property for assessing the wood's stability and potential for deformation under shear stress. The values of shear strength range from 13.32 MPa to 34.7 MPa, with *A. nilotica* subspecies *nilotica* and *A. leiocarpus* having higher values compared to other species. This indicates that these species may perform better in situations where shear forces are a concern, such as in framing or joinery where wood components are subjected to lateral loads.

The tensile strength, although available for only a few species, shows *A. indica* at 52.19 MPa and *S. birrea* at 27.85 MPa. These values are indicative of the species' ability to withstand pulling or stretching forces. A higher tensile strength suggests that *A. indica* might be more appropriate for applications where the wood is subject to tensile stresses, such as in rope or cable products, whereas the lower value for *S. birrea* suggests that it may be less suitable for such uses.

Ultimate compressive strength (US) and ultimate shear (UBS) are also important in evaluating the wood's performance under extreme stresses. The value for *A. nilotica* subspecies *nilotica* (234.64 MPa) suggests its high ultimate strength under compressive loads, reinforcing its suitability for applications where the wood is exposed to heavy loads. Similarly, the Hardness (H) of *A. indica* and *E. camaldulensis*, measuring 87 and 46 respectively, indicates their relative resistance to indentation, which is important in flooring and other high-contact applications.

Poisson's Ratio, which is a measure of the material's tendency to expand in directions perpendicular to the direction of compression, is reported as 0.297 for *A. nilotica* subspecies *nilotica*, which is within a typical range for hardwoods. This ratio reflects the expected deformation behavior of the wood under load and helps predict how the material will perform in practical applications (Table 10).

Overall, the mechanical properties of these Sudanese hardwood species show substantial variation, with *Acacia nilotica* subspecies *nilotica* demonstrating superior strength and stiffness across multiple metrics such as MOR, MOE, and CS. These properties make it an excellent candidate for structural and construction applications. Species like *Balanites aegyptiaca* and *Sclerocarya birrea*, with lower MOR and MOE values, may be better suited for lighter, less demanding applications. The variety in mechanical properties between these species suggests that each species has distinct advantages depending on the specific engineering requirements, such as strength, flexibility, and resistance to deformation. Future studies should explore how these mechanical properties correlate with the wood's long-term performance in real-world applications, such as in varying environmental conditions or under different load scenarios.

3.4.4 The chemical properties

Table 11 provides a detailed comparison of the chemical composition of seven Sudanese hardwood species. These species were analyzed for several key chemical properties, including ash content, silica content, tannins, extractives, cellulose, holocellulose, alpha-cellulose, pentosans, and lignin. These chemical constituents are important for understanding the wood's overall quality, durability, and potential uses in various industries, such as paper production, wood preservation, and bioenergy.

Ash Content is a key indicator of the mineral content in wood. Ash content is generally low across all species, with *Acacia nilotica* subspecies *nilotica* showing an ash content of 0.7%. This is typical for hardwood species, indicating a relatively low mineral content. High ash content can negatively affect the burning properties of wood and the efficiency of thermal treatments, making it less desirable for applications

such as bioenergy production. The low ash content of these species suggests that they may be better suited for uses in which low mineral content is advantageous.

Silica content in wood is another important factor, particularly for its effect on the wood's processing, such as in the paper and pulp industries. *A. nilotica* subspecies *nilotica* shows a very low silica content of 0.1%, which suggests that this species may be less abrasive and easier to process compared to others with higher silica levels. Silica is often undesirable in papermaking as it can lead to wear and tear on machinery. As the silica content in these species is low, they may be suitable for industries that require low abrasiveness in raw materials.

Tannins are polyphenolic compounds that affect the wood's resistance to decay and its use in certain industries. The tannin content in *A. nilotica* subspecies *nilotica* is relatively high at 11.8%, which may contribute to its resistance to biological degradation. Tannins also play an important role in the leather and wood treatment industries due to their natural preservative qualities. High tannin content can make the wood less susceptible to fungal and insect damage, which could be beneficial for outdoor applications or in wood preservation treatments.

The extractives content refers to the chemical compounds that can be extracted from the wood using solvents like hot water, NaOH, and alcohol-benzene. *A. nilotica* subspecies *nilotica* has an extractive content of 11.8%, and *A. leiocarpus* shows a slightly higher range (11.03–17.83%, with an average of 14.43%). These extractives are important as they can influence the wood's performance in various applications.

Chemical composition	Species						
	<i>A. nilotica</i> subs. <i>Nilotica</i>	<i>A. leiocarpus</i>	<i>A. indica</i>	<i>B. aegyptiaca</i>	<i>S. birrea</i>	<i>K. senegalensis</i>	<i>E. camaldulensis</i>
Ash	0.7						
Silica	0.1						
Tannins	11.80						
Extractives content	11.8	11.03–17.83 (14.43)			13.85		
Soluble in hot water	5.7						
Soluble in NaOH	16.5						
Soluble in alcohol-benzene	5.5						
Cellulose, kurschner-Hoffer	47.8						
holocellulose	76.8						
Alpha-cellulose	51.9						
Pentosans	18.7						
Lignin	26.8						
Cellulose/lignin	1.8						

Table 11.
 Chemical composition drowns from the literature.

Extractives can affect the wood's durability, color, odor, and resistance to decay. Species with higher extractives may have better natural resistance to environmental stresses and could be more suitable for outdoor or marine applications where such properties are needed.

The solubility in solvents is a measure of how much of the wood's chemical compounds can be dissolved in specific solvents. *A. nilotica* subspecies *nilotica* shows solubility values of 5.7% in hot water, 16.5% in NaOH, and 5.5% in alcohol-benzene. These solubility measurements indicate the ease with which the wood's chemical components can be extracted and processed. High solubility in NaOH is particularly relevant for paper production, as alkali treatments are commonly used to break down lignin and hemicelluloses in wood fibers.

Cellulose and Hemicelluloses are major components of the wood's structure and are crucial for its strength and utility. The cellulose content in *A. nilotica* subspecies *nilotica* is reported as 47.8%, and the holocellulose content is 76.8%. Holocellulose refers to the combined content of cellulose and hemicelluloses. *A. nilotica* subspecies *nilotica* also shows a relatively high alpha-cellulose content of 51.9%, which is the most crystalline and strongest form of cellulose. Higher alpha-cellulose content typically correlates with better quality pulp and paper production, as alpha-cellulose is more easily processed. The high cellulose and holocellulose contents of this species suggest that it could be well-suited for pulp and paper production or for bioenergy applications.

Lignin, which serves as the glue that binds cellulose fibers in the wood, is another important component of the chemical makeup. *A. nilotica* subspecies *nilotica* contains 26.8% lignin, which is a moderate value for hardwood species. Lignin content is significant because it influences the wood's rigidity and resistance to decay, but it also impacts the wood's digestibility for bioenergy and its suitability for certain types of processing. Lower lignin content typically leads to easier processing, such as in the case of pulping for paper or biofuel production, but too little lignin can reduce the wood's strength and resistance to environmental stresses.

The cellulose-to-lignin ratio is an important indicator of the wood's suitability for specific applications. In this case, *A. nilotica* subspecies *nilotica* has a cellulose-to-lignin ratio of 1.8, which suggests a favorable balance between strength and processability. A higher ratio is generally desirable for paper and bioenergy production, as it indicates that the wood contains more cellulose relative to lignin, making it easier to break down for these purposes.

Overall, *A. nilotica* subspecies *nilotica* appears to have a well-rounded chemical profile that makes it suitable for a variety of industrial applications, particularly in paper production and bioenergy. Its high cellulose, holocellulose, and alpha-cellulose content, combined with its relatively low lignin and silica content, suggest that it can be processed efficiently for these uses. Other species such as *A. leiocarpus* and *S. birrea* also show promising chemical profiles, but *A. nilotica* subspecies *nilotica* stands out for its balanced chemical composition, which enhances its versatility for different industrial applications. Future research into the specific interactions between these chemical components and the wood's mechanical properties could provide valuable insights into optimizing the use of these species in various industries.

4. Conclusions

Sudanese hardwood species are vital to both economic and environmental sustainability, offering essential resources for local communities and industries. This study

has examined the diverse properties of key hardwood species, focusing on their structural strength, durability, and adaptability to varying climatic conditions, which makes them suitable for timber, fuelwood, furniture, and medicinal applications. However, challenges such as deforestation, land-use change, and climate variability threaten their long-term sustainability. The review emphasizes the need for enhanced forest management strategies, research on wood properties, and conservation efforts to ensure a balance between resource use and environmental preservation. Future actions should focus on promoting reforestation, implementing sustainable harvesting practices, and strengthening local knowledge about the ecological and economic benefits of these species. By adopting effective forest governance and conservation measures, Sudan can secure the long-term viability of its hardwood resources while supporting both economic growth and environmental resilience. Additionally, future research should address key areas like the variation in wood properties across growth stages, the impact of environmental stressors, and the potential for these species in industries such as pulp and paper production, bioenergy, and agroforestry. Standardizing testing methodologies and conducting life cycle analysis (LCA) will provide reliable data for better land management decisions and ensure the sustainable utilization of these valuable hardwood species.

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Conflict of interest

The authors declare no conflict of interest.

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