REVIEW ON WOOD PROPERTIES OF INDIGENOUS TREE SPECIES FOR PULP AND PAPER PRODUCTION IN TROPICAL REGIONS

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Abstract. This comparative review of the anatomical and chemical properties of indigenous tree species to determine their suitability for pulp and paper production, a sector crucial for industrial and economic development. Recognizing the critical gap in comprehensive documentation on the wood properties essential for paper production, this paper aims to serve as a benchmark for future research, guiding pulp, and paper producers in selecting the most appropriate materials. It delves into the global and Indian scenarios, highlighting the pressing need for sustainable materials in the face of escalating greenhouse gas emissions from the building sector and the burgeoning demand for wood amidst dwindling supplies. By examining a variety of species, such as

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Albizia lebbeck, *Albizia falcataria*, *Gmelina arborea*, *Melia dubia*, *Leucaena leucocephala*, *Acacia auriculiformis*, and *Dalbergia sissoo*. The study not only explores their potential in pulp and paper production but also considers their ecological values, thereby emphasizing a holistic approach to resource utilization.

Keywords: Indigenous tree species, wood properties, sustainable utilization, anatomical and chemical composition.

INTRODUCTION

Various studies have extensively documented the crucial role of forests in maintaining ecological stability and preserving biodiversity, as well as the challenges they face due to deforestation. Forests play a vital role as habitats for diverse species and are indispensable for providing a wide array of ecosystem services essential for human well-being. Recent research increasingly demonstrates the importance of biodiversity in sustaining the functioning of forest ecosystems and the delivery of ecosystem services, including but not limited to biomass production, habitat provision, pollination, seed dispersal, and carbon sequestration (Brockerhoff et al 2017). Additionally, global forests, which are crucial for supplying resources like energy, building materials, and food, and for offering services such as carbon storage and climate regulation, are at risk due to factors such as climate change, air pollution, and the spread of invasive pests (Trumbore et al 2015).

In India, the situation reflects a global trend where deforestation has been a major concern until legislative actions, such as the Forest Conservation Act of 1980; helped to mitigate the loss. The reduction in forest cover not only jeopardizes ecological balance but also underlines the significant gap between the supply and demand for wood, leading to environmental instability. The Forest Policy of 1988 aimed to address these issues by mandating sustainable sourcing for forest-based industries, highlighting the need for sustainable forest management practices to reconcile the demand for forest products with the necessity of conserving forest resources

The invention of papermaking and the widespread use of paper products illustrate the critical role forests play beyond their ecological importance, influencing every aspect of human life from communication and information dissemination to personal hygiene. This underscores the challenge of balancing the demand for paper and other forest products with the imperative of conserving and sustainably managing forest resources to ensure their continuous ability to fulfill vital ecological functions and support economic prosperity (Liang et al 2016).

A thorough understanding of the properties of any material is crucial for optimizing its use, a principle that holds particularly true for wood due to its cellular composition and intricate cell wall structure. As stated eloquently by renowned architect Frank Lloyd Wright in 1928, "We may use wood with intelligence only if we understand wood" (Jozsa and Middleton 1994). Consequently, resource managers and foresters aiming to enhance forest values must grasp not only the fundamentals of tree growth but also the macroscopic and microscopic characteristics influencing wood quality (Jozsa and Middleton 1994).

Wood is most likely one of the first natural resources that have ever been used by humans (Anoop et al 2011). Wood, a dense fibrous substance present in numerous tree species, has served various purposes such as fuel, construction, and industrial resources for millennia. Comprising cellulose fibers intertwined with lignin, a sturdy compound resistant to compression, wood is often classified as the secondary xylem within tree stems (Riki et al 2019). Its significance lies in being the primary resource for pulp and paper production, thus contributing significantly to a nation's industrial and economic advancement.

Amidst numerous factors contributing to the significance of wood as a valuable raw material for pulp and paper production, particular emphasis is placed on its anatomical and chemical composition. While extensive research has explored the potential of various wood species for pulp and paper manufacturing, a comprehensive overview of their anatomical and chemical characteristic, crucial for guiding researchers and industry professionals in material selection, remains lacking. This study aims to fill this gap by reviewing the principal anatomical and chemical properties of wood and their practical implications in pulp and paper production. It is anticipated that this review will serve as a valuable resource for pulp and paper producers, researchers, and aspiring scientists seeking guidance in the evaluation of lignocellulosic materials for papermaking purposes.

GLOBAL SCENARIO

The total global production of pulp for paper stood at 198.57 million metric tons in 2022—an increase of over 1% from the previous year. The annual production of pulp for paper has increased massively since the 1960s, though output has slowed in recent decades. The United States was the largest pulp for paper producer in 2022; accounting for roughly a quarter of global production. In 2022; worldwide pulp production for paper reached 198.57 million metric tons, marking a growth of more than 1% compared with the year before. Since the 1960s, there has been a significant rise in the production of paper pulp, although the rate of increase has decelerated in the later years. The United States emerged as the top producer of paper pulp in 2022; contributing approximately 25% to the global output paper in 2022; contributing approximately 25% to the global output (Statista 2024). In Europe, the production of paper and paperboard saw a 4.9% decrease in 2022; dropping to 95.5 million tons due to the high costs of energy and raw materials affecting the region. Despite these challenges, the apparent consumption of paper and paperboard remained stable at 89.9 million tons. The latter part of 2022 witnessed several shutdowns of paper machines attributed to reduced demand, spurred by increased raw material costs and decreased advertising budgets for printed materials, with this trend extending into 2023 (FAO 2023).

Wood pulp production in 2022 decreased by 1.6% to 39.0 million tons, with a notable decline

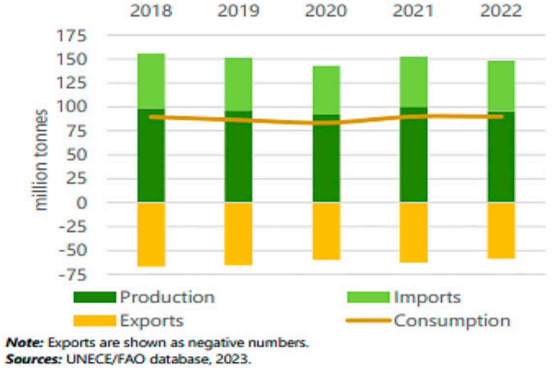

Figure 1. Europe: Paper production, trade and consumption 2018-2022 (FAO 2023).

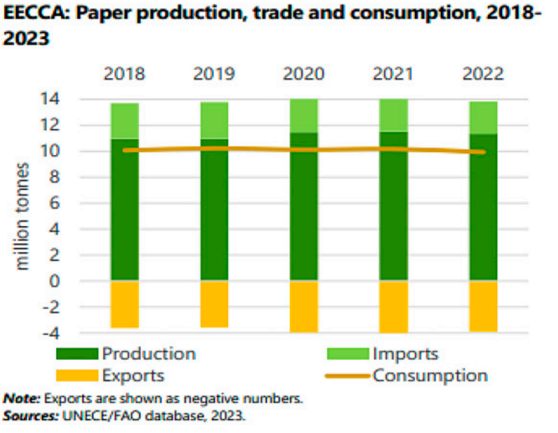

Figure 2. EECCA: Paper production, trade and consumption 2018-2022 (FAO 2023).

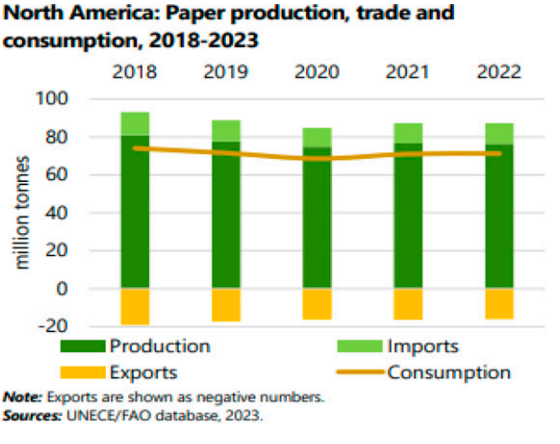

Figure 3. North America: Paper production, trade, and consumption 2018-2022 (FAO 2023).

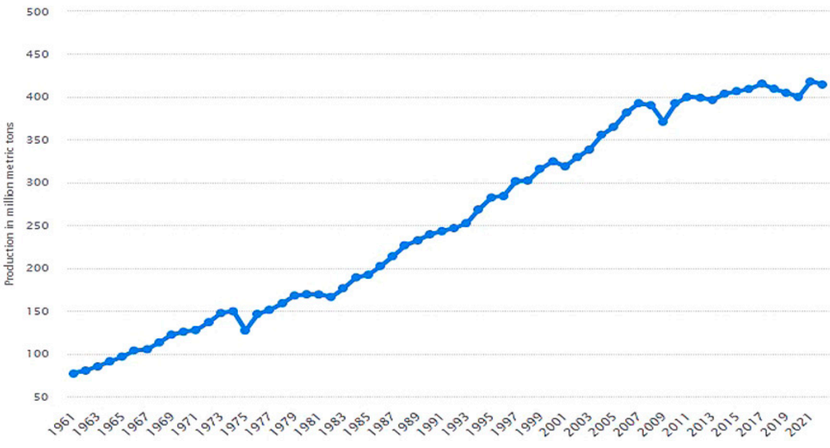

Figure 4. Production of pulp and paper worldwide from 1961 to 2021 (Statista 2024).

in chemical grades by 1.9%. Despite closures, many mills kept their integrated pulp lines operational, selling excess tonnage on the market. Market pulp production fell by 3.6% to 14.4 million tons, attributed to high energy prices and reduced log availability from the Russian Federation, prompting a 4.9% increase in woodpulp imports to 20.3 million tons. Woodpulp exports grew by 2.8% to 16.6 million tons, as mills without operational paper machines sold off their pulp. The apparent consumption of woodpulp slightly decreased by 0.1% to 43.0 million tons, whereas market pulp consumption saw a 3.1% rise to 16.9 million tons (FAO 2023).

The recycling sector also faced challenges in 2022; with a 6.4% reduction in paper recycling utilization to 47.5 million tons, driven by decreased packaging production and high costs for electricity, gas, and CO_2, which disproportionately impacted recycling mills. Paper collection dropped by 5.0% to 52.6 million tons, and the recycling rate decreased to 70.5% from 72.8% in the previous year. This underscores the ongoing need for substantial green investments to align with the EUs climate goals (FAO 2023).

In 2022, the Eastern Europe, Caucasus, and Central Asia (EECCA) region experienced a slight decline in paper and paperboard production, falling by 1.5% to 11.3 million tons, with apparent consumption also decreasing by 2.4% to 10 million tons. Notably, the production of sanitary and household papers saw a small increase of 1.3% to 893,000 t, and their consumption rose by 2.0% to 877,000 t. However, packaging material production dropped by 2.2% to 7.6 million tons, and its consumption decreased by 2.1% to 6.9 million tons. Specifically, case material production fell by 3.4% to 5.3 million tons, whereas carton board production barely decreased by 0.3% to 1.1 million tons. Consumption patterns reflected these production changes, with case materials consumption decreasing by 4.4% to 4.4 million tons, while carton board consumption grew by 3.7% to 1.8 million tons. Wood pulp production and consumption remained steady at 9.1 and 6.7 million tons, respectively. Exports stayed constant at 2.7 million tons, but imports saw a 4.6% reduction to 323,000 t, with significant trade focused between the Russian Federation, Belarus, China, and India (FAO 2023).

In North America, paper and paperboard production slightly declined by 0.3% to 76.5 million tons in 2022 due to market shifts and unplanned downtime, including the shutdown of high-cost facilities. Despite this, apparent consumption marginally increased by 0.3% to 71.2 million tons, spurred by postpandemic market recovery and the reopening of trade routes between Canada and the United States. Graphic grade production remained steady, while there was a modest rise in uncoated wood free and coated papers, but newsprint and sanitary paper production declined. Packaging material production also saw a slight decrease. Interestingly, the consumption of graphic grades and uncoated wood-free paper increased, suggesting a recovery from the pandemic, though consumption of newsprint significantly dropped. Packaging materials consumption remained stable with a minor decrease, reflecting adjustments in the market. Wood pulp production decreased by 1.1%, but exports of chemical market pulp increased, indicating a shift toward selling pulp in the global market. Overall, the industry faced challenges from higher prices and shifting consumption patterns, leading to closures and adjustments in production strategies (FAO 2023).

Meanwhile, Brazil's pulp production rose by 10.9% to 25.0 million tons in 2022; fueled by capacity expansions, with exports climbing by 22.1% to 19.1 million tons, primarily of bleached eucalyptus kraft pulp. Conversely, Chile faced a competitive squeeze, notably from Brazil's capacity increase, leading to a 5% decline in market pulp exports to 4.1 million tons. However, exports of specific pulp types like bleached radiata pine and unbleached kraft saw increases, despite overall challenges including high prices and expansion projects affecting the market dynamics. This scenario underscores the competitive and rapidly evolving nature of the global pulp and paper industry, with significant developments in China, Brazil, and Chile impacting international market trends and trade flows (FAO 2023).

INDIAN SCENARIO

India's paper and pulp sector is witnessing the most rapid expansion globally. There is a consistent rise in the need for various paper commodities, encompassing packaging materials, writing and printing papers, as well as niche paper products. India's paper sector is at the forefront of recycling endeavors, advocating for the use of repurposed paper to safeguard natural assets and lessen ecological footprints. Renowned for its eco-friendly methods, the industry in India is also recognized for its commitment to sustainability and utilization of renewable resources. Globally, 410 million tons of paper are used each year, and India's usage accounts for 22.05 million tons of this total, representing 4.72% of worldwide paper consumption. India's paper usage has been on an upward trajectory, correlating with the country's economic growth starting in the early 1990s. From 2010-2011 to 2019-2020, paper consumption in India increased from 13.96 to 22.05 million tons. However, the international paper and pulp mills sector has seen a slight downturn in the last half-decade, largely due to the adoption

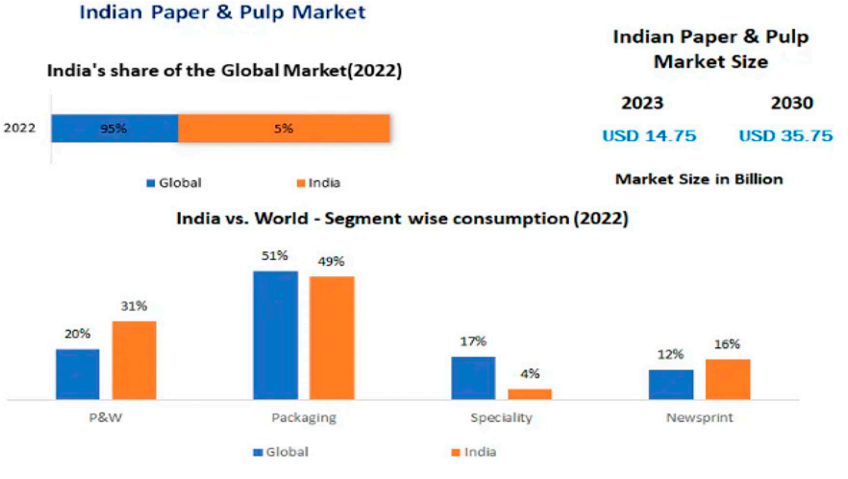

Figure 5. Indian vs World Pulp and Paper Market (MMR 2023).

Table 1. Location of large paper units (both integrated and nonintegrated) across different states in India (MMR 2023).

Name of state	No of units
Andhra Pradesh	4
Gujarat	10
Himachal Pradesh	1
Karnataka	1
Maharashtra	3
Odisha	2
Punjab	4
Tamil Nadu	7
Telangana	1
Uttar Pradesh	9
Uttarakhand	2
West Bengal	2

of digital media and a move toward paperless communication in many advanced economies. The market value of the Indian paper and pulp sector stood at USD 14.75 billion in 2023; and it is projected to grow to USD 35.57 billion by 2030. This growth is anticipated to occur at a compound annual growth rate (CAGR) of 13.4% throughout the forecast period (MMR 2023).

Figure 5 presents an overview of the Indian paper and pulp market within the global context for the year 2022; indicating India's modest but significant presence in the industry, with a particular emphasis on various market segments such as printing and writing, packaging, specialty papers, and newsprint. It shows India's market size for paper and pulp with an optimistic growth forecast, projecting a substantial increase in market value from 2023 to 2030; highlighting a robust CAGR, signaling a rapidly expanding sector within the Indian economy. The displayed data suggests a narrative of India as an emerging player in the paper and pulp industry with expectations of continued growth and increased influence on the global stage over the coming years.

Table 2. Showing the estimated number of wood-based industries in India (Kant and Nautiyal 2021).

Industry	Number of units
Sawmilling and planning industry	27,680
Veneer sheet, plywood, laminated board, particleboard, and other panels industry	47,403
Carpentry and joinery industry	2599
Packing case industry	16,580
Pulp, paper and paperboard industry	24,880
Corrugated paper and paperboard industry	92,871
Manufacture of other articles of paper and paperboard industry	26,894
Total	238,907

Table 3. Showing the annual estimated wood production in India (Shrivastava and Saxena 2017).

Source of wood production	Production (in million m^3)
Timber production from forest (excluding Forest Development Corporation [FDCs])	1.205
Timber production from FDCs	1.97
Annual production of timber from Tree outside the forest (TOF)	44.34
Bamboo production in India	5.38
Imports (all timber and allied products)	18.01
Fuel-wood production	385.25
Total	456.15

DEMAND AND SUPPLY

Since the conclusion of World War II, there has been a fluctuating demand for wood, reaching its zenith in 1973 at 120 million m^3 before declining to less than 95 million m^3 between 1981 and 1986. However, a resurgence occurred in 1987; attributed to a surge in new home construction driven by domestic economic policies and heightened paper demand stemming from increased office automation. Despite a temporary downturn due to economic recession, the demand rebounded to 111.93 million m^3 in 1995; primarily fueled by renewed paper and paperboard demand. Domestic wood supply dwindled to 22.92 million m^3, a mere fifth

Table 4. Showing the annual estimated wood consumption in India (Shrivastava and Saxena 2017).

Source of wood consumption	Consumption (in million m^3)
Construction, furniture, and agricultural implements	48.0
Plywood and panel	8.47
Paper, paperboard, and newsprint	12.52
Fuel wood consumption	333
Total	402

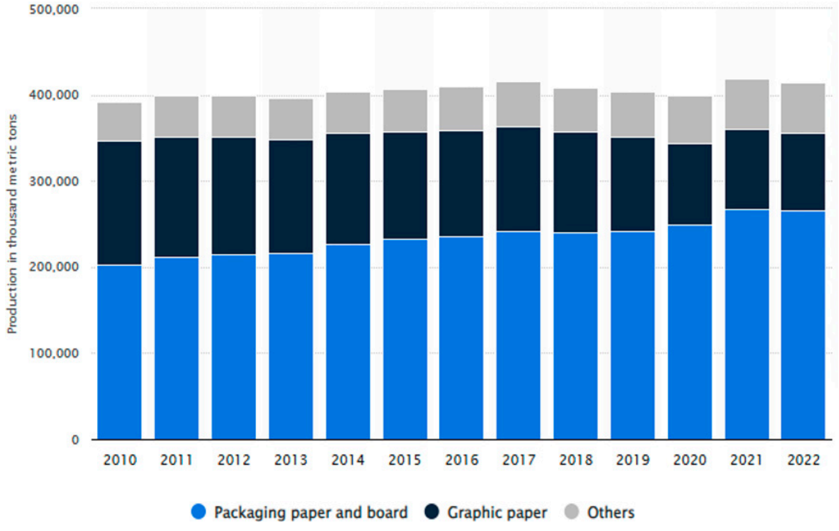

Figure 6. Production volume of paper and paperboard worldwide from 2010 to 2022; by type (in 1000 t) (Statista 2024).

of the total supply in 1995; owing to constraints in domestic forest resources and hindered supply capacity due to delays in wood production infrastructure development. The import share of wood surged from over 50% in 1969 to approximately 70% by 1979.

According to the economic survey by the Ministry of Finance in 2011; forestry and logging contributed 1.2% to India's GDP. In the same year, the Indian forest products industry generated a total revenue of $65,844.6 million, indicating a CAGR of 5.5% from 2007 to 2011. Consumption volumes within the industry saw a marginal increase, with a CAGR of 0.2% from 2007 to 2011; reaching 355.4 million m^3 in 2011. Projections suggest a further acceleration in industry performance, with an anticipated CAGR of 7.7% from 2011 to 2016; poised to elevate the industry's value to $95,467 million by the close of 2016. Annually, approximately 405 million tons of paper

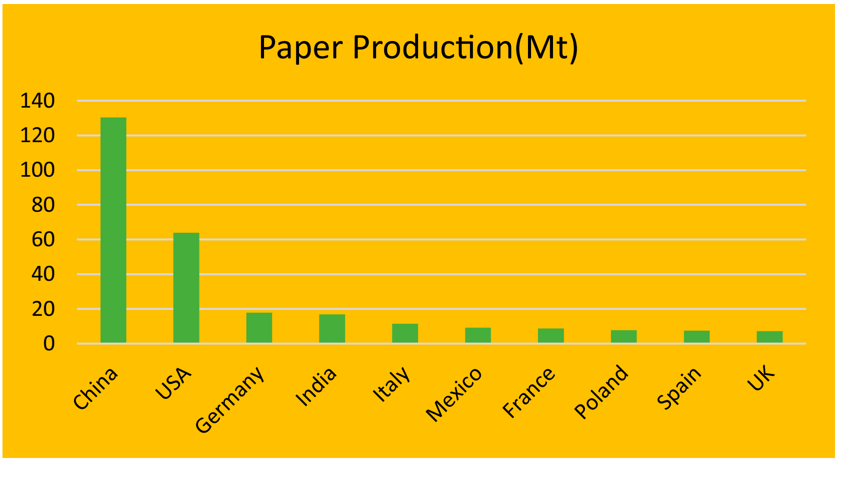

Figure 7. Production of paper and paperboard in selected countries worldwide in 2022 (in 1000 t) (Statista 2024).

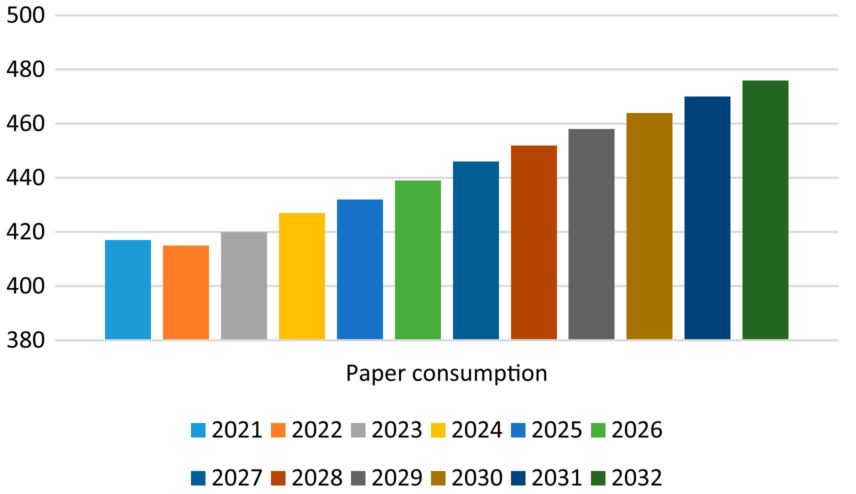

Figure 8. Paper consumption worldwide from 2021 to 2032*(in million metric tons) (Statista 2024).

and paperboard are manufactured, accounting for about 13-15% of the world's total wood usage. As the demand for paper goods rises, it is projected that worldwide output may reach twice the current amount by the year 2050. The paper manufacturing industry has a considerable environmental impact; it ranks as the fourth highest in terms of energy use. Furthermore, the production of paper necessitates a substantial volume of water, which varies with the mill's efficiency, and it exceeds the water consumption of other sectors such as steel and oil (Sunny 2018).

VARIOUS INDEGENIOUS WOOD

Albizia lebbeck

The *Albizia* genus encompasses around 150 taxonomically recognized species, found extensively across Asia, Africa, Australia, and tropical/subtropical regions of the Americas (He 2020). *Albizia lebbeck*, primarily found in the Indian subcontinent and Myanmar (Burma), has a broad distribution spanning Western and Southeast Asia, Australia, Northern and West Africa, the Caribbean, Central America, and parts of South America (Fig 1) (Parrotta 2006). In forestry, *A. lebbeck* plays a crucial role in reforestation and afforestation projects, especially in tropical and subtropical regions. Stems of *A. lebbeck* were easily pulped with Alkaline Sulphite Anthra quinone and Methanol, yielding high viscosities, low kappa numbers, good to exceptional physical characteristics, and high yields (Elzaki et al 2012).

The environmental benefits of *A. lebbeck* extend beyond its utility in paper production (Balkrishna et al 2022). Research on *A. lebbeck* has explored its potential in forestry and pulp and paper production, highlighting its versatility and benefits. One study explores the delignification of refiner mechanical pulp from *A. lebbeck* using the soda

Figure 9. *Albizia lebbeck* (CABI Digital library 2017).

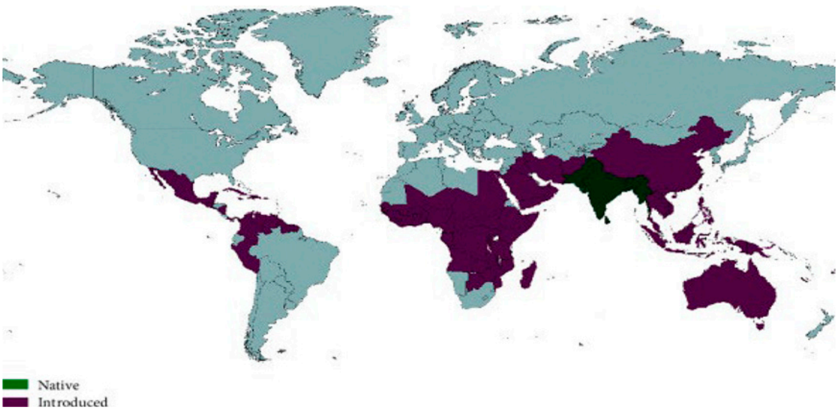

Figure 10. Global distribution of *Albizia lebbeck* (L.) Benth (Balkrishna et al. 2022).

process, demonstrating that high-yield pulps with comparable strength properties to conventional chemical pulps can be produced, highlighting the wood's potential for sustainable pulp production (Kalra 1990). Additionally, the restoration potential of *A. lebbeck* has been examined, showing its superior performance in improving soil properties, biomass accumulation, and net primary production in mine spoils, which could indirectly benefit forestry and pulp and paper industries by enhancing raw material quality and availability (Singh et al 2004).

Albizia falcataria

Albizia falcataria, also known as *Falcataria moluccana*, is a tropical hardwood tree extensively utilized in Southeast Asia for its significant value in timber production. It is renowned for its rapid growth and adaptability to a range of environmental conditions, making it an excellent candidate for reforestation and afforestation projects. Research highlights its wide adaptability and suitability for social forestry, particularly in areas with high rainfall, due to its minimal soil demands (Bahuguna et al 1989). The wood's physical properties have also been enhanced through densification, addressing its low-density limitations for commercial applications (Julian et al 2022). For the pulp and paper industry, *A. falcataria* presents a viable and sustainable raw material option. The tree's fast growth rate and high cellulose content make it an excellent source for pulp production, contributing to meeting the global demand for paper and paperboard products. The pulp derived from *falcataria* is known for its high quality, which is suitable for producing a wide range of paper products, including writing paper, packaging materials, and tissue papers. Heartwood is a commonly used material for lightweight packaging materials, lightweight buildings, paneling, cabinets, and furniture. It is also easily worked and ideal for pulping, paper, and matchsticks (Rojas-Sandoval 2009).

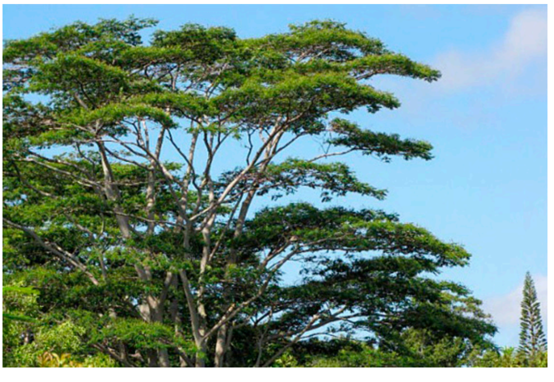

Figure 11. *Albizia falcataria* (https://www.ecured.cu/index.php/Falcata_*Albizia_falcataria*).

The utilization of *A. falcataria* in the pulp and paper industry also aligns with environmental sustainability goals. The cultivation of *A. falcataria* for pulp production can be integrated into agroforestry systems, promoting land use efficiency and providing additional income sources for farmers.

Furthermore, as the industry seeks to reduce its reliance on traditional wood sources and increase the use of more sustainable raw materials, *A. falcataria* offers a pathway to achieve these objectives without compromising on the quality of the final paper products (Setyawan et al. 2018). Studies on the utilization of *A. falcataria* specifically for forestry, pulp, and paper industries are not directly available. However, related research offers insights into the broader context of pulpwood plantation, genetic modifications for pulp production, and the use of hybrid species for increasing forest biodiversity and supporting the pulp/paper industry. For instance, Kröger and Nylund (2012) applied ethical analysis to assess conflicts in the expansion of pulpwood plantations in Brazil, highlighting the complexities of social, ecological, and economic dynamics in large-scale forestry investments. Unnikrishnan and Gurumurthy (2015) reviewed genetic modifications in major tree species used in India's pulp and paper industry, aiming to enhance growth, wood characteristics, and stress tolerance. Sunarti and Nirsatmanto (2021) discussed the use of interspecific *Acacia* hybrids in Indonesia for pulp/paper industry support and forest biodiversity increase, emphasizing the development of hybrids with fast growth, good wood properties, and tolerance to pests and diseases. These studies reflect the broader research efforts and considerations in the domain of forestry, pulp, and paper production, which may inform the utilization and management of *A. falcataria* in related contexts. *Albizia falcataria* can be employed in generating pulp and paper making (Olufunmilayo 2013). *Albizia falcataria* is one hardwood species that works well for producing high-quality, high-yield kraft pulp (Akhtaruzzaman and Chowdhury 1991).

These studies collectively underscore the multifaceted importance of *Albizia falcataria* in forestry, ecological studies, and industrial applications, highlighting its potential for future research and utilization.

Gmelina arborea

Gmelina arborea, commonly known as yemane, is a fast-growing hardwood species valued for its timber. It is extensively used in furniture, construction, and paper production due to its desirable properties. Research on *G. arborea* has highlighted its significant mechanical properties and adaptability, making it a preferred choice in forestry and agriculture. For instance, studies conducted on Nigerian-grown *G. arborea* revealed variations in wood properties with age and sampling position, indicating increases in strength properties with age, which is crucial for its utilization in construction and furniture making (Ogunsanwo and Akinlade 2011). In Bangladesh, designated forestlands are planted with Gamari (*G. arborea*) to produce pulpwood (Sarwar Jahan et al 2018). Similarly, extensive research on the mechanical properties of *G. arborea* for engineering design underscored its potential for load-bearing structures, comparing favorably with European softwood species and highlighting its suitability as a construction material (Iwuoha et al 2021). *Gmelina arborea* is one of the hardwoods found in Nigeria's forest reserves. About 50 yr ago, several plantations of the tree were planted, primarily in southern Nigeria, with the intention of providing pulp wood for the paper industry (Akeem Azeez et al 2016). Additionally, the impact of soil moisture regimes on the growth and wood properties of *G. arborea* seedlings has been studied, providing insights into its adaptability and the quality of paper produced from its wood, which is crucial for pulp and paper manufacturing (Ogbonnaya et al 1992). Studies on *G. arborea* have explored its significance in forestry and the pulp and paper industry, highlighting its utility based on geographical variations, growth characteristics, and suitability for pulp production. For instance, research by Soosai Raj et al (2017) examined the pulping properties of *G. arborea* from different regions in Tamil Nadu, India, identifying trees with favorable traits for pulp and paper manufacturing due to their superior slenderness ratio and fiber dimensions (Soosai Raj et al. 2017). Research by Olufunmilayo (2013) compared the pulp and paper-making suitability of *G. arborea* with other species, highlighting its advantages and proposing methods for identifying suitable hardwood species for the industry. *Gmelina arborea*

Roxb. deciduous tree species is indigenous to Bangladesh and grows quickly. It has been widely planted in Bangladesh's hilly regions for the commercial production of pulpwood since 1992 (Khushi et al 2019). These studies collectively underscore the potential of *G. arborea* in enhancing forestry, pulp, and paper production through genetic selection, growth modeling, and comparative analysis with other species.

Melia dubia

Melia dubia, also known as Malabar Neem, is a fast-growing tree species valued for its diverse applications ranging from agroforestry to the timber industry. Its wood properties, including basic density, fiber dimensions, and chemical composition, vary with age, influencing its suitability for pulp and paper production. Sinha et al (2019) highlighted that the wood's basic density, fiber length, cellulose, and lignin content increase with tree age, making it suitable for high-quality pulp and paper at ages 4 and 5. Moreover, Chavan et al (2021) discussed its economic viability in agroforestry systems in India, noting its high biomass production and profitability, making it a favored species for wood-based industries. Additionally, Gupta et al (2019) reported on the wood's working qualities, indicating its potential in the plywood industry due to its satisfactory planning and shaping properties. Goswami et al (2020) emphasized its rapid growth and high demand in various industries, alongside its notable medicinal and pharmacological properties. Research on *M. dubia* has highlighted its potential for forestry, pulp, and paper industries, with studies focusing on its growth performance, wood properties, and suitability for pulp production. *Melia dubia* is unique among traditional raw materials used in the pulp and paper industry because of its exceptional fiber strength and excellent pulp recovery (Dhaka et al 2020).

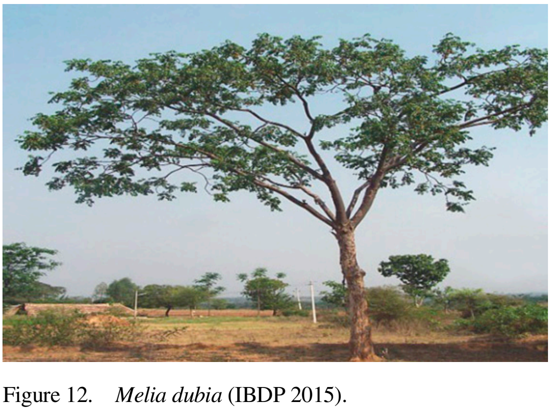

Figure 12. *Melia dubia* (IBDP 2015).

Sinha et al (2019) found that *M. dubia* exhibits favorable wood properties for pulp and paper quality, with basic density, fiber dimensions, and cellulose content improving with tree age, suggesting the optimal harvesting period for high-quality pulp is at 4 to 5 yr. *Melia dubia* is a species that can be used in agroforestry and farm forestry plantation programs due to its many uses, including pulpwood, timber, fuel wood, and plywood (Saravanan et al 2013). These studies collectively emphasize the significant potential of *M. dubia* in contributing to sustainable forestry practices and supporting the pulp and paper industries through its fast growth, quality wood properties, and versatility in applications. These studies collectively underscore. In India, the *Melia* genus is making a comeback and gaining popularity as a substitute for eucalyptus and poplar as an indigenous source of pulp and plywood (Chavan et al 2021).

Melia dubia significance in sustainable forestry and agroforestry practices, highlighting its potential for economic and environmental benefits.

Leucaena leucocephala

Leucaena leucocephala, commonly known as the White Leadtree, demonstrates versatile applications and environmental benefits, particularly in the contexts of agroforestry, phytoremediation, and material production. Its ability to rapidly metabolize soil and groundwater contaminants such as ethylene dibromide and trichloroethylene positions it as an effective tool for environmental cleanup, especially in tropical regions (Doty et al 2003). Additionally, *L. leucocephala* suitability for biomass and paper production, even from its varieties like giant leucaena, underscores its potential for sustainable agroforestry and as a renewable energy source, supporting industries

Figure 13. *Leuceana leucocephala* (Mónica Sánchez).

ranging from timber and paper pulp to biofuel production (Bageel et al 2020). Research on *L. leucocephala* has demonstrated its potential in the forestry and pulp and paper industries due to its rapid growth and suitable wood properties. López et al (2008) evaluated Leucaena species for biomass and paper production, finding *L. leucocephala* among others to show good adaptation and productivity, with properties favorable for papermaking, such as lower lignin content and suitable cellulose levels. Shaik et al (2009) focused on optimizing a regeneration system for *L. leucocephala*, which is crucial for genetic engineering aimed at modifying lignin content to improve paper quality. Bhola and Sharma (1982) demonstrated that *L. leucocephala* could produce high yields of unbleached kraft pulp with low alkali consumption, suggesting its suitability for sustainable pulp production. *Leucaena leucocephala* is a good choice for making unbleached kraft pulp because of its medium basic density and medium-sized fiber length (Gillah and Ishengoma 1993).

Kumar et al (2013) identified and characterized cinnamate 4-hydroxylase genes from *L. leucocephala,* providing insights into the genetic basis for its growth and wood properties, which are relevant for pulp and paper production. *Leucaena* has drawn a lot of attention due to its widespread use as a raw material in the pulp and paper industries as well as in the production of packaging materials (Pandey and Kumar 2013). *Leucaena leucocephala* is a versatile, quickly growing legume tree that can be used for pulp, paper, leaf compost, and fodder (Shaik et al 2009). These studies collectively underscore the versatility and potential of *L. leucocephala* in contributing to the forestry sector, particularly for pulp and paper manufacturing, through its favorable growth characteristics and wood properties.

Acacia auriculiformis

Acacia auriculiformis, commonly known as ear-leaf acacia, is recognized for its significant contribution to the timber and pulpwood industry due to its desirable wood properties. Research has highlighted the genetic variation in wood stiffness and strength, which are crucial for structural and appearance-grade timber applications. Studies from southern Vietnam demonstrate significant variation among clones in static bending stiffness and strength, indicating the potential for genetic improvement (Hai et al 2010). Additionally, investigations into the wood property variation in 11-yr-old *A. auriculiformis* grown in Bangladesh revealed that basic density, fiber length, and compressive strength increase with radial distance from the pith, suggesting the potential for tree selection to enhance wood quality through breeding (Chowdhury et al 2009). Moreover, the anatomical and physico-mechanical properties of the species to age and soil type in Benin, West

Figure 14. *Acacia auriculiformis* (Aggarwal 1988).

Africa, emphasize the influence of environmental factors on wood density and structural integrity, which are key considerations for timber use (Tonouéwa et al 2020). The leaf of *A. auriculiformis* contains lignin, hemicellulose, and cellulose. *Acacia auriculiformis* has lignin contents ranging from 19 to 20% (Abdullah et al 2021). These findings underscore the importance of *A. auriculiformis* in forestry and wood industries, highlighting its adaptability and the potential for targeted genetic and environmental management to optimize wood properties for various applications. *Auriculiformis* cultivated in many regions of the world had nearly identical features to that of *A. auriculiformis* planted in social forestry programs in Bangladesh and other nations. This species holds great potential for pulp production in Bangladesh and other Southeast Asian nations (Haque et al 2021).

Dalbergia sissoo

Dalbergia sissoo, a prominent deciduous tree, can ascend to heights of 30 m with a girth of 80 cm, forming a notable presence with a wide, sparse canopy. Its gray bark, etched with longitudinal furrows, tends to peel. The tree develops a central taproot and spreading lateral roots in its youth. Known for its robust growth, *D. sissoo* bark, roots, and young shoots demonstrate its adaptability, with a crown supported by strong limbs, making it a significant species both ecologically and economically (Hossen et al 2023). *Dalbergia sissoo*, a significant tree species, boasts considerable economic value. Its heartwood is characterized by its brown hue and dark streaks, noted for its hardness, strength, and long-lasting quality. Recognized as one of India's four main timbers—alongside *Tectona grandis* (Teak), *Shorea robusta* (Sal), and *Cedrus deodara* (Cedar)—it is prized for its robustness, flexibility, and endurance, making it a preferred material for construction and various other utilities. *Dalbergia sissoo* is also an ideal species for reforestation projects in challenging environments, such as saline and alkaline terrains, mining areas, and eroded landscapes. Its resilience makes it suitable for restoring degraded woodlands, contributing to environmental conservation efforts (Singh 2015). Research on *D. sissoo* (Indian rosewood) has explored various aspects of its potential in forestry and the pulp and paper industry, focusing on its growth performance, wood properties, and disease susceptibility. Hannan et al (2001) investigated the physical properties of sound and disease-affected *D. sissoo* wood, revealing significant differences in shrinkage and

Figure 15. *Dalbergia sissoo* (Singh 2015).

Table 5. Anatomical properties of indigenous wood property (Anoop et al. 2011).

Species	Fiber length (mm)	Fiber diameter (µm)	Lumen diameter (µm)	CellWall thickness (µm)	Vessel element presence
Albizia lebbeck	0.8-1.5	15-25	5-10	2-5	Moderate
Albizia falcataria	1.0-1.8	20-30	10-15	2-4	Sparse
Gmelina arborea	0.9-1.4	18-28	8-12	1.5-3.5	Moderate to High
Melia dubia	0.6-1.2	10-20	5-10	1-3	Sparse to Moderate
Leucaena leucocephala	0.7-1.3	15-25	7-13	2-4	Moderate
Acacia auriculiformis	0.5-1.0	10-20	4-8	1.5-3	High
Dalbergia sissoo	1.0-1.5	15-25	6-11	2-4.5	Moderate

In a study by Vennila and Parthiban (2021) they studied various properties of Indigenous species for pulp and paper production given in Tables 6 and 7.

Table 6. Physical characteristics of hardwood chips (Vennila and Parthiban 2021).

Sl. No.	Species	Moisture (%) as received	Bulk density (OD basis) (kg/m^3)	Basic density (OD basis) (kg/m^3)	Chips classification: +45 mm	+8 mm (over thick)	+7 mm (accepts)	+3 mm (pin chips)	−3 mm (dust)
1	*Albizia lebbeck*	9.0	266	530	Nil	3.9	81.2	14.2	0.7
2	*Dalbergia sissoo*	9.6	280	580	Nil	4.8	79.8	14.6	0.8
3	*Erythrina indica*	9.9	266	438	Nil	4.8	79.5	15.3	0.4
4	*Grewia tillifolia*	10.3	220	485	Nil	5.1	78.6	15.7	0.6
5	*Melia dubia*	9.1	240	520	Nil	6.2	79.2	14.2	0.4
6	*Melia composita*	9.9	190	505	Nil	6.5	82.6	10.1	0.8
7	*Neolamarckia cadamba*	8.5	160	380	Nil	4.1	79.8	15.6	0.5
8	*Sterculia alata*	10.9	240	510	Nil	6.2	77.8	15.4	0.6

specific gravity that affect its timber quality. This study underscores the importance of managing disease to maintain the wood's value for construction and utility purposes (Hannan et al 2001). These studies collectively highlight the significance of *D. sissoo* in forestry and the pulp and paper industry, its ecological and economic benefits, and the challenges it faces, including disease and the need for accurate species identification to prevent illegal trade.

PROBLEMS AND CONSTRAINTS

Studying the anatomical properties of indigenous tree species for pulp and paper production presents a range of challenges and constraints, both scientific and practical. One of the primary difficulties is the variability in wood properties not only between species but also within a single species due to environmental factors, age, and growth conditions. This variability can significantly impact the reliability of comparative studies, making it challenging to draw definitive conclusions about the suitability of a particular species for pulp and paper production (Downes et al 1997).

Moreover, access to representative samples can be a constraint. Many indigenous tree species are found in remote or protected areas, complicating sample collection efforts. Additionally, there are ethical and legal considerations regarding the use of indigenous species, especially those that may be endangered or hold cultural significance (FAO Report 2011). These factors necessitate careful planning and consultation with local communities and regulatory bodies, which can prolong the research process.

Another significant challenge is the technological and economic feasibility of utilizing new or underutilized species for pulp and paper production. The existing pulp and paper industry infrastructure is optimized for a few well-studied species. Incorporating new species into the production

Table 7. Chemical characteristics of hardwood chips (Vennila and Parthiban 2021).

Sl. No.	Species	Ash content (%)	Acid insoluble lignin (%)	Pentosans (%)	Hollo cellulose (%)	Solubility in (%) – Hot water	1% NaOH	Alcohol benzene
1	*Albizia lebbeck*	0.54	24.1	18.2	71.5**	2.75	12.5	3.2
2	*Dalbergia sissoo*	0.62*	23.9	17.6	70.4	3.05	15.7**	3.8*
3	*Erythrina indica*	0.61	24.3	17.2	69.4	2.80	14.2	4.2*
4	*Grewia tiliifolia*	0.66**	23.7	17.2	68.9	3.75	16.1**	2.7
5	*Melia dubia*	0.64**	22.5	18.7	72.8**	2.75	13.7	3.8*
6	*Melia composita*	0.53	24.5	18.5	69.5	3.65	16.8**	3.4
7	*Neolamarckia cadamba*	0.74**	25.5**	20.4**	70.5	3.12	11.8	3.6
8	*Sterculia alata*	0.54	23.5	16.7	63.5	3.60*	15.9**	2.8

Table 8. Strength characteristics of hardwood chips (Vennila and Parthiban 2021).

Species	Tensile strengh	Tensile index (Nm/g)	Breaking length (M)	Tear strength	Tear index (mNm^2/g)	Tear factor	Bursting strength	Burst index ($kPam^2/g$)	Burst factor
Albizia lebbeck	1270	20.95	2038	180	3.0	30.29	78	1.3	13.12
Dalbergia sissoo	1380	22.81	2257	190	3.1	32.04	74	1.2	12.48
Erythrina indica	1120	18.18	1877	168	2.7	27.81	82	1.3	13.57
Grewia tiliifolia	1150	18.98	1877	184	3.0	30.98	68	1.1	11.45
Melia dubia	1310	22.47	2195	190	3.3	33.24	92	1.6	16.10
Melia composita	1080	18.60	1833	185	3.2	32.49	102	1.8	17.92
Neolamarckia cadamba	1110	17.76	1797	169	2.7	27.58	88	1.4	14.36
Sterculia alata	1210	20.79	2023	175	3.0	30.68	78	1.3	13.67

cycle may require adjustments in processing techniques and equipment, which could be cost-prohibitive (Hendarto 2006). Moreover, the lack of existing knowledge on the best practices for cultivating, harvesting, and processing these species adds another layer of complexity.

Current laws forbid leasing property to private persons, businesses, or joint sector projects. Examples of these laws are the Property Reforms Act of several states, the Forest Conservation Act of 1980; and the National Forest Policy of 1988. Fearing that such land would be permanently taken away, the corporate sector has refrained from actively participating in afforestation (Sharda et al 2000).

Finally, modern technologies and procedures are continually being created in the paper business to increase quality, production, and efficiency. The industry participants may find themselves at a competitive disadvantage if they are unable to keep up with these technical improvements. One of the numerous issues facing the business is the absence of domestic plant and machinery manufacturing capacity.

THE WAY FORWARD

The way forward in leveraging indigenous tree species for pulp and paper production necessitates a multifaceted and sustainable approach. Critical to this endeavor is the advancement of research and development focused on understanding the specific anatomical and chemical properties of these species to optimize their use in paper manufacturing processes. This involves not only detailed scientific studies but also the development of innovative technologies that can efficiently process diverse wood properties while minimizing environmental impact. Collaboration between academia, industry, and government agencies is essential to ensure that the cultivation and harvesting of these species are done sustainably, incorporating best practices for forest management and conservation. Moreover, engaging with local communities and indigenous peoples is crucial to respecting rights and traditions, ensuring equitable benefits, and fostering the sustainable management of forest resources. Developing policies that support the sustainable commercialization of indigenous tree species, coupled with investments in infrastructure that can adapt to a wider range of raw materials, will be key. Ultimately, a holistic approach that balances economic viability with environmental sustainability and social equity will pave the way for the responsible expansion of the pulp and paper industry using indigenous tree species. This path forward promises not only to enhance the sustainability of the industry but also to contribute to biodiversity conservation and the economic development of regions rich in these native species.

CONCLUSION

The comparative review underscores the imperative for a sustainable, multifaceted approach in harnessing indigenous tree species for pulp and paper production. It highlights the necessity of advancing research to uncover the distinct anatomical and chemical traits of these species, which are pivotal for their optimal use in the paper manufacturing industry. The collaboration across academia, industry, and governmental bodies is emphasized as crucial for ensuring the sustainable cultivation and harvesting of these resources. Furthermore, the study advocates for engagement with local communities and indigenous peoples to ensure that the exploitation of these species is equitable and respects cultural traditions. The development of supportive policies and the investment in adaptable infrastructure emerge as essential components for facilitating the sustainable commercialization of indigenous tree species. This approach not only aims to improve the sustainability of the pulp and paper industry but also contributes to biodiversity conservation and the economic upliftment of areas endowed with these native species, marking a significant step toward environmental stewardship and sustainable development.

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