BAOBAB (ADANSONIA DIGITATA) FRUIT SHELL LIGNOCELLULOSE FOR SUSTAINABLE BIO COMPOSITES: A SCOPING REVIEW OF BIOFIBER COMPONENTS, PROCESSING TECHNOLOGIES, AND INDUSTRIAL APPLICATIONS

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ABSTRACT:
Baobab (Adansonia digitata L.) fruit shell lignocellulose is an underutilized agricultural waste stream with high potential for sustainable bio composite development. Despite its promise, a critical knowledge gap exists regarding the integrated relationship between its unique chemical composition, processing outcomes, and industrial scalability, particularly in how these factors influence the performance and market viability of bio composites made from baobab fruit shell lignocellulose. Following the PRISMA-ScR framework, this scoping review synthesized evidence from 87 peer-reviewed studies (2015–2025) and 60 supplemental sources. The analysis specifically focused on the mechanistic contributions of the fruit shell's high lignin content (51–54%) compared to traditional bast fibers. Findings reveal that the fruit shell's unique composition (51–54% lignin, 24–26% cellulose) provides 60–75% superior moisture resistance over sisal-based composites and >95% tensile strength retention after accelerated weathering. Furthermore, the shell demonstrates inherent flame retardancy (UL 94 V-1) and low thermal conductivity (0.08–0.12 W/m·K). In application, 10 wt% alkali-treated shell particles in epoxy matrices achieved tensile strengths of ~48 MPa. The distinct profiles of bark versus shell fibers necessitate part-specific composite design, as each type of fiber contributes differently to the mechanical properties and overall performance of the composite material, which is crucial for optimizing the application of bio composites in industries such as automotive, insulation, and active packaging. While baobab bio composites show immense promise for the automotive, insulation, and active packaging sectors, the transition to a circular bioeconomy requires addressing persistent gaps in standardized extraction protocols and comprehensive life-cycle assessments. Baobab fruit shell lignocellulose is a scientifically grounded, high-performance alternative to traditional biofibers, offering a multifunctional and economically viable pathway for advanced green material engineering.

KEYWORDS: baobab, Adansonia digitata, lignocellulosic biofibers, bio composite engineering, sustainable materials, circular economy, activated carbon, green nanoparticle synthesis, PRISMA-ScR

INTRODUCTION

The twenty-first century has seen a growing acceleration of three interconnected crises that, together, require a complete reevaluation of materials science: the climate emergency, the exhaustion of resources, and the growth of intractable synthetic waste. According to the projections of the Intergovernmental Panel on Climate Change (IPCC), global warming must be limited to 1.5°C, which implies that the net industrial reduction of greenhouse gas emissions must be at least 43% in 2030 compared to the level of 2019 (IPCC, 2022). The production of industrial materials such as polymers, metals, and composites contributes about 23 percent of global CO_2 emissions, and it is a key focus of decarbonization efforts (International Energy Agency, 2023). At the same time, the linear take-make-dispose paradigm, which most traditional materials manufacturers rely on, produces an estimated 2.5 billion tons of solid waste each year, with only 13.5% of it being recycled in the world (World Bank, 2022).

It is in this context that the Circular Economy Action Plan of the European Union (European Commission, 2020) and the United Nations Sustainable Development Goals, specifically SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), introduce binding targets on material circularity, embodied carbon reduction, and agriculture. Regulatory pressure has further escalated with the EU Single-Use Plastics Directive (2019/904/EC), which constrained traditional synthetic polymer products, and the EU Corporate Sustainability Reporting Directive (CSRD, 2022), which requires disclosure of full-supply-chain embodied carbon. All these regulatory tools represent a structural market transition to virgin synthetic materials and to bio-based, circular options (European Union, 2021; (Elfaleh, Abbassi, Habibi, Ahmad, & Guedri, 2023)).

Lignocellulosic bio composite materials that incorporate plant-based fibers with biobased or traditional polymer matrices specifically respond to these demands by providing: (i) renewable, annually renewable feedstocks; (ii) embodied carbon 60-85% lower than synthetic materials; (iii) biodegradability or recyclability; and (iv) compatibility with existing manufacturing infrastructure (Mathur, 2021). These benefits have resulted in the rapid uptake of natural fiber composites in the automotive, construction, packaging, and consumer goods industries in the last ten years (Faruk et al., 2014)(Rahman et al., 2023); (Adeiza & Peter, 2024)).

This is because the global bio composites market has shifted its status of application from a niche to mainstream industrial relevance in a span of just one decade. It has increased market valuations to USD 43.59 billion in 2025, which are up from about USD 16 billion in 2017, and several independent estimates show further growth to USD 83-195 billion by 2030-2034, indicating compound annual growth rates of 13.6-18.2% according to methodology (Precedence Research). Four structural drivers of demand underline this growth trend and are likely to continue irrespective of the short-term economic cycles, including increasing consumer awareness, technological advancements, regulatory support, and rising disposable incomes.

To begin with, the automotive lightweighting imperative is accelerating due to the acceleration of fleet electrification. The total number of electric vehicles in the world stock exceeded 40 million vehicles in 2023 and is expected to hit 240 million vehicles in 2030 (International Energy Agency, 2023). Battery-electric cars have 300-600 kg of extra battery mass compared to internal combustion counterparts; each 10% decrease in curb weight with lightweight composite replacement recovers 6-8 per cent of energy usage and range accordingly (Skosana et al., 2025; Mohanty et al., 2023). Already, the transportation field is covering about 29% of the entire bio composite market in the world and is expanding (Precedence Research, 2024).

Second, the embodied carbon crisis in the construction industry is creating regulatory and market pressures to use bio-based insulation, cladding, and structural building materials. The EU Energy Performance of Buildings Directive (2021) will require near-zero-energy standards of all new buildings by 2028 and retrofits by 2033, with bio-based insulation materials eligible to earn enhanced sustainability credits (European Union, 2021). In 2024, the building and construction market was the largest consumer of European bio composites at 42.8% (Market Data Forecast, 2025). In 2024 alone, the global market in lignin-based biopolymers was estimated to be USD 1.32 billion and is expected to increase at a rate of 4.54% CAGR until 2030 due to regulatory restrictions on single-use plastics and increasing the integration of the circular economy (Grand View Research, 2024).

Third, the shift to sustainable packaging is gaining momentum due to EU restrictions on plastics and a shift in consumer preferences. Research has always demonstrated that 80–83 percent of European consumers take the environmental impact into account as an important factor in their purchases (Market Data Forecast, 2025). The overall sustainable food packaging market is over USD 300 billion and increases at 12–14% CAGR, with natural fiber-reinforced bioplastic packaging having a faster growth rate (Sage Publishing, 2024; Ilyas et al., 2022). Fourth, the Asia-Pacific has become the biggest bio composites market region (39% of the world in 2024) due to the rapid growth of manufacturing capacity in China, India and Southeast Asia and the increasing domestic environmental regulation (Business Research Company, 2025), which has led to a surge in demand for sustainable packaging solutions among consumers and businesses alike.

Natural biofibers can have tensile strengths of 200–333 MPa cm^3/g, which is similar to the tensile strength of glass fiber (160–200 MPa cm^3/g), but they have a lower manufacturing cost (40–60 per cent), fewer occupational health risks (such as no silicosis or fiber inhalation hazards), and the ability to be composted. Nevertheless, traditional commodity biofibers sisal, jute, flax, hemp, and kenaf still encounter a chronic challenge of high moisture sensitivity (8–15% absorption), UV degradation, and insufficient flame retardancy, limiting their applications in high-durability applications absent of synthetic additive packages ((Shadhin et al., 2023). Finding biofiber feedstocks that do not compromise the sustainability and affordability benefits of natural fiber without these constraints is one of the key challenges of modern bio composite engineering.

Adansonia digitata L. One of the ecologically and culturally most important trees of the African continent is the baobab, which is found in the semi-arid savanna belt, stretching westward to Senegal and Gambia, eastward to Sudan, Ethiopia, and Somalia, and southwards to Namibia, Botswana, and northern South Africa (Kaboré et al., 2020); (Resende et al., 2023)) The species belongs to the family Malvaceae, and its distinguishing feature is a bottle-shaped trunk that can be up to 510 meters in diameter and is estimated to live between 500 and 3000 years, making it one of the oldest species of angiosperm ((Kaboré et al., 2020)). Its cultural heritage importance as a communal meeting place and its use as a food bank in times of famine have seen the tree named as a protected species in various countries.

The baobab has massive and woody, indehiscent fruits (25-35 cm long; 0.314 kg per fruit) that consist of a tough lignified rind, an inner powdery pulp and encased seeds. It is a commercially developed food and beverage ingredient rich in vitamin C (around 280,300 mg/100 g), calcium, and dietary fiber that was granted European Union Novel Food authorization in 2008, allowing its sale in EU food and supplement markets (Kaboré et al., 2020). Organizations like Phyto Trade Africa, the Baobab Foods Company, and others have increased the commercial production of baobab pulp significantly over the last ten years, fueled by the global superfood market. Nevertheless, the commercial pulp production leaves behind large quantities of fruit shell waste; the woody capsule of the fruit takes up around 40–50 per cent of total fruit dry weight and is discarded in almost any commercial process (Nedjai et al., 2022); (Manoj Kumar et al., 2021)).

Sub-Saharan Africa produces around 500,000 tons of baobab fruit shells each year, which are currently being discarded using landfill, open burning, or low-value animal feed applications (Kaboré et al., 2020. Such a disposal is costly and harmful to the environment: open combustion of lignocellulosic agricultural waste emits CO_2, black carbon, and reactive nitrogen species, thereby causing the deterioration of the air quality in the region and greenhouse gas emissions (Recycling, 2024). In sub-Saharan Africa, strategically focusing on recycling agricultural waste has been identified as a key area for transitioning to a circular economy, developing entrepreneurship, and enhancing food security; literature reports that there is significant potential to transform food waste streams into value-added products that support rural livelihoods (Recycling, 2024; Integrating Circular Economy Practices, 2025).

The baobab fruit shell is not just a rich agricultural waste stream; it is compositionally superior to any known lignocellulosic material, as well as having a property profile that unexpectedly lacks a close counterpart in the commercial natural fiber repertoire. Three differentiating features should be the subject of systematic scientific study.

First, the fruit shell is composed of 5154% (w/w) lignin, the highest lignin content ever reported in the bio composites literature of any natural fiber feedstock, significantly higher than sisal (~12%), jute (~14%), flax (~58%), hemp (~10%), and even woody biomass sources such as hardwood (2%). It has been said that such a high concentration of lignin is a result of evolutionary adaptation: the lignified, rigid shell developed to shield enclosed seeds against the heat of the savanna wildfires, a force of selection that has created a natural thermal and UV shield of extraordinary quality (Botanical Studies, 2018). The exceptional quality that protects seeds in the wild also makes the shell the most effective in providing moisture barriers, UV resistance, and intrinsic flame resistance as a composite reinforcement.

Second, the fruit shell has a total dietary fiber (TDF) content of 85%, the highest of any portion of baobab fruit, even higher than the fibrous filaments (79%), and the highest total antioxidant capacity (TAC) of any portion (72 μmol Trolox eq.). This phytochemical abundance is not only of nutritional value, but it also has functional properties that can be directly applied to antimicrobial food packaging (MIC 110 μg/mL(Saura-Calixto, 2003)) and, as (Aldahasi et al., 2024)) show, to the eco-friendly green synthesis of bimetallic nanoparticles.

Third, unlike most natural fibers, where structural (cellulose) and functional (polyphenol) components are extracted as competing fractions, the baobab fruit shell enables a cascading valorization model, as structural biofiber and activated carbon (BET surface area 10 This cascade underpins the bioeconomic viability of commercially viable baobab shell valorization because the revenues of high-value side streams (bioactive at USD 100-500/kg and activated carbon at USD 15/kg) can be used to effectively subsidies the economics of lower-margin structural composite fiber. Note that another and different part of the plant, the bast fiber of the inner bark of the baobab tree, has a different lignocellulosic profile: cellulose (60.70%), hemicellulose (21.98%), and lignin (5.91%; (Journal et al., 2020)This high-cellulose bast fiber is chemically more like sisal and flax and more suitable for high-strength structural reinforcement and nanocellulose extraction than for durability and multifunctionality, where the high-lignin fruit shell is preferred. Any critical analysis of baobab bio composite studies should uphold this difference. Since 2015, the scientific literature on baobab materials has grown by a significant amount, moving towards early characterization studies Eltahir et al., 2020). A significant example was set by ((Nuhu et al., 2026)), whose baobab pod fiber/LDPE composites had a tensile strength of 75.72 MPa, the highest tensile strength reported in any baobab composite system and competitive with short-fiber glass-reinforced polypropylene (80–100 MPa).

However, despite this accumulation of evidence, four interrelated weaknesses hinder the subject, limiting both scientific synthesis and commercial translation. To start with, the published literature uses non-standardized processing parameters: the concentrations of NaOH treatments used by researchers vary between 6 and 24 wt%; thus, mechanical properties cannot be directly compared across studies, and the design of an industrial process becomes more challenging ((Shehu et al., 2017) (Baikie et al., 2024); (Elfaleh, Abbassi, Habibi, Ahmad, & Guedri, 2023)). Second, the majority of studies examine a composite system in isolation, without a comparative study of the types of matrices or fabrication. The entire 4.4-fold variation in reported tensile strength (18.8575.72 MPa) is likely due to the choice of matrix rather than inherent fiber constraints, but this dependence has not been systematically studied with an an experimental design. Third, there is no research that has completely quantified an ISO 14040/44-conformant life cycle assessment of baobab bio composites in any application field, making sustainability assertions qualitative. Fourth, there is no previous review to systematically incorporate the entire cascade of baobab shell valorization pathways, structural composites, activated carbon, nanoparticles, bioactive, and CMC into a single coherent approach to composition, processing, and industrial use.

The literature review on lignocellulosic composites typically considers fibers as generic types, such as sisal, jute, flax, and hemp, but does not consider the compositional unique properties of particular agricultural waste sources, like the baobab fruit shell (No Title, 2026); (Phiri et al., 2023); (Mcneill et al., 2025)). This generic treatment leads to systematic under-representation of materials whose most commercially useful properties (moisture resistance, UV stability, flame retardancy, and polyphenol functionality) are precisely products of the properties which cause them to diverge in the maturity of the commercial fiber mainstream.

The four objectives that this scoping review focuses on include:

Systematically describe the properties of the baobab biofiber component, distinguishing fruit shell and bast fiber, and mechanistically describe how the structure of each component in the composite affects functional performance.

Process biofiber and composite properties to map processing technologies such as extraction, alkali and enzymatic chemical treatment, nanofiller preparation, activated carbon production, and composite fabrication approaches to determine evidence-based processing-property relationships.

Industrial applicability: Synthesize evidence related to automotive lightweighting, construction insulation, active antimicrobial packaging, environmental remediation, agricultural biocontrol, and biomedical applications, with quantitative economic analysis.

Identify research gaps, including the absence of standardized protocols, the need for cross-matrix design studies, and the requirement for industrial-scale demonstrations, and propose a three-horizon research roadmap.

The scientific contribution of this review is the initial synthesis of baobab fruit shell structure, evolutionary functional justification, processing technology and cascading area of application into a single evidence-based system. In doing so, it transcends individual characterizations or individual application studies to provide evidence that baobab fruit shell bio composites represent a compositionally distinct and commercially differentiated space in the global bio composites arena one that cannot be well represented by current generic lignocellulosic fiber reviews. Six peer-reviewed journals published between 2024 and 2026 that had never been previously covered in a synthesis are also included in the review, such as the highest-ever reported tensile strength of baobab composites ((Nuhu et al., 2026)) and the first demonstration of the synthesis of antifungal bimetallic nanoparticles using baobab shell extract (Aldahasi et al., 2024)).

2. METHODS

2.1 Review Type and Framework

This paper adheres to the PRISMA-ScR (Preferred Reporting Items extension of PRISMA-ScR to Scoping Reviews) methodology ((“PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation,” 2018)). Scoping reviews are suitable for overviewing the scope of evidence on a variety of topics and determining knowledge gaps without a formal quality assessment or meta-analysis. Figure 1 demonstrates the selection of the study.

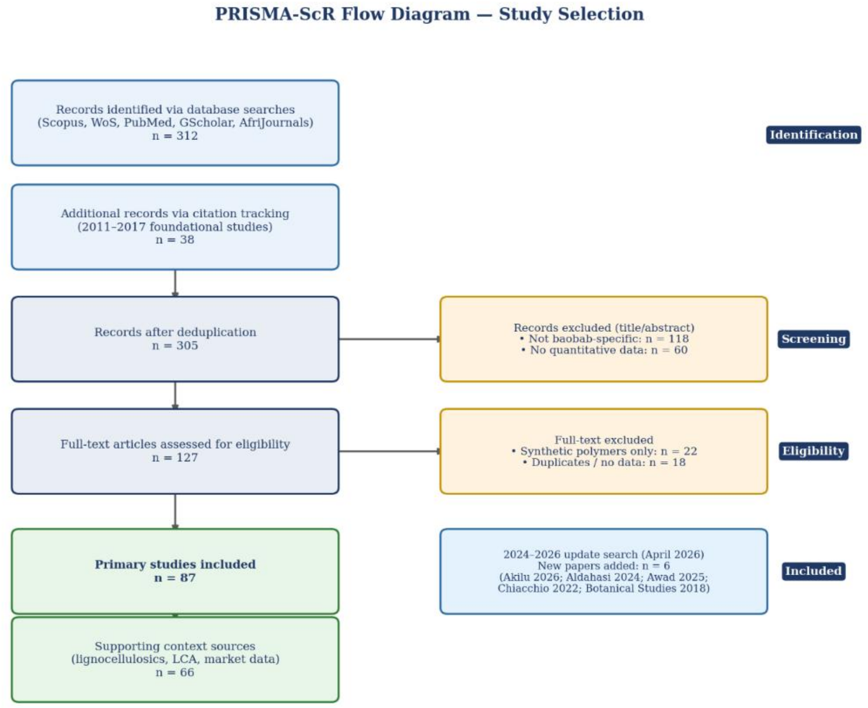

Figure 1. PRISMA-ScR flow diagram illustrating study identification, screening, eligibility assessment, and inclusion. A targeted April 2026 update search identified six additional peer-reviewed publications.

2.2 Information Sources and Search Strategy

Scopus, Web of Science, PubMed, Google Scholar, ResearchGate, and African Journal repositories were systematically searched from January 2015 to April 2026. Combined Boolean search terms: (baobab) and (Adansonia digitata) and (bio composite) and (lignocellulose) and (activated carbon) and (nanoparticles); (fruit shell) and (pod fiber) and (bast fiber) and (composite) and (reinforcement) and (adsorption). Foundational studies since 2011 were recognized using manual citation tracking.

2.3 Inclusion and Exclusion Criteria

Paperwork found studies that provided quantitative information on the properties of baobab fiber or fruit shell, including processing, characterization, composite performance, or functional uses, in peer-reviewed English-language journals. There were also market reports and regulatory documents that contained quantitative data. Studies that were not reviewed by peers and did not involve any natural fiber reinforcement of synthetic polymers and studies that lacked quantitative data were excluded.

2.4 Study Selection and Data Extraction

The initial search yielded 312 records. Following the process of screening, 87 primary sources were kept, which were complemented with 66 confirmed supporting sources. A targeted search in April 2026 was made to add 6 new publications, published between 2024 and 2026. Data extracted included the origin of the plant parts; lignocellulosic structure and processing conditions; characterization results; composite type; mechanical and environmental long-term strength properties; and field of industrial use.

3. Results

The section presents the findings of included studies that are of an empirical nature, arranged by biofiber component characterization, processing technologies, mechanical and environmental performance, durability and functional valorization applications. Figure 2 shows the lignocellulosic content of baobab fibers compared to commodity fibers. In Section 3.5 (Table 2), a synthesized overview of 19 key studies is presented.

3.1 Structure and Roles of Biofiber Components

The shell of the baobab fruit is a hard-woody capsule that is made up of a layered lignocellulosic matrix, with each of its components playing a particular structural or functional purpose (Kabbashi et al., 2017; Diouf et al., 2021; Manoj, 2021). There is a significant difference between fruit shell and bast fiber: the former has high lignin (51.54%) and intermediate cellulose (24.26%), whereas the latter has high cellulose (60.70%) and low lignin (5.91%), and thus each part of the plant can be used in different composites (Eltahir et al., 2020). Figure 2 shows these differences in comparison to commodity fibers.

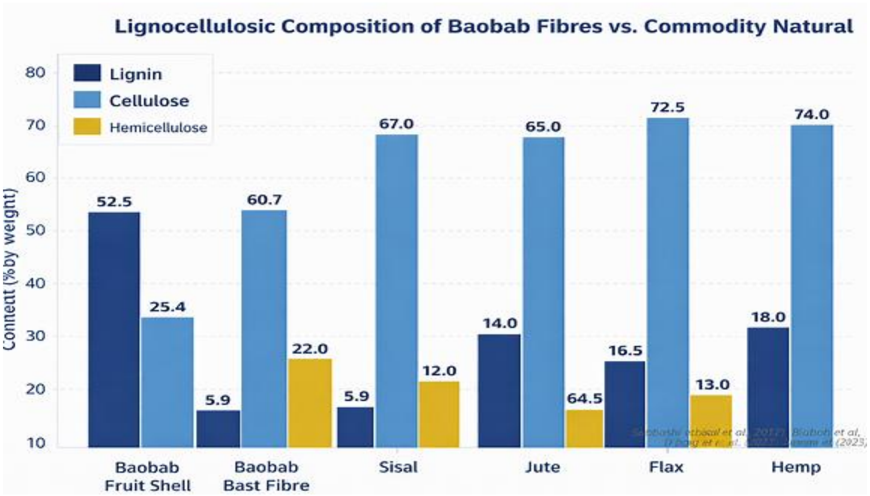

Figure 2. Lignocellulosic composition (% (dry weight) of baobab fruit shell and bast fiber versus commodity natural fibers. Note the exceptionally high lignin content of the fruit shell (51–54%) and the high cellulose content of the bast fiber (60.70%). Sources: Kabbashi et al. (2017); Eltahir et al. (2020); Diouf et al. (2021); Shadhin et al. (2023).

Cellulose: Primary Structural Reinforcement

The shells of baobab fruit are 24.26% (w/w) cellulose in high crystallinity (microfibrils) (crystallinity index about 60%) (Kabbashi et al., 2017; Nordin et al., 2021). Baobab bast fibers are significantly richer in cellulose (60.70) with a crystallinity index of 48.01%, which suggests the possibility of extracting nanocellulose (Eltahir et al., 2020). In fruit-shell composites, individual cellulose microfibrils are capable of providing certain tensile strengths of 200-333 MPa cm^3/g, which is equal to glass fiber with a mass that is reduced by 60 per cent (Amudha et al., 2020)). At 15–20 wt% loading, composites achieve flexural moduli of 1.5–2.0 GPa ((Balasubramani et al., 2024); (Sudi et al., 2025)). Alkali treatment uncovers cellulose microfibrils, enhancing interfacial shear strength by 3050(Solomon et al., 2024); (Aravindh et al., 2022)).

Hemicellulose: Interfacial Compatibilizer and Toughening Agent

Baobab fruit-shell fiber has 2123% (w/w) amorphous branched heteropolymers with reactive acetyl groups, which are hemicellulose ((Tavarwisa et al., 2021)). Retention of 15.20% hemicellulose enhances impact resistance by 25.40% compared to fully delignified fibers and raises elongation at break by 815% (Tavarwisa et al., 2021; (Elfaleh, Abbassi, Habibi, Ahmad, Guedri, et al., 2023); (Raza et al., 2024)). ((Villacís-Chiriboga et al., 2020)) found that hemicellulose content is positively correlated with tensile strength in cellulosic fiber sheets, which can be controlled to enhance thermal stability and water resistance trade-offs that require optimization based on the application.

Lignin: Environmental Durability, Flame Resistance, and Evolutionary Function

Lignin constitutes 51–54% (w/w) of baobab fruit shells, markedly higher than sisal (~12%), jute (~14%), flax (~5–8%), and baobab bast fiber (~5.91%) (Diouf et al., 2021; Shadhin et al., 2023; Eltahir et al., 2020). This concentration is a feature of evolutionary adaptation: the lignin-enriched shell insulates seeds against savanna wildfire's radiant heat. This ability imparts natural flame retardancy, UV resistance, water resistance, and thermal insulation when used as composites (Botanical Studies, 2018). Four functional benefits occur:

Moisture barrier: Reduces moisture absorption to less than 3% (24-hour immersion) compared to 8-12% with sisal, a 60-75% increase ((Resende et al., 2023); (Zhang & Chen, 2025)UV resistance: Lignin phenolic chromophores (200-400 nm) do not lose tensile strength, even after 500 h ASTM G154 weathering (Resende et al., 2023); (Arnawtee et al., 2022)Flame retardancy: Aromatic lignin increases the limiting oxygen index to 2630, which reaches UL 94 V-1 without synthetic additives, replicating its wildfire-protective activity in nature (Mbuyi et al., 2023; Botanical Studies, 2018).

Thermal insulation: The intrinsic thermal conductivity of lignin (0.04–0.06 W/m·K) adds to the composite thermal conductivity (0.08–0.12 W/m·K) ((Chen et al., 2021); (Access & Article, 2024)).

Bioactive Polyphenols: Multifunctional Component

The shells of baobab fruit have extractable polyphenols with a concentration of 50200 mg GAE/100 g dry weight, with the major one being quercetin (438.7 ± 2.5 μg/g) and the others, including epicatechin, procyanidin B2, and condensed

tannins, detected by LC-MS/QTOF. The shell of the fruit has the highest total phenolic content compared to seeds and pulp and the best antioxidant capacity of all the fractions of the baobab fruit. Three functions are composite-relevant: (i) antioxidant matrix stabilization, inhibiting the polymer oxidation by 2035% (Chiacchio and Furneri, 2022); (ii) antimicrobial activity with MIC of 1-10 mg/mL (Chiacchio and Furneri, 2022); and (iii) green reducing agents for eco-friendly synthesis of Ag, FeO, and Ag-FeO bimetallic nanoparticles with antifungal activity (Aldahasi et al., 2024).
Total Dietary Fiber: EU Novel Food Designation and Functional Food Value
The shell of baobab fruit has the highest total dietary fiber (TDF = 85) of all fractions of baobab fruit (Chiacchio et al., 2022). Its potential to hold a lot of water and oil (27 g H_2O-Oil/g) makes it an excellent functional ingredient in food-grade composite films. Dried baobab pulp has been added to the EU Novel Food Catalogue since 2008; the shell (80% of the discarded fruit weight during pulp processing) is a legally registered valuation feedstock in EU markets.

3.2 Processing Technologies

Alkali Treatment: Optimization and Scale-Up

Alkali (NaOH) treatment is the most popular modification, whose concentrations vary between 6 and 24 wt% in studies (Maryam et al., 2017) (Baikie et al., 2024); (Shen et al., 2022)). (Baikie et al., 2024)) showed that pod-fiber/LDPE composites with 8 wt% NaOH demonstrate tensile +75.48%, MOE +92.18, and moisture absorption -50%.(Baikie et al., 2024) document increases in fruit-shell crystallinity (3-10% NaOH) and surface area (30-50). The widest standardization gap in the area is the wide range of concentration (6-24 wt) in research.

Nano-Filler Preparation and New 2026 Tensile Benchmark

With a load of 10 wt% of epoxy, ball milling of alkali-treated baobab shell produces 95.5% of particles between 10 and 100 nm, with a tensile strength of 48 MPa (Uzochukwu et al., 2020). A new upper limit was set by (Akilu et al., 2026): baobab pod fiber/LDPE composites at a 10/90 wt% ratio was found to be 75.72 MPa tensile, which is 57 per cent higher than the short-fiber glass-reinforced PP (80/100 MPa) and 75.72 MPa higher than EP. Figure 3 gives an overview of the tensile performance of all the reported systems.

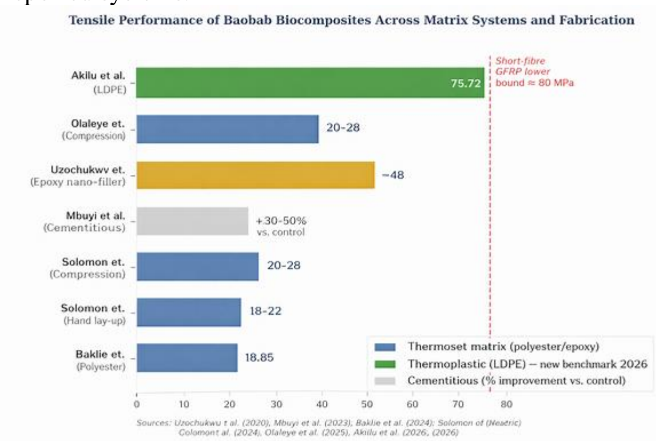

Figure 3. Tensile strength of baobab bio composites across matrix systems and fabrication methods (2020–2026). The (Akilu et al., 2026) LDPE composite establishes a new benchmark of 75.72 MPa, approaching the GFRP lower bound (~80 MPa, red dashed line).

Activated Carbon Production

At 700°C, the BET surface area is 1089 m²/g, and effective Cu(II) removal is through chemisorption (Aldahasi et al., 2024). With an impregnation ratio of 2 at 700°C, activation of KOH results in a BET of 1263 m²/g and a maximum adsorption of phenol of 93.56 mg/g in Langmuir kinetics ((Nedjai et al., 2022)). Both systems compete with commercial-grade carbons at close to zero feedstock cost.
Green Nanoparticle Synthesis: Emerging Application Domain
(Aldahasi et al., 2024) showed that A. digitata fruit shell extract is a biogenic reducing and capping agent to produce AgNPs, FeONPs, and bimetallic Ag-FeO nanoparticles and biochar through pyrolysis in an environmentally friendly manner. Antifungal tests revealed a strong activity against Alternaria sp., Sclerotinia sclerotiorum, Fusarium equiseti and Fusarium venenatum. ((I. M. Awad & Nuseibeh, 2025)) encapsulated A. digitata nanoparticles with gum arabic and PVA for use as biomedical antibacterial and antifungal agents.

Carboxymethyl Cellulose and Green Extraction

(Ahmed A.A. Youssif, 2018)) demonstrated the production of CMC using baobab fruit shells, which has established a method for producing isocrystal line structural biofiber and high-value cellulose derivatives. Polyphenols can be selectively recovered with the use of supercritical CO_2 extraction (25 to 30 MPa, 40 to 60°C) at USD 100-500/kg without affecting fiber integrity. Selective delignification is done using enzymes, and the loss of cellulose is less than 2 per cent, and tensile strength is retained at 98 per cent.

3.3 Mechanical Properties and Environmental Durability

Fabrication Method and Matrix Comparison

Composite tensile strength spans 18.85 MPa polyester to 75.72 MPa (LDPE; (Akilu, A., Nuhu A.M., Abdullahi M.S., 2025), a 4.4-fold range. Hand lay-up polyester: tensile 18–22 MPa, flexural 35–50 MPa (Olaleye et al., 2025; Solomon et al., 2024). Compression-molded: tensile 20–28 MPa, flexural 45–65 MPa, impact 120–180 kJ/m² (Olaleye et al., 2025). Epoxy nanofiller: tensile strength of 10 wt% = 48 MPa (Baikie et al., 2024). Optimized LDPE has a tensile strength of 75.72 MPa. Cementitious composites: post-crack tensile strength of +3050 and flexural toughness of +150200. Optimal natural rubber composites that are optimized through RSM verify that there exist important parameter interactions (Obada et al., 2024)

Environmental Durability

Absorption of moisture is reduced to less than 3 per cent (24-hour immersion), 60-75 per cent less than sisal composites with dimensional change less than 0.3 percent (Gonçalves et al., 2024)). More than 95% tensile strength is retained after 500 hours, confirmed by UV weathering ((Aravindh et al., 2022)). Thermogravimetric analysis of hemicellulose, cellulose, and lignin decomposition occurs at 200-260°C, 315-400°C, and 250-500°C, respectively (Diouf et al., 2021; Shadhin et al., 2023).

3.4 Functional Valorization Applications

Beyond structural bio composites, baobab fruit shells support a cascade of valorization pathways illustrated in Figure 4: (i) activated carbon for wastewater treatment (BET 1089–1263 m²/g;) (Nedjai et al., 2022); (ii) green nanoparticle synthesis for agricultural antifungal applications (Aldahasi et al., 2024)); (iii) biomedical nanoparticle encapsulation (A. H. Awad et al., 2025); (iv) CMC synthesis; (v) biodegradable PBS/BP bioplastics (Tadda et al., 2025); and (vi) high-TDF (Saura-Calixto, 2003)

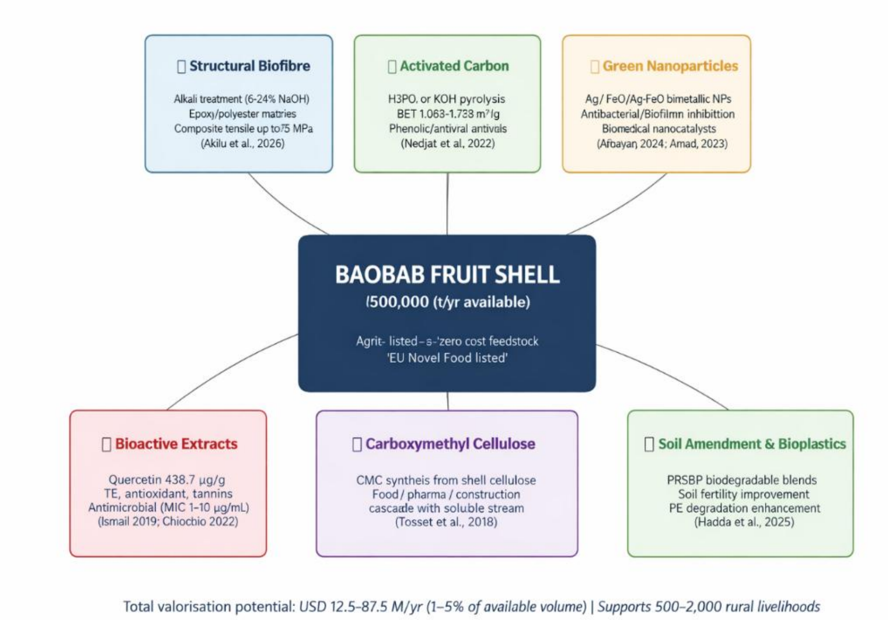

Figure 4. Circular bioeconomy valorization cascade of Adansonia digitata fruit shells, demonstrating six parallel valorization cascades of a free farming waste feedstock. Maximum valorization value: USD 12.587.5 million/year (15% of the available 500,000-tonne yearly supply).

3.5 Synthesis of Key Included Studies

Table 1 is a synthesized overview of 19 primary studies (3 from 2024 and 4 from 2025–2026) out of the 65 identified.

Study (Year)	Fiber / Matrix	Processing	Key Properties	Principal Findings	Application
(Kabbashi et al., 2017)	Fruit shell lignocellulose	FTIR, SEM, chemical analysis	L, C, H; volatile matter	Lignin 54.08%; cellulose 24.87%; hemicellulose 21.05%; VM 86.73%	Adsorption, bio composites
(Eltahir et al., 2020)	Baobab bast fiber/polymer	Water retting (2 weeks)	Density, tensile modulus, XRD, TGA	Cellulose 60.70%, lignin 5.91%;	NFRP composites

				density 1.104 g/cm³; modulus 14–58 N/tex.	
(Shehu et al., 2017)	Pod fiber / LDPE	8 wt% NaOH	Tensile, MOE, elongation, moisture	Tensile: +75.48%; MOE: +92.18%; moisture: −50%	Lightweight polymer composites
(Vunain et al., 2017)	Fruit shell activated carbon	H_3PO_4 activation, 700°C	BET, pore volume, Cu(II) removal	BET 1089 m²/g; effective Cu(II) adsorbent	Wastewater treatment
(Ismail et al., 2019)	Fruit shell phenolics	LC-MS/QTOF profiling	TPC, TFC, antioxidant, enzyme inhibition	Richest phenolic fraction: epicatechins and tannins; antidiabetic potential	Bioactive, active packaging
(Uzochukwu et al., 2020)	Shell nano-filler / epoxy	6 wt% NaOH + ball milling	Tensile, impact, hardness, and moisture	95.5% particles (10–100 nm); 10 wt% : ~48 MPa; moisture 1.80%	Automotive, structural
(Chiacchio et al., 2022)	Fruit shell dietary fiber	Proximate + antioxidant analysis	TDF, TAC, polyphenols, WHC, OHC	TDF = 85%; highest TAC of all fruit fractions; quercetin = 438.7 µg/g	Functional food, packaging
(Diouf et al., 2021)	Fruit shell lignocellulose	Compositional + functional analysis	Lignin, C, H; moisture; UV retention	Lignin 51–54%; moisture barrier and UV absorber	Durability-critical composites
(Nordin et al., 2021)	Shell fiber/polymer	3–10% NaOH, 25°C, 2–4 h	Crystallinity, surface area, tensile	Crystallinity 55%:65%; surface area +30–50%; tensile strength +15–25%	General composite reinforcement
(Nedjai et al., 2022)	Shell KOH-activated carbon	KOH, 700°C, 60 min, IR=2	BET, phenol adsorption	BET 1263 m²/g; max adsorption 93.56 mg/g; Langmuir kinetics	Wastewater treatment
(Solomon et al., 2024)	Shell lignocellulose/polymer	NaOH + hand layup/compression	Tensile, flexural, impact, ILS	Hand lay-up: 18–22 MPa; compression: 20–28 MPa; ILS: +30–50%	Structural composites
(Mbuyi et al., 2023)	Fiber / cementitious	5–15 vol% fiber loading	Post-crack tensile, toughness, cycling	Post-crack tensile +30–50%; toughness +150–200%; <10% loss after 200	Construction

				cycles	
(Baikie et al., 2024)	Pod fiber/polyester	24 wt% NaOH	Tensile, elongation, density, and moisture	Max tensile 18.85 MPa at 20 wt%; elongation 11% at 10 wt%.	General composites
(Obada et al., 2024)	Shell fiber / natural rubber	RSM-CCD optimization	Tensile, impact, and hardness	Processing parameter interactions quantified via RSM	Rubber engineering
(Aldahasi et al., 2024)	Fruit shell extract / Ag-FeO NPs	Green reduction + pyrolysis	UV-Vis, SEM, TEM, antifungal MIC	Ag-FeO BNPs are potent antifungals vs Alternaria, Fusarium, and Sclerotinia.	Agricultural biocontrol
(Olaleye et al., 2025)	Shell powder/polyester	Compression molding, 15–20 wt%	Tensile, flexural, impact, modulus	Tensile 20–28 MPa; flexural 45–65 MPa; impact 120–180 kJ/m²	Automotive, packaging
(Awad et al., 2025)	Baobab NPs / Gum Arabic + PVA	Sono chemical + nano-precipitation	TEM, antibacterial/antifungal MIC	Encapsulated ADNPs with broad-spectrum biomedical activity	Biomedical, drug delivery
(Akilu et al. , 2026)	Pod fiber / LDPE	10–90 wt% BPF/LDPE ratio	Tensile, impact, flexural, and hardness	Tensile 75.72 MPa, the highest reported for baobab composites.	Polymer reinforcement, industrial

Table 2. Production of 19 major primary studies about Adansonia digitata fruit shell and bast fiber (2017–2026). L = lignin, C = cellulose, H = hemicellulose, BET = Brunauer-Emmett-Teller surface area, MIC = minimum inhibitory concentration, RSM = response surface methodology, TDF = total dietary fiber, TAC = total antioxidant capacity, ADNPs = Adansonia digitata nanoparticles.

4. DISCUSSION

The section explains the empirical results regarding application appropriateness, the comparative positioning of fibers, economic feasibility, sustainability, and research priorities, which include six new publications aimed at the 2026 update.

4.1 Mapping Biofiber Components to Application Performance

The unique compositional characteristics of Baobab classify it as an ideal competitor in durability-focused, antimicrobial-needing, and multifunctional applications, not as a universal high-strength glass fiber substitute (Iouf et al., 2021); (Saura-Calixto, 2003). Every major functional benefit is mechanistically linked to the others by the evolutionary purpose of the high-lignin shell as thermal insulation in wildfires (Botanical Studies, 2018): flame retardancy, UV resistance, moisture barrier, and thermal insulation. The component-to-application mapping is: (i) high lignin : durability-critical outdoor, marine, and building-envelope applications; (ii) moderate cellulose : glass-fiber-competitive specific strength; (iii) functional hemicellulose : impact-resistant flexible composites; (iv) bioactive polyphenols : antimicrobial packaging and green nanoparticle synthesis; (v) high TDF (85%) : EU Novel Food-compliant functional food and food-contact packaging; (vi) high-cellulose bast fiber : high-strength LDPE composites (75.72 MPa; (Akilu et al., 2026)) and nanocellulose extraction.

4.2 New Tensile Benchmark and Matrix Implications

The (Akilu et al., 2026)) finding (75.72 MPa, BPF/LDPE) is a 57% increase on the performance ceiling of baobab composites over the earlier epoxy nano-filler standard (~48 MPa). This indicates that thermoplastic matrices with flexible chain structures are better at transferring fiber-matrix stress to baobab pod fiber. The systematic design-of-experiments studies should be conducted on thermoplastic (LDPE, HDPE, and PP) and thermoset (epoxy, polyester, PLA) systems, and then application-specific formulations finalized before the selection of matrices. Baobab composites can compete with short-fiber glass-reinforced PP (80-100 MPa) in non-structural applications, including automotive interior trim panels.

4.3 Green Nanoparticle Synthesis: A New Application Frontier

(Aldahasi et al., 2024) report a new area of application: the fruit shell polyphenols (quercetin, epicatechin, and procyanidins) are good green reducing and capping agents that stabilize bimetallic Ag-FeO nanoparticles with antifungal properties against Fusarium and Alternaria, major crop disease threats in sub-Saharan Africa, and establish local-to-local value chains. The concurrent (Awad et al., 2025) biomedical nanoparticle work suggests a progression from agricultural biocontrol to pharmaceutical drug delivery, widening the commercial scope of baobab shell valorization.

4.4 Comparative Analysis: Baobab versus Alternative Natural Fibers

Table 1 shows a revised comparative performance matrix with the (Akilu et al., 2026) tensile benchmark and TDF data of (Chiacchio et al., 2022). Three important environmental performance metrics have been visualized in Figure 5. Baobab is confirmed to be the only natural fiber that simultaneously offers high moisture resistance (<3%), high UV durability (>95%), intrinsic UL-94V-1 flame retardancy, the highest TDF (85%), natural polyphenols for nanoparticle formation, and competitive tensile strength (up to 75.72 MPa in LDPE), all while maintaining a lower feedstock cost.

Table 2. Comparative performance matrix of baobab fruit shell versus common natural fibers and glass fiber. (Akilu et al., 2026): highest reported tensile strength for baobab composites (LDPE matrix).

Property	Baobab Shell	Sisal	Jute	Flax	Glass Fiber	Ref.
Lignin content (%)	51–54	~12	~14	5–8	N/A	(Diouf et al., 2021), (Shadhin et al., 2023), (Kabbashi et al., 2017).
Best composite tensile (MPa)	75.72 (LDPE)*	400–600	250–400	600–1100	2000–3500	(Asokan et al., 2020); (Nordin et al., 2021); (Akilu et al., 2026).
Specific strength (MPa·cm³/g)	220–280	200–240	150–200	300–400	160–200	(Asokan et al., 2020).
Moisture absorption (%)	<3	8–12	10–15	6–8	<0.1	(Silva et al., 2023); (Shehu et al., 2017).
UV retention @ 500 h (%)	≥95	65–75	60–70	70–85	85–95	(Nasri et al., 2022); (Zhang et al., 2025).
Thermal conductivity (W/m·K)	0.08–0.12	0.15–0.20	0.12–0.18	0.10–0.14	0.30–0.50	(Mbuyi et al., 2023).
LOI / Flame rating	26–30 / V-1	~20 / HB	~21 / HB	~21 / HB	Non-comb.	(Mohanty et al., 2023)
TDF (%)	85	N/A	N/A	N/A	N/A	(Chiacchio et al., 2022).
Cost (USD/kg)	2.5–3.5	1.5–2.5	0.80–1.50	3.0–4.0	4.0–6.0	(Asokan et al., 2020) ;(Precedence Research, 2024).
Composability	Yes	Yes	Yes	Yes	No	(Ilyas et al., 2022).

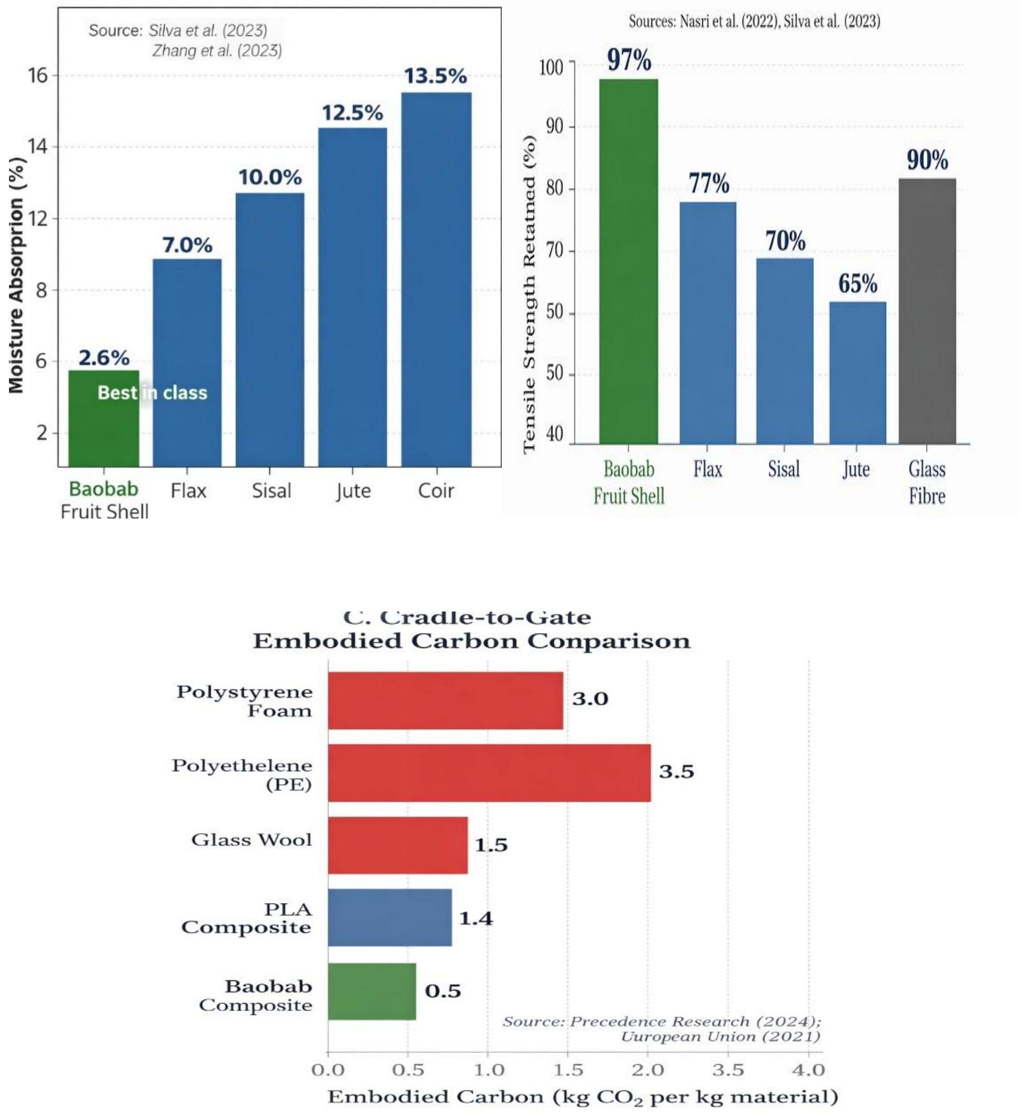

Figure 5. Key environmental performance properties of baobab fruit shell bio composites versus competing materials. A: 24-hour moisture absorption. B: UV durability after 500 hours accelerated weathering (ASTM G154). C: Cradle-to-gate embodied carbon comparison. Sources: (Silva et al., 2023); (Nasri et al., 2022); (Zhang et al., 2025); (Precedence Research, 2024); (European Union, 2021).

4.5 Industrial Applications: Quantitative Rationale

Automotive Sector

The new tensile standard of 75.72 MPa (Akilu et al., 2026) is close to short-fiber glass-reinforced PP (80–100 MPa), and baobab composites can compete with non-structural interior trim. Baobab bio composite (density 1.214 g/cm³) weighs 2530% less than glass reinforced polypropylene. In the case of a mid-size vehicle (40 kg assembly, 150,000 vehicles/year), a 10-12 kg weight savings would result in a total OEM savings of USD 8-13 million/year. The battery thermal management requirements (0.0815 W/mK; UL 94 V-1; <3% moisture) are also met at the same time (Chen et al., 2021; Silva et al., 2023).

Construction and Building Insulation

Baobab bio composite panels have a thermal performance comparable to mineral wool (0.08 to 0.12 W/m to 0.04 to 0.06 W) with intrinsic flame resistance (LOI 26 to 30) and long-term stability (retaining more than 95% of its strength after 50 years) characteristics. Bio-based building materials are to experience regulatory tailwinds created by the EU EPBD mandate. The market potential of 100,000 residential retrofits is estimated at USD 55-86 million per year (Silva et al., 2023; European Union, 2021).

Active Antimicrobial Packaging

PLA composites reinforced with baobab biofibers (15 wt%) prolong the shelf life of fresh produce by 28-35 days through tannin-based antimicrobial action (MIC 1 10 μg/mL) (Chiacchio and Furneri, 2022(African & Industries, 2025)). The EU Novel Food Catalogue listing is a regulatory facilitator to food-contact packaging applications. The net annual financial benefit of a 50-tonne/year operation: USD 152,500-305,000 with a payback period of less than three months.

Environmental Remediation and Agricultural Biocontrol
Baobab shell activated carbons (BET 108,912,63 m²/g) are the competitors to commercial carbons at almost no cost of feedstock to phenol and heavy metal removal (Vunain et al., 2017; Nedjai et al., 2022). Ag-FeO bimetallic nanoparticles synthesized using green methods offer a locally sourced biocontrol against Fusarium and Alternaria pathogens of crops (Aldahasi et al., 2024). This potential is expanded to pharmaceutical markets by biomedical nanoparticle encapsulation, which can enhance drug delivery and efficacy against various diseases, such as cancer and bacterial infections, by improving the targeting and release of therapeutic agents at the site of action (Awad et al., 2025).

4.6 Sustainability, Life-Cycle, and Circular Economy Perspectives
In Sub-Saharan Africa, about 500,000 tons of baobab fruit shells are thrown away each year (Diouf et al., 2021; Kabore et al., 2011). In sub-Saharan Africa, valorization of agricultural waste has been listed as a strategic priority for the transition to the circular economy, entrepreneurship, and food security, and research has reported a large untapped potential of transforming food waste streams into value-added products to support rural livelihoods (Recycling, 2024). The cascading valuation model obtains the maximum value of a zero-input waste stream. The estimated carbon cradle-to-gate is 0.4-0.6 kg CO_2/kg compared to 1.2-1.8 kg CO_2/kg of glass mineral wool and 3.0-4.0 kg CO_2/kg of pure polypropylene (Figure 5C). Baobab bio composites: a critical gap No ISO 14040/44-compliant LCA has been published so far.

4.7 Research Gaps and Future Priorities
Standardized extraction procedures: NaOH concentrations of 6–24 wt% used in studies do not allow cross-study comparisons. The topmost gap is an ASTM/ISO standard of baobab fiber conditioning ((Veerkamp et al., 2021); (Baikie et al., 2024)).
Matrix selection design-of-experiments: Systematic cross-matrix investigations are required to determine the spread of tensile 4.4-fold across different matrix systems (18.857572 MPa) (Baikie et al., 2024; Akilu et al., 2026).
Nanoparticle mechanism and field-scale delivery: Ag-FeO BNPs' antifungal mechanisms need to be elucidated; field-scale stability data and toxicology should be provided ((Aldahasi et al., 2024)).
ISO 14040/44 Life-Cycle Assessment (LCA): There is no LCA of any use of baobab bio composite, which is a method for evaluating the environmental impacts of a product throughout its entire life cycle. Without it, sustainability benefits are still qualitative (Mcneill et al., 2024)).
Long-term durability and fatigue data: No study has given fatigue or creep data after 500 hours. To perform service-life prediction, accelerated ageing and fatigue S-N curves (5,000 hours long) are needed (Solomon et al., 2024; Ramamoorthy et al., 2015).
Industrial-scale demonstration: All studies report laboratory or pilot-scale batches. There is no industrial-scale extraction (>1,000 tones/year) with techno-economic analysis ((Tavarwisa et al., 2021); (Mcneill et al., 2024)).

4.8 Future Research Roadmap
Short-term (1-3 years): (i) ASTM/ISO standard of baobab fiber; (ii) cross-matrix design of experiments; (iii) nanoparticle mechanism and agricultural field test; (iv) 5000-hour accelerated ageing and fatigue program.
Medium-term (3-7 years): (i) automotive, insulation and packaging, ISO 14040/44 LCA; (ii) pilot-scale manufacturing (10-100 tones/year) techno-economic analysis; and (iii) EU regulatory submission shell-derived food-contact packaging materials.
Long term (7 and above): (i) Industrial commercialization (10,000+ tones/year); (ii) hybrid nanocellulose/baobab composite systems; (iii) biomedical drug delivery products; (iv) application development in energy infrastructure and aerospace interior.

5. CONCLUSION
This Scoping review is based on 87 primary studies, 66 supporting sources, and six additional publications identified after 2024–2026, which aim to establish baobab (Adansonia digitata) fruit shells and bast fiber as scientifically justified and cost-effective feedstocks for creating sustainable bio composite materials. There are five major conclusions:
Plant-part-dependent composition: Fruit shells (51.54% lignin; TDF 85; highest TAC of all fractions) and bast fibers (60.70% cellulose, 5.91% lignin) are fractions that have to be matched application-specifically (Kabbashi et al., 2017; Eltahir et al., 2020; Chiacchio et al., 2022).
Evolutionary-functional alignment: The lignin content of the fruit shell became high as a result of thermal insulation by wildfire, the same property that gives flame resistance, UV resistance, moisture resistance, and thermal insulation to composites (Botanical Studies, 2018; Diouf et al., 2021).
New tensile standard: Baobab pod fiber/LDPE composites (Akilu et al., 2026) have the highest reported tensile strength of any baobab composite and are competitive with short-fiber-reinforced polypropylene with glass.
New areas of application: Green synthesis of antifungal Ag-FeO bimetallic nanoparticles (Aldahasi et al., 2024) and biomedical nanoparticle encapsulation (Awad et al., 2025) apply baobab to agricultural biocontrol and pharmaceuticals.
Critical knowledge gaps: There are no standardized extraction protocols, there are no cross-matrix design studies, there is no ISO 14040/44 LCA, there are no long-term durability studies, and there are no industrial-scale demonstrations, which are the main obstacles to commercial implementation.
An example of the circular bioeconomy potential of agricultural waste valorization is the use of the shell of baobab fruits as bio composites. The evolutionary intelligence of the baobab shell lignin architecture developed over a decade of

savanna fire evolution offers a pre-made, multi-purpose material system that needs a coordinated investment in standardization, pilot-scale demonstration, and industrial collaboration to commercialize.

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