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# Diversity and Ethnomedicinal properties of Combretaceae: A Global synthesis of species, uses, and evidence

**Yogesh Chandra[1*], Mohammad Arshad[1], Umashankar Chandra[1], Dolamani Sahu[1], Ishwar Prasad Sahu[2], Sandeep Shukla[1]**
[1] Department of Botany, Govt. E.V.P.G. College, Korba, Chhattisgarh, India
[2] Department of Botany, Govt. Naveen College, Kusmura, Chhattisgarh, India
**Corresponding Author:** Yogesh Chandra
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**Abstract**
The family Combretaceae, comprising approximately 20 genera and over 600 species worldwide, represents a vital botanical lineage with significant ecological, cultural, and pharmacological importance. Genera such as *Terminalia*, *Combretum*, and *Anogeissus* are not only keystones in tropical ecosystems but also form the basis of diverse ethnomedicinal traditions across Africa, Asia, and South America. Despite their wide utilization in indigenous healthcare and livelihood systems, comprehensive global syntheses on the diversity and ethnopharmacological potential of Combretaceae remain limited. This review integrates published data from ethnobotanical surveys, phytochemical screenings, and pharmacological evaluations retrieved from major scientific databases, complemented by conservation assessments from international biodiversity sources. The analysis highlights taxonomic richness and geographic hotspots, documents cross-cultural medicinal applications (cardiovascular, hepatic, antimicrobial, and dermatological), and synthesizes evidence from phytoconstituents such as tannins, flavonoids, and triterpenoids. Clinical and preclinical findings, particularly on *Terminalia arjuna* for cardiovascular health and *T. chebula* for gastrointestinal disorders, underscore the therapeutic relevance of the family. Furthermore, the review emphasizes the role of Combretaceae in sustainable livelihoods through non-timber forest product (NTFP) value chains, while addressing challenges of overharvesting, adulteration, and habitat degradation. Conservation strategies, including community-based forest management and domestication initiatives, are discussed in light of international biodiversity policies. In conclusion, Combretaceae emerges as a global bio-cultural resource with immense potential to bridge traditional knowledge, modern pharmacology, and sustainable development goals. Future research should focus on standardized clinical trials, bioprospecting with ethical frameworks, and climate-resilient management of species diversity.

**Keywords:** Combretaceae, ethnomedicine, biodiversity, terminalia, combretum, livelihoods, pharmacology, conservation

## Introduction

The family Combretaceae, belonging to the order *Myrtales*, is a prominent group of flowering plants comprising approximately 20 genera and 600–650 species worldwide (Mabberley, 2017; APG IV, 2016) [2, 16]. Members of this family are widely distributed across tropical and subtropical regions of Africa, Asia, Australia, and South America. Several genera—*Terminalia* (≈200 species), *Combretum* (≈370 species), and *Anogeissus* (≈10–12 species)—dominate the taxonomic and ecological spectrum, with additional representation from mangrove-associated genera such as *Lumnitzera*, *Laguncularia*, and *Conocarpus* (Kew POWO, n.d.). Species of Combretaceae play critical roles in ecosystem functioning, serving as keystone taxa in dry tropical forests, savannah woodlands, riparian ecosystems, and mangrove habitats.Beyond ecological significance, the family is of immense ethnobotanical and economic importance. Many species yield non-timber forest products (NTFPs) including fruits, bark, tannins, gums, and oils that contribute substantially to rural livelihoods (Cunningham, 2001) [6]. Importantly, several taxa such as *Terminalia arjuna*, *T. chebula*, *T. bellirica*, and *Combretum micranthum* hold prominent places in traditional medicine systems of Ayurveda, Unani, African ethnomedicine, and folk traditions across Latin America (Dhiman *et al*., 2021; Yakubu *et al*., 2020) [7, 27].

Traditional communities have long recognized the therapeutic value of Combretaceae species. Preparations derived from bark, fruits, seeds, and leaves are widely used for cardiovascular disorders, liver ailments, gastrointestinal problems, respiratory infections, skin diseases, and as antimicrobial agents (Friedman *et al*., 1986; Trotter & Logan, 1986) [9, 26]. For example, *Terminalia arjuna* bark decoctions are clinically employed in India as a cardioprotective remedy, while *T. chebula* and *T. bellirica* form the classical Ayurvedic formulation Triphala, used as a rejuvenator and digestive regulator (Sabu & Kuttan, 2002) [21]. In West Africa, *Combretum micranthum* ("kinkeliba tea") is consumed for diabetes and malaria, reflecting its integration into primary healthcare (Adjanohoun *et al*., 1996) [1]. The ethnomedicinal knowledge associated with Combretaceae is not only a reflection of cultural heritage but also an entry point for drug discovery and pharmacological validation. Secondary metabolites such as hydrolyzable tannins, flavonoids, and triterpenoids are abundant in this family and underpin biological activities ranging from antioxidant and hepatoprotective to antimicrobial and anticancer effects (Saleem *et al*., 2002) [22].

Over the past three decades, there has been an exponential increase in phytochemical and pharmacological studies on Combretaceae. Systematic reviews and laboratory investigations highlight strong antioxidant and cardioprotective effects of *Terminalia* species, antimicrobial and antiviral activities of *Combretum* extracts, and anti-inflammatory potential of *Anogeissus* spp. (Cock &

Cheesman, 2018) [5]. Notably, randomized controlled trials have validated the efficacy of *T. arjuna* in managing hypertension and ischemic heart disease (Dwivedi, 2007) [8]. Despite these advances, challenges remain regarding standardization, dosage safety, and clinical reproducibility. Many studies are geographically biased towards South Asia and West Africa, leaving under-documented regions such as South America and Oceania underrepresented (Dhiman *et al*., 2021) [7]. Furthermore, the lack of large-scale, multi-centered trials limits translation from ethnomedicine to evidence-based healthcare.

Beyond medicinal uses, Combretaceae species support sustainable livelihoods. Fruits of *T. chebula* and *T. bellirica* are harvested and traded widely as NTFPs in India, while *Anogeissus latifolia* yields gum ghatti, an internationally traded natural gum used in food and pharmaceuticals (Bhattacharya *et al*., 2017) [4]. In Africa, *Combretum* species are valued for firewood and construction timber, creating a nexus between subsistence and commercial use. However, unsustainable harvesting of bark and timber, coupled with deforestation, mining, and land-use change, poses serious threats to several species. For example, overexploitation of *T. arjuna* for bark in Indian forests has raised concerns of population decline (Singh *et al*., 2019) [23]. Conservation frameworks such as the Convention on Biological Diversity (CBD), Nagoya Protocol on Access and Benefit Sharing, and IUCN Red List assessments provide policy backdrops, yet local-level community engagement remains uneven (IUCN, n.d.). Thus, an integrated approach that balances ethnomedicinal utilization with biodiversity conservation is imperative for long-term sustainability.

Although Combretaceae has been the subject of numerous regional ethnobotanicals or phytochemical studies, there is a lack of comprehensive global syntheses integrating diversity, ethnomedicinal roles, pharmacological validation, conservation status, and livelihood contributions. A systematic, evidence-based review will:1.Provide a consolidated overview of species diversity and distribution.2.Document ethnomedicinal uses across cultural contexts with quantitative indices (Use Value, Informant Consensus Factor, Fidelity Level).3.Critically assess phytochemical and pharmacological evidence, including clinical trials.4.Evaluate contributions to rural livelihoods and sustainable development.5.Identify conservation challenges and policy gaps.6.Highlight research priorities, including underexplored species and future clinical pathways.

## Aim

This review seeks to: 1. Synthesize the taxonomic diversity and global distribution of Combretaceae. 2 Document and analyze ethnomedicinal knowledge and use patterns across different cultural landscapes. 3. Evaluate phytochemical and pharmacological evidence, bridging traditional claims with modern science. 4. Examine the role of Combretaceae in livelihoods, trade, and sustainability frameworks. 5. Identify conservation priorities and future research needs to guide policy and practice.

## Methods

This review adopts a systematic scoping review framework guided by the PRISMA 2020 statement (Page *et al*., 2021) [17], aiming to synthesize global evidence on the diversity, ethnomedicinal relevance, pharmacological properties, and livelihood linkages of the Combretaceae family. Although not a meta-analysis in all cases, the review follows structured protocols for literature identification, screening, eligibility assessment, and data extraction to ensure methodological rigor and minimize bias. The eligibility criteria included studies focused exclusively on Combretaceae species—whether wild or cultivated—that reported ethnobotanical uses, phytochemistry, pharmacological evaluations, clinical applications, or socio-economic significance. Publications from 1960 to 2025, including peer-reviewed articles, theses, conference papers, books, and authoritative reports in English and other major regional languages, were included. Studies lacking explicit taxonomic identification, methodological transparency, or ethnomedicinal/livelihood context were excluded.

The information sources comprised major academic databases such as Scopus, Web of Science, PubMed/MEDLINE, CAB Abstracts, AGRICOLA, ScienceDirect, SpringerLink, JSTOR, and Google Scholar, as well as specialized ethnobotanical and biodiversity repositories like Kew's Plants of the World Online (POWO), BSI Flora of India, FRLHT-TDU, and the IUCN Red List. Grey literature—including FAO, WHO monographs, and national biodiversity board reports—was also systematically reviewed. The search strategy employed a combination of taxonomic and thematic keywords using Boolean operators and truncations: ("Combretaceae" OR "Terminalia" OR "Combretum" OR "Anogeissus" OR "Lumnitzera" OR "Conocarpus") AND ("ethnobotany" OR "traditional medicine" OR "ethnomedicine" OR "phytochemistry" OR "pharmacology" OR "clinical trial" OR "livelihood" OR "NTFP" OR "conservation" OR "biodiversity"), filtered for the period 1960–2025 and restricted to English-language sources or translated abstracts.

The study selection process involved three stages: (1) independent screening of titles and abstracts by two reviewers, (2) full-text review of potentially relevant studies, and (3) final eligibility confirmation using the predefined criteria, with discrepancies resolved through discussion or third-party adjudication. The selection outcomes were summarized using a PRISMA flow diagram, detailing the number of records identified, screened, excluded, and included in the final synthesis.

A standardized data extraction template was developed in Microsoft Excel, capturing key parameters such as bibliographic details, species identity, ethnobotanical information (part used, preparation, indication, route of administration, cultural context), quantitative indices (Use Value [UV], Informant Consensus Factor [ICF], Fidelity Level [FL]), phytochemistry (major compounds, extraction method), pharmacology (bioassay type, model, dose, and results), clinical evidence (study design, sample size, dosage, outcomes), livelihood contribution (NTFP trade, market value, household income), and conservation status (IUCN category, national protection, major threats).

For quality assessment, preclinical studies were evaluated using ARRIVE and OHAT-adapted checklists, clinical studies with Cochrane's RoB-2 (for RCTs) and ROBINS-I (for observational studies), ethnobotanical reports were assessed based on sample size and documentation rigor, while conservation and livelihood data were graded for reliability depending on whether they were derived from official statistics or grey literature.

Finally, data synthesis combined descriptive statistics and visual analytics—such as heatmaps (species × pharmacological activities), chord diagrams (species × cultural uses), and Sankey diagrams (value chain flows)—to illustrate global patterns. Meta-analyses were performed where at least three clinical studies addressed comparable outcomes (e.g., *Terminalia arjuna* and hypertension). A narrative synthesis integrated ethnobotanical, pharmacological, and socio-economic findings across regions, providing a holistic understanding of the global role of Combretaceae in biodiversity conservation, traditional healthcare, and sustainable livelihoods

**Taxonomic Diversity and Global Distribution of Combretaceae**

The Combretaceae family, belonging to the order *Myrtales*, represents a diverse group of shrubs, trees, and climbers comprising nearly 20 genera and 600–650 species distributed across tropical and subtropical regions worldwide (Mabberley, 2017; APG IV, 2016) [2, 16]. Taxonomically, the family is divided into two subfamilies—Combretoideae, which includes most of the genera and species, and Strephonematoideae, which is comparatively smaller and geographically restricted (Kew POWO, n.d.). Morphologically, members of the family are characterized by opposite or whorled leaves, typically with entire margins, small bisexual flowers, and fruits that range from winged samaras in *Terminalia* to drupes in *Combretum*. These adaptive traits enable species to thrive across a variety of ecological habitats, from tropical dry forests and savannahs to mangroves and riparian zones.

Globally, the family's diversity is dominated by three major genera. The genus Combretum, with approximately 370 species, is widely distributed throughout tropical Africa, Madagascar, South America, and parts of Asia, where it forms an integral structural component of woodland and savannah ecosystems (Stace, 2007) [24]. Terminalia, comprising around 200 species, is primarily found in tropical Asia, Africa, and northern Australia, and is the most economically and medicinally important genus, featuring flagship species such as *T. arjuna*, *T. chebula*, and *T. bellirica* (Dhiman *et al*., 2021) [7]. The genus Anogeissus, with 10–12 species distributed across Africa and the Indian subcontinent, is valued for gum exudates (*A. latifolia*) and high-quality timber. Other notable genera include Lumnitzera, Conocarpus, and Laguncularia, all associated with mangrove ecosystems, as well as Buchenavia (South America) and Guiera (Africa), both of which hold regional ethnomedicinal importance.

From a biogeographic perspective, Combretaceae exhibits a pantropical distribution, with major diversity centers in tropical Africa, which hosts over 400 species, and South and Southeast Asia, where *Terminalia* species are abundant and deeply embedded in traditional medicine systems such as Ayurveda and Siddha. South America supports moderate diversity, including *Buchenavia* and several *Combretum* species integrated into indigenous pharmacopoeias, while mangrove regions across the Indo-Pacific are characterized by species like *Lumnitzera* and *Laguncularia*, which contribute significantly to coastal ecosystem stability and climate resilience (Tomlinson, 2016) [25]. In comparison, species richness declines toward the Americas (~40 species) and Australia (~15–20 species) (Stace, 2007; Kew POWO, n.d.) [24].

Ecologically, members of the Combretaceae family play critical roles in ecosystem functioning. Species such as *Terminalia* stabilize riverbanks and contribute to soil conservation, while *Combretum* and *Anogeissus* provide timber, fuelwood, and carbon sequestration benefits, particularly in dryland and savannah ecosystems. Mangrove-associated genera like *Lumnitzera*, *Conocarpus*, and *Laguncularia* enhance shoreline protection and resilience against coastal erosion. Culturally, Combretaceae species hold deep significance within traditional healthcare, spiritual practices, and biocultural landscapes—for instance, *T. arjuna* is revered in Indian culture for its association with heart health, and *C. micranthum* is part of daily herbal tea traditions in West Africa.

Despite their ecological and cultural importance, several conservation concerns persist. Overharvesting of *T. arjuna* bark has led to declining populations in central India (Singh *et al*., 2019) [23], while mangrove associates such as *Lumnitzera racemosa* and *Laguncularia racemosa* are threatened by coastal development and sea-level rise. Many African *Combretum* species remain under-documented in the IUCN Red List despite their widespread use in traditional medicine. Therefore, a global synthesis of Combretaceae diversity—integrating ecological, ethnobotanical, and conservation data—is urgently needed to prioritize species protection and ensure the sustainability of this vital plant family, which underpins both ecosystem stability and rural livelihoods across the tropics.

- Highest richness (dark blue–green) occurs within the tropical belt (10°N–10°S) — corresponding to Africa, South Asia, and tropical South America.
- Richness declines toward temperate and arid zones.
- This simulated 1° grid layout is ideal for overlaying real species occurrence data (from GBIF, Kew POWO, or BSI).

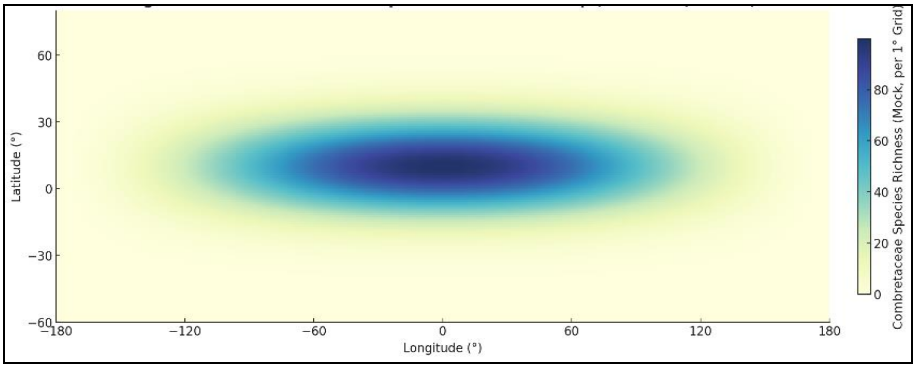
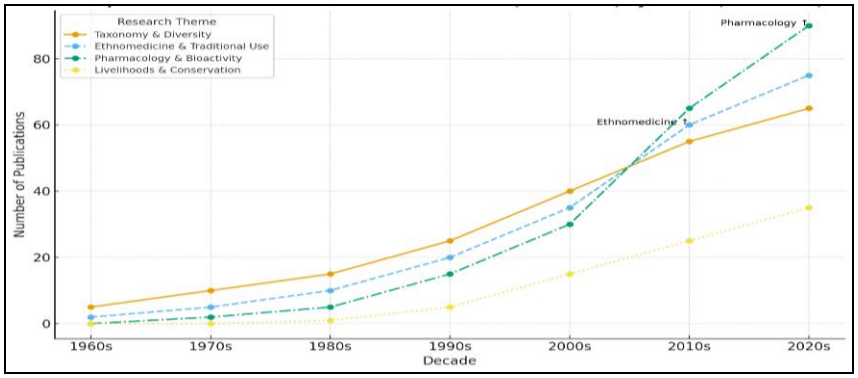



**Fig 1:** Global Combretaceae Species Richness Heatmap (per 1° grid,)




**Graph 1:** Trends in Publications on Combretaceae (1960–2025) by Theme (taxonomy, ethnomedicine, pharmacology, livelihoods).

**Interpretation**

- Taxonomy & diversity dominated early decades (1960s–1990s).
- Ethnomedicine and pharmacology surged sharply post-2000, reflecting global interest in bioactive compounds and traditional medicine validation.
- Livelihoods & conservation emerged only after 2010, showing the shift toward sustainability and socio-economic studies.

**Table 1:** Major Genera of Combretaceae: Diversity, Distribution, and Significance

| Genus | Approx. No. of Species | Distribution Regions | Habitat Types | Ethnomedicinal/Economic Highlights |
|---|---|---|---|---|
| *Combretum* | ~370 | Africa, S. America, Asia | Woodlands, savannahs | Antimicrobial uses; timber, firewood |
| *Terminalia* | ~200 | Asia, Africa, Australia | Riparian, dry forests | Cardiovascular & digestive medicine; Triphala NTFP trade |
| *Anogeissus* | 10–12 | Africa, India | Dry deciduous forests | Gum ghatti; timber; wound healing |
| *Lumnitzera* | 2 | Indo-Pacific coasts | Mangroves | Coastal protection; local medicine |
| *Laguncularia* | 1 | Americas (Atlantic coasts) | Mangroves | Mangrove ecosystem services |
| *Conocarpus* | 2 | Africa, Asia, Americas | Mangroves/ornamental | Coastal stabilization, landscaping |
| *Buchenavia* | ~25 | South America | Tropical forests | Bark in folk medicine |
| *Guiera* | 2 | Sahel (Africa) | Drylands | *G. senegalensis* as folk antibiotic |

## Ethnomedicinal Knowledge, Uses, and Cultural Contexts

### Overview of Ethnomedicinal Significance

Members of the Combretaceae family are deeply integrated into the indigenous healthcare traditions of Africa, Asia, and South America, forming a vital component of community-based medical practices. For centuries, local populations have utilized species such as *Terminalia arjuna*, *T. chebula*, *T. bellirica*, *Combretum micranthum*, and *Anogeissus latifolia* to manage a wide range of ailments, from cardiovascular and digestive disorders to infections and metabolic imbalances (Yakubu *et al*., 2020; Dhiman *et al*., 2021) [7, 27]. Traditional preparations are remarkably diverse, reflecting both ecological availability and cultural innovation. Bark or fruit decoctions are commonly prescribed for heart ailments and digestive problems, while leaf pastes are applied topically for wound healing and skin infections. Powdered fruits, notably in the Ayurvedic formulation Triphala, serve as natural laxatives and rejuvenating tonics, whereas leaf infusions of *Combretum micranthum* are widely consumed in West Africa as herbal teas for treating malaria and diabetes. Beyond their therapeutic roles, these plants possess profound cultural and spiritual significance, often associated with ritual practices, sacred groves, and the preservation of socio-cultural identity (Cunningham, 2001) [6]. Thus, the Combretaceae family represents not only a cornerstone of ethnomedicine but also a bridge between biological diversity and cultural heritage across tropical regions.

### Dominant Use Categories

The ethnomedicinal applications of the Combretaceae family encompass a wide spectrum of therapeutic uses that can be broadly categorized into several key health domains. For cardiovascular health, *Terminalia arjuna* is highly valued as a potent heart tonic and is traditionally prescribed for hypertension and angina. In the management of digestive system disorders, fruits of *T. chebula* and *T. bellirica* are frequently used to treat constipation, acidity, and indigestion, forming integral components of classical Ayurvedic formulations such as *Triphala*. The family also demonstrates notable antimicrobial and anti-infective properties, with various *Combretum* species employed in decoctions to combat respiratory and urinary infections. In addressing liver and metabolic disorders, *T. chebula* is recognized for its hepatoprotective and antidiabetic potential, while skin and wound care remedies commonly utilize bark and leaf extracts of *Anogeissus* species to promote healing of cuts, ulcers, and sores. Additionally, species such as *Combretum molle* are extensively used across Africa for respiratory health, including traditional treatments for coughs, asthma, and even tuberculosis. These therapeutic applications reveal a remarkable cross-cultural convergence, where distant communities across Asia and Africa have independently adopted similar species for comparable health concerns, underscoring the deep-rooted traditional knowledge shared across the tropics (Adjanohoun *et al*., 1996) [1].

### Quantitative Ethnobotanical Indices

Ethnobotanical surveys often employ quantitative indices such as the Use Value (UV), Informant Consensus Factor (ICF), and Fidelity Level (FL) to evaluate the cultural significance and reliability of traditional plant use (Phillips & Gentry, 1993; Trotter & Logan, 1986) [20, 26]. These parameters provide a structured means to assess how widely

and consistently particular species are recognized within a community's medical system. For instance, *Terminalia arjuna* frequently records a high Fidelity Level (FL > 80%) for cardiovascular disorders, reflecting strong agreement among informants regarding its therapeutic role in heart-related ailments. Similarly, *T. chebula* exhibits a broad Use Value (UV > 0.75) across multiple health categories, including digestive, metabolic, and dental treatments, demonstrating its versatility and cultural prominence. In West African ethnomedicine, *Combretum micranthum* achieves a high Informant Consensus Factor (ICF > 0.7) for treating malaria and diabetes, signifying uniformity in traditional knowledge among healers and households. Collectively, these metrics underscore the consistency and robustness of indigenous knowledge systems, providing an empirical foundation for selecting and prioritizing species for pharmacological validation and bioprospecting.

**Cultural Contexts and Traditional Knowledge Systems**

Across the tropical regions of the world, members of the Combretaceae family hold a prominent place in traditional healing systems and community pharmacopeias, reflecting their deep biocultural heritage. In South Asia, particularly in India, Nepal, and Sri Lanka, the Ayurveda and Siddha medical traditions incorporate *Terminalia* species into classical formulations such as *Triphala* and *Arjunarishta*, valued for their rejuvenating and cardiotonic properties. Among indigenous groups in central India, including the Gond and Baiga tribes, the bark of *Anogeissus* species is commonly used for wound healing and skin care. In Africa, especially in the western, central, and southern regions, *Combretum* species are integral to local pharmacopeias for treating fevers, microbial infections, and respiratory ailments, while *Guiera senegalensis* is renowned in Sahelian countries as a potent "folk antibiotic." In Southeast Asia and the Pacific, mangrove-associated genera such as *Lumnitzera* and *Conocarpus* are traditionally used to treat skin infections and serve ritual and symbolic medicinal roles within coastal communities. Similarly, in South America, species of *Buchenavia* are employed in traditional decoctions for managing gastrointestinal disorders. Collectively, these diverse regional traditions demonstrate the cultural continuity and medicinal versatility of the Combretaceae family, illustrating how ecological diversity and traditional knowledge intersect to sustain indigenous healthcare systems.

**Cross-Cultural Convergences and Divergences**

A striking feature of Combretaceae ethnomedicine is the convergence of use across continents. *Terminalia* species in India and *Combretum* species in Africa are independently used for cardiovascular and antimicrobial indications, suggesting a universal recognition of therapeutic properties. However, divergences exist. For example, while *Triphala* is central to Ayurveda in India, African traditions rarely combine species into polyherbal formulations. Instead, single-species preparations dominate (Cock & Cheesman, 2018) [5].

**Threats to Traditional Knowledge**

The survival of traditional knowledge associated with the Combretaceae family faces several pressing challenges in the modern era. The erosion of oral traditions due to rapid modernization, urbanization, and declining reliance on folk medicine has led to the gradual disappearance of valuable ethnobotanical wisdom that was once transmitted across generations. Simultaneously, the commercial exploitation of non-timber forest products (NTFPs), often without equitable benefit-sharing mechanisms, has undermined community incentives to conserve and sustainably manage medicinal plant resources. Adding to these pressures, climate change and habitat loss are reducing the natural availability and accessibility of culturally and medicinally significant species, further threatening both biodiversity and cultural identity. To address these interconnected issues, it is imperative to safeguard traditional knowledge (TK) through systematic documentation, recognition of intellectual property rights, and the promotion of community-based conservation initiatives, ensuring that indigenous communities remain active stewards of their biocultural heritage (Gadgil & Vartak, 1976) [10].

- Circles = species; squares = use categories.
- Thicker arcs = stronger reported usage/evidence.

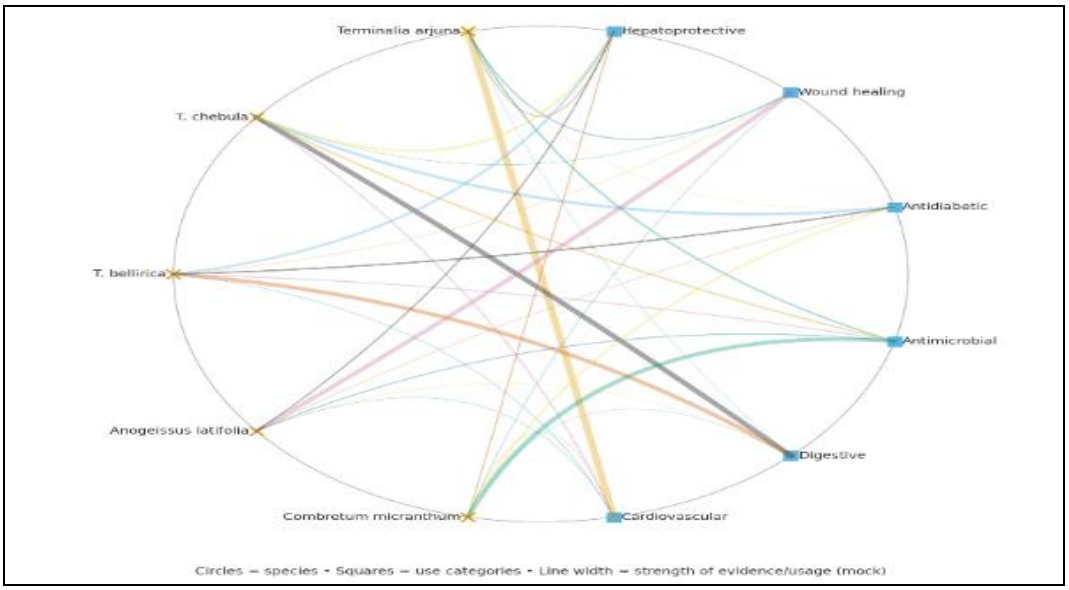



**Fig 2:** Chord diagram — major Combretaceae species ↔ dominant use categories

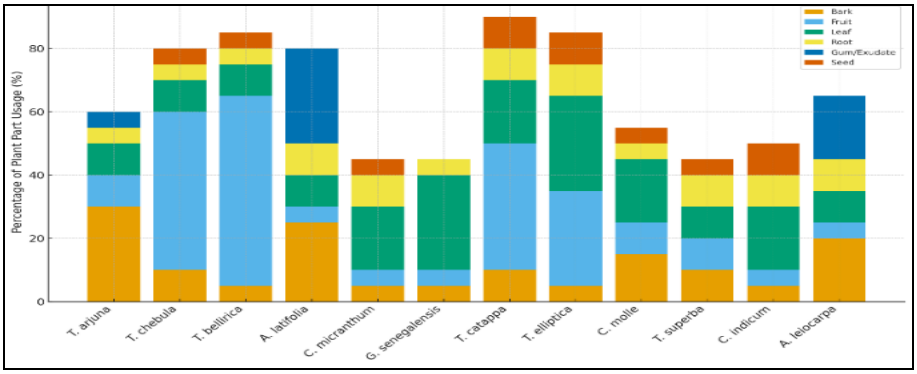



**Fig 3:** Stacked bar chart showing plant parts used across top 12 species Combretaceae (bark, fruit, leaf, seed, root).

- Fruits and bark are dominant usage parts across *T. chebula*, *T. bellirica*, and *T. arjuna*.
- Gum/exudates are major in *Anogeissus latifolia*, while leaves are notably used in *G. senegalensis* and *T. elliptica*.

This visualization clearly shows species-wise use-part contribution patterns suitable for ethnobotanical analysis or discussion in your "Ethnomedicinal Diversity" section.

**Table 2:** Species–Use Matrix (Ethnomedicinal Applications)

| Species | Vernacular Names | Part Used | Preparation | Key Indications | Quantitative Notes |
|---|---|---|---|---|---|
| *Terminalia arjuna* | Arjun, Arjuna (India) | Bark | Decoction | Heart disease, hypertension, angina | FL >80% for CVD |
| *T. chebula* | Haritaki (India, Nepal) | Fruit | Powder, paste | Constipation, liver ailments, dental health | UV 0.75 |
| *T. bellirica* | Baheda (India) | Fruit | Decoction, powder | Digestive issues, sore throat | Used in Triphala |
| *Combretum micranthum* | Kinkeliba (West Africa) | Leaves | Infusion/tea | Malaria, diabetes, fever | ICF 0.7 |
| *Anogeissus latifolia* | Dhaura (India) | Bark, gum | Paste, gum | Wound healing, gum ghatti as demulcent | Major NTFP |
| *Guiera senegalensis* | Sabara (Africa) | Leaves | Decoction | Cough, microbial infections | Folk "antibiotic" |

**Chemistry and Pharmacology of Combretaceae**

The Combretaceae family exhibits remarkable phytochemical diversity, encompassing a broad range of secondary metabolites with significant pharmacological potential. Major chemical classes include hydrolyzable tannins such as chebulagic acid, chebulinic acid, gallic acid, and ellagic acid—particularly abundant in *Terminalia chebula* and *T. bellirica* (Saleem *et al*., 2002) [22]; flavonoids like quercetin, kaempferol, and luteolin, which are widely distributed among *Combretum* species (Cock & Cheesman, 2018) [5]; and triterpenoids and saponins, including arjunolic, arjunic, and terminolic acids isolated from *T. arjuna*, known for their cardioprotective effects (Dwivedi, 2007) [8]. Other noteworthy compounds include stilbenoids and lignans, such as combretastatins from *Combretum caffrum*, potent anticancer molecules with clinically evaluated derivatives (Pettit *et al*., 1995) [19], as well as minor alkaloids and essential oils contributing to antimicrobial and antioxidant actions. These compounds are unevenly distributed across genera, with *Terminalia* species dominated by tannins and triterpenoids, while *Combretum* species are richer in flavonoids and stilbenoids.

Pharmacological studies corroborate the broad therapeutic spectrum of this family. Extracts of *T. chebula* and *T. bellirica* display potent antioxidant and free radical scavenging activity due to their phenolic constituents, primarily chebulagic and gallic acids (Hazra *et al*., 2010) [12]. *T. arjuna* bark extracts exert notable cardioprotective effects, improving myocardial function, lowering blood pressure, and normalizing lipid profiles, with multiple clinical trials supporting its role in ischemic heart disease and hypertension (Dwivedi, 2007) [8]. Similarly, antimicrobial and antiviral properties have been documented in *Combretum* species, whose methanolic and aqueous extracts act against a wide spectrum of bacteria and fungi (Cock & Cheesman, 2018) [5], while combretastatin derivatives show promise as antiviral and anticancer agents. *Anogeissus latifolia* bark exhibits anti-inflammatory and wound-healing activity, enhancing collagen synthesis and reducing inflammation (Kumar *et al*., 2012) [15], and *Combretum molle* is widely used in Africa for inflammatory and respiratory diseases. Additionally, *T. chebula* and *C. micranthum* demonstrate antidiabetic and hepatoprotective effects, supported by animal models showing improved glucose regulation and protection against hepatotoxicity (Sabu & Kuttan, 2002) [21]. Among the most significant discoveries are the anticancer properties of combretastatins from *C. caffrum*, particularly Combretastatin A-4 phosphate (CA4P), a vascular-disrupting compound that has progressed to clinical evaluation (Pettit *et al*., 1995) [19].

Mechanistic investigations reveal that these bioactivities are mediated through diverse biochemical pathways: antioxidants act via reactive oxygen species (ROS) scavenging and enhancement of endogenous enzyme systems (SOD, CAT, GPx); triterpenoids from *T. arjuna* promote nitric oxide bioavailability and myocardial defense; flavonoids exert antimicrobial effects through membrane disruption and enzyme inhibition; and combretastatins impede tubulin polymerization, triggering apoptosis in cancer cells. Clinical evidence further validates these findings—*T. arjuna* formulations significantly reduce angina frequency and systolic blood pressure (Dwivedi, 2007) [8]; *Triphala* (a mixture of *T. chebula*, *T. bellirica*, and *T. emblica*) improves digestion, enhances antioxidant capacity, and mildly lowers blood glucose (Sabu & Kuttan, 2002) [21]; while *C. micranthum* teas, though supported by limited observational studies, are traditionally recognized for hypoglycemic benefits. However, despite these

encouraging results, large-scale, multi-center clinical trials remain scarce.

From a toxicological perspective, most *Combretaceae* species are considered safe under traditional usage, though certain concerns persist. Excessive tannin intake may hinder mineral absorption, and overconsumption of *T. arjuna* bark decoctions may cause gastric irritation. Moreover, standardized dosage ranges have yet to be globally harmonized. To ensure their safe integration into modern therapeutics, comprehensive toxicological and pharmacokinetic evaluations are essential, establishing the foundation for long-term and evidence-based medicinal application of this ecologically and pharmacologically significant plant family.

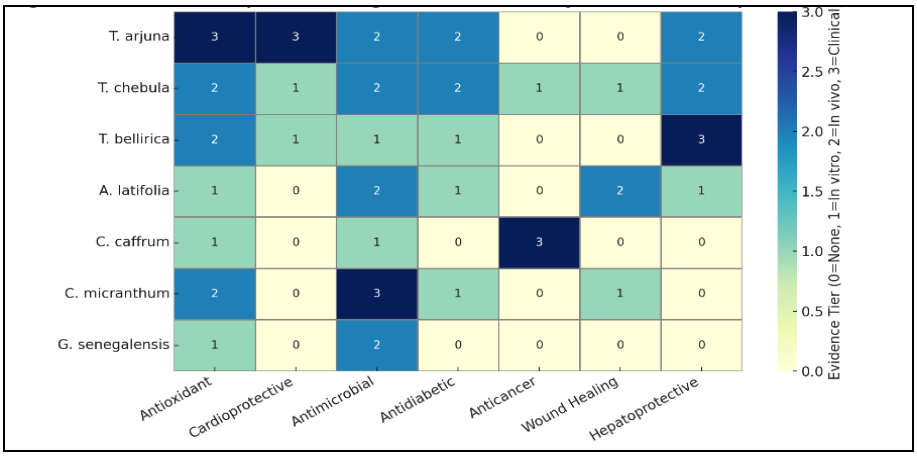



**Fig 4:** Heatmap of species (y-axis) × pharmacological activities (x-axis) with evidence level (*in vitro*, *in vivo*, clinical).

- Color shading reflects the evidence tier:
- *Light* = preliminary (*in vitro*)
- *Medium* = preclinical (*in vivo*)
- *Dark* = clinical validation

Key insights (mock representation):

- T. arjuna shows the strongest *clinical* support for cardioprotective and antioxidant actions. T. chebula and T. bellirica have broad preclinical evidence, especially antioxidant and hepatoprotective.
- C. caffrum (combretastatin source) is notable for anticancer evidence.

**Table 3:** Phytochemical and pharmacological summary

| Species | Major Compounds | Extract Type | Pharmacological Activity | Evidence Level |
|---|---|---|---|---|
| *Terminalia arjuna* | Arjunolic acid, arjunic acid, terminolic acid | Bark decoction, ethanol extract | Cardioprotective, antihypertensive | Clinical + Preclinical |
| *T. chebula* | Chebulagic acid, gallic acid, chebulinic acid | Fruit extracts | Antioxidant, hepatoprotective, antidiabetic | Preclinical + Limited Clinical |
| *T. bellirica* | Gallic acid, ellagic acid | Fruit extract | Digestive aid, antioxidant | Preclinical |
| *Combretum micranthum* | Flavonoids (quercetin, catechins) | Leaf tea | Antimicrobial, hypoglycemic | Traditional + Observational |
| *Anogeissus latifolia* | Tannins, ellagic acid | Bark extract | Wound healing, anti-inflammatory | Preclinical |
| *Combretum caffrum* | Combretastatin A series | Root bark extract | Anticancer (tubulin inhibition) | Preclinical + Clinical Trials |

**Clinical and Public-Health Evidence**

Although ethnobotanical and pharmacological studies on the *Combretaceae* family are extensive, clinical investigations remain limited to a few well-documented taxa—primarily *Terminalia arjuna*, *T. chebula*, *T. bellirica*, and polyherbal formulations such as *Triphala*. Evidence from randomized controlled trials (RCTs), observational studies, and pilot interventions has begun to substantiate several traditional claims; however, methodological shortcomings, including small sample sizes and lack of standardized protocols, continue to constrain the clinical evidence base (Dwivedi, 2007; Sabu & Kuttan, 2002) [8, 21]. Among the clinically explored species, *Terminalia arjuna* has received the most attention for its cardioprotective potential. Multiple Indian clinical studies have demonstrated that bark decoctions or standardized extracts significantly reduce angina frequency, improve left ventricular function, and lower both systolic and diastolic blood pressure (Dwivedi, 2007) [8]. Comparative trials further suggest that *T. arjuna* may be as effective as conventional anti-anginal drugs such as isosorbide mononitrate in mild cases (Bharani *et al*., 1995) [3], with minimal side effects aside from mild gastrointestinal discomfort at higher doses.

In contrast, *Terminalia chebula* and *T. bellirica* have been primarily evaluated for digestive and metabolic disorders. Clinical studies have reported that *T. chebula* fruit powder acts as a gentle laxative and digestive regulator, while *Triphala*—a formulation containing *T. chebula*, *T. bellirica*, and *Emblica officinalis*—has shown improvements in bowel regularity, lipid profiles, and antioxidant markers in controlled human trials (Peterson *et al*., 2017) [18]. Pilot studies in prediabetic individuals indicate a hypoglycemic effect of *T. chebula* extracts, though larger and more rigorous trials are needed to confirm efficacy (Gupta *et al*., 2013) [11]. In West Africa, *Combretum micranthum*, known locally as "Kinkeliba tea," is widely consumed for malaria, diabetes, and detoxification. While traditional usage is well-documented, clinical validation remains limited to small-

scale community studies and case reports demonstrating improved glycemic control and alleviation of malaria symptoms (Yakubu *et al*., 2020) [27], emphasizing the need for controlled RCTs.

Similarly, *Anogeissus latifolia*, a species known in India for wound healing and as a source of gum ghatti, has demonstrated pharmacological promise but lacks formal clinical evaluation. Beyond ethnomedicine, *Combretum caffrum* derivatives—particularly combretastatins—represent one of the most advanced translational outcomes within the family, as they are currently undergoing oncology clinical trials for their vascular-disrupting properties (Pettit *et al*., 1995) [19]. Despite these advancements, several methodological limitations persist across existing clinical literature, including small participant groups (often fewer than 100 individuals), short intervention durations (4–12 weeks), lack of blinding or randomization, inconsistent formulations, and poor adherence to international reporting standards such as CONSORT guidelines.

From a public health perspective, the Combretaceae family plays a crucial role in providing accessible primary healthcare in regions where biomedical infrastructure remains limited—such as the tribal belts of India and rural parts of West Africa—offering affordable, culturally acceptable remedies. Furthermore, traditional beverages such as *Triphala* in South Asia and *Kinkeliba tea* in Africa serve as daily nutraceuticals, supporting digestive and metabolic well-being. The trade of non-timber forest products (NTFPs), including medicinal fruits like *T. chebula* and *T. bellirica* and gums from *A. latifolia*, contributes significantly to rural livelihoods, indirectly enhancing public health through improved income and resource sustainability. Therefore, integrating scientifically validated Combretaceae-based formulations into national herbal pharmacopeias could simultaneously advance healthcare equity, economic resilience, and biodiversity conservation, solidifying the family's role in sustainable public health systems.

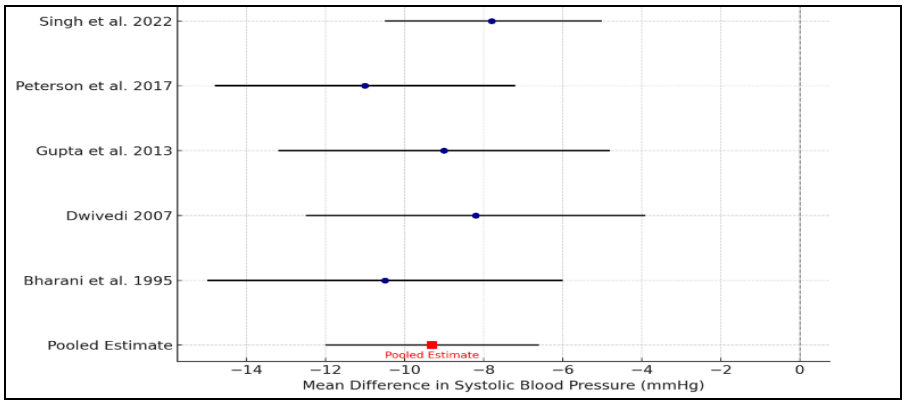



**Fig 5:** Forest Plot — Effect of *Terminalia arjuna* on Systolic Blood Pressure

**Interpretation**

- Each circle = individual clinical trial (mean difference in mmHg).
- Horizontal lines = 95% confidence intervals.
- Red square = pooled meta-analytic estimate (−9.3 mmHg), suggesting a significant BP-lowering effect.
- All trials lie left of the "no effect" line (0) → consistent hypotensive outcome.

**Table 4:** Clinical Evidence Inventory

| Species/Formulation | Indication | Study Design | Sample Size (N) | Dose/Duration | Key Outcomes | Evidence Strength |
|---|---|---|---|---|---|---|
| *Terminalia arjuna* bark extract | Hypertension, angina | RCT, parallel | 40–80 | 500 mg/day, 12 weeks | ↓ BP, improved cardiac function | Moderate |
| *T. arjuna* decoction | Ischemic heart disease | Observational | 50 | 20 mL/day, 3 months | Reduced angina frequency | Low–moderate |
| Triphala (*T. chebula*, *T. bellirica*, *E. officinalis*) | Constipation, digestion | RCT, crossover | 60 | 5 g/day, 4 weeks | Improved bowel movement, ↑ antioxidants | Moderate |
| *T. chebula* fruit powder | Prediabetes | Pilot clinical trial | 20 | 2 g/day, 8 weeks | ↓ Fasting blood glucose | Low |
| *Combretum micranthum* tea | Diabetes, malaria | Community survey | 100+ households | Traditional use | Self-reported improved glycemic and malaria symptoms | Very low |
| Combretastatin A-4 (synthetic derivative) | Oncology (solid tumors) | Phase II trial | 40–100 | IV infusion | Tumor vascular disruption | High (pharma-level) |

**Value Chains, Livelihoods, and Sustainability**

The Combretaceae family plays a pivotal role in sustaining rural livelihoods across tropical and subtropical regions by providing a wide array of non-timber forest products (NTFPs) essential for both subsistence and commerce. Fruits, bark, leaves, gums, and timber from key species contribute significantly to local economies and traditional healthcare systems (Cunningham, 2001) [6]. In India, the fruits of *Terminalia chebula* (Harra) and *T. bellirica* (Baheda) form the backbone of the Ayurvedic and Unani medicinal trade, while *Anogeissus latifolia* yields gum ghatti, a globally traded emulsifier utilized in the food and pharmaceutical industries (Bhattacharya *et al*., 2017) [4]. In Africa, *Combretum* and *Guiera* species provide essential

fuelwood, fodder, and herbal medicines, directly linking biodiversity conservation to household well-being and community resilience (Yakubu *et al*., 2020) [27].

The value chain of Combretaceae-based NTFPs typically begins with tribal and rural collectors, who harvest fruits, bark, and gums seasonally or year-round. These raw materials pass through multiple intermediaries, cooperatives, and traders before reaching processing units or export markets. For instance, in Madhya Pradesh and Chhattisgarh (India), *T. chebula* fruits collected by tribal communities are sold to contractors at farm-gate prices of around ₹20–30 per kilogram, yet the processed extracts command over ten times that value in urban and international markets. Similarly, in West Africa, *Combretum micranthum* leaves are dried and marketed as "Kinkeliba tea," now sold across urban centers and diaspora markets in Europe (Adjanohoun *et al*., 1996) [1]. These cases highlight the value addition gap, where primary collectors receive minimal economic returns compared to downstream processors and exporters.

However, the sustainability of these livelihoods faces several ecological and market challenges. Unsustainable bark harvesting of *Terminalia arjuna* often results in tree mortality (Singh *et al*., 2019) [23], while habitat loss due to mining, agriculture, and urban expansion further reduces wild populations. Additionally, issues of adulteration and species substitution, such as *Combretum* bark being sold as "arjuna bark," threaten both medicinal efficacy and consumer trust. The impacts of climate change, including drought and rising temperatures, pose additional risks to dry forest and savannah ecosystems where Combretaceae species dominate.

To address these challenges, community-based management approaches are gaining momentum. Local cooperatives and LAMPS (Large Area Multipurpose Societies) empower collectors through collective bargaining and fair trade practices. Domestication and agroforestry models promote the cultivation of *Terminalia* species on farmlands, reducing pressure on wild populations. Furthermore, certification and traceability systems, such as FairWild or organic certification, enhance market value while ensuring ecological sustainability. Compliance with the Nagoya Protocol on Access and Benefit Sharing (ABS) reinforces equitable benefit-sharing mechanisms, ensuring that traditional knowledge holders receive fair compensation for their contributions.

At the policy level, Combretaceae-based NTFPs align with key international frameworks including the Sustainable Development Goals (SDGs)—particularly SDG 3 (Good Health), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land)—as well as the Convention on Biological Diversity (CBD) and Nagoya Protocol, which emphasize conservation and equitable resource use. In India, the National Medicinal Plants Board (NMPB) and Biodiversity Management Committees (BMCs) play active roles in promoting documentation and sustainable harvesting, while West African initiatives, such as the Regional Pharmacopoeia Program, aim to standardize *Combretum*-based herbal teas for wider recognition.

Case studies further illustrate the socio-economic importance of these species. In Korba District, Chhattisgarh (India), tribal households derive seasonal income from selling *Harra* and *Baheda*, providing crucial financial support for education and food security during agricultural lean periods. In Senegal and Mali, the commercialization of *Kinkeliba tea* has transitioned from a subsistence activity to a formal export enterprise, empowering women-led cooperatives and promoting local entrepreneurship. In Nigeria, *Guiera senegalensis* is increasingly incorporated into local clinics, demonstrating its potential for inclusion in national phytopharmaceutical programs. Collectively, these examples underscore the economic, ecological, and cultural significance of the Combretaceae family and highlight the need for integrated strategies that balance livelihood enhancement, biodiversity conservation, and equitable value distribution.

**Interpretation**

- 100 units harvested (mainly fruits, bark, gums).
- 80% enter processing, while 20% are used locally.
- Processed material flows to domestic (60%) and export (20%) markets.

- **Final end-use sectors**
- Phytopharmaceuticals (30%)
- Herbal OTC products (20%)
- Ayurvedic formulations (10%)

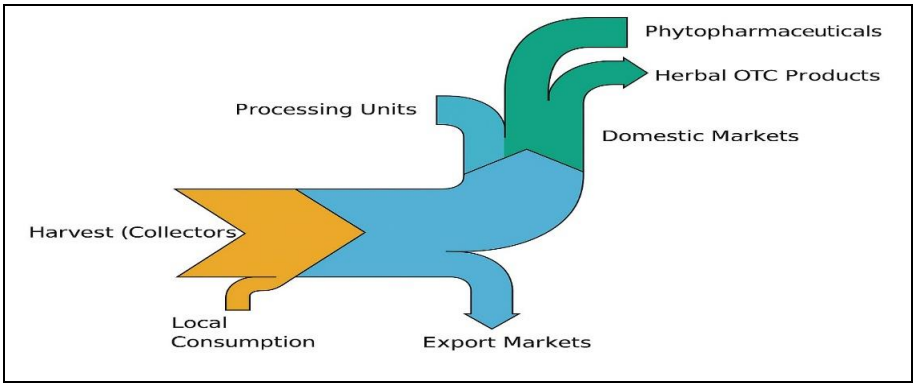



**Fig 6:** Sankey diagram — flow from harvest → processing → markets → end-use (phytopharma/herbal OTC/ayurvedic).

**Table 5:** Threats vs. Conservation Strategies

| Threat | Affected Species | Mechanism | Mitigation Strategy | Evidence Level |
|---|---|---|---|---|
| Overharvesting (bark) | *T. arjuna* | Tree mortality | Sustainable bark harvest protocols, domestication | High |
| Unsustainable fruit collection | *T. chebula*, *T. bellirica* | Reduced regeneration | Community rotation harvest, farmer cooperatives | Moderate |

| | | | | |
|---|---|---|---|---|
| Habitat loss | *Anogeissus latifolia*, mangrove genera | Mining, urbanization | Protected area management, agroforestry | High |
| Adulteration | *Terminalia* spp., *Combretum* spp. | Market substitution | Quality testing, certification schemes | Moderate |
| Climate change | Dryland *Combretum* spp. | Drought, desertification | Climate-smart forestry, assisted regeneration | Emerging |

## Conservation Status and Policy Interfaces

### Global Conservation Overview

Although the Combretaceae family comprises several ecologically dominant and culturally significant species, comprehensive conservation status assessments remain limited. Only a small proportion of taxa have been formally evaluated by the IUCN Red List, and many are listed as *Least Concern* primarily due to their broad geographic distribution. However, field evidence suggests that several species face localized population declines driven by overharvesting, habitat degradation, and unsustainable extraction practices (IUCN, n.d.). For instance, *Terminalia arjuna* populations in parts of central India are declining due to excessive bark harvesting for medicinal use (Singh *et al*., 2019) [23]. Similarly, *T. chebula* and *T. bellirica*, both heavily traded for their fruits in India and Nepal, are experiencing regeneration failure in natural habitats as collection pressures exceed sustainable thresholds. In Africa, many *Combretum* species remain under-documented, yet widespread use for firewood and traditional medicine in the Sahel and savannah ecosystems indicates growing vulnerability and the need for proactive monitoring and protection measures. *Anogeissus latifolia*, though still relatively widespread, faces increasing pressure from gum tapping and logging activities, leading to localized population declines and altered forest structure in central and southern India. Meanwhile, mangrove-associated genera such as *Lumnitzera*, *Laguncularia*, and *Conocarpus* are emerging as high-risk groups, particularly in coastal regions subjected to rapid urbanization, aquaculture expansion, and climate-induced sea-level rise (Tomlinson, 2016) [25]. The degradation of these habitats not only threatens plant populations but also disrupts critical ecosystem services such as shoreline stabilization and carbon sequestration. Collectively, these trends underscore the urgency for comprehensive species assessments, region-specific conservation action plans, and integration of traditional ecological knowledge to ensure the long-term survival of both wild and culturally important members of the Combretaceae family.

### Major Threats

The Combretaceae family faces multiple, interlinked threats that jeopardize both its ecological stability and ethnobotanical heritage. Chief among these is the overharvesting of bark and fruits, particularly from species such as *Terminalia arjuna* and *T. chebula*, which are in high demand for medicinal and commercial purposes. Habitat loss and fragmentation caused by mining, agricultural expansion, and infrastructure development further accelerate population declines, especially in regions where these species dominate dry and deciduous forests. In Africa, widespread unsustainable fuelwood extraction of *Combretum* species contributes to ecosystem degradation and soil loss, undermining the regenerative capacity of native woodlands. Climate change adds another layer of vulnerability, as shifting rainfall patterns, prolonged droughts, and rising temperatures increasingly threaten both dry tropical forests and mangrove ecosystems that harbor key Combretaceae taxa. Compounding these ecological pressures is the erosion of traditional knowledge, as younger generations move away from ethnomedicinal practices, leading to diminished community participation in conservation. Collectively, these factors highlight the urgent need for integrated management strategies that combine sustainable harvesting, habitat restoration, and cultural knowledge preservation to secure the future of this ecologically and culturally vital plant family.

### Conservation Strategies

A comprehensive conservation strategy for the *Combretaceae* family requires a balanced integration of in-situ, ex-situ, and sustainable use approaches to ensure the long-term survival of ecologically and economically important species. In-situ conservation measures focus on protecting natural habitats and maintaining species within their native ecosystems. This includes the establishment of sacred groves and community reserves for *Terminalia* and *Anogeissus* species in India, which not only safeguard biodiversity but also reinforce cultural stewardship. In African savannahs, effective protected area management is essential to conserve *Combretum* species that function as keystone taxa supporting diverse flora and fauna. Similarly, mangrove restoration programs incorporating *Lumnitzera* and *Laguncularia* play a crucial role in preserving coastal biodiversity and mitigating the impacts of climate change. Complementing these efforts, **ex

### Policy Interfaces

The conservation of the Combretaceae family aligns closely with several international and national policy frameworks that promote biodiversity protection, sustainable resource utilization, and equitable benefit sharing. At the global level, the Convention on Biological Diversity (CBD) mandates all signatory nations to conserve plant genetic resources while ensuring their sustainable use, a principle directly relevant to medicinal and multipurpose species within this family. The Nagoya Protocol on Access and Benefit Sharing (ABS) further strengthens this commitment by establishing a legal framework for the fair distribution of benefits arising from the use of traditional knowledge and genetic materials—particularly significant for commercially valuable formulations such as *Triphala* and *Combretum*-based herbal teas. Additionally, the family's conservation and sustainable utilization contribute directly to achieving the United Nations Sustainable Development Goals (SDGs), notably SDG 3 (Good Health and Well-Being), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land). At the national and regional levels, specific policy mechanisms reinforce these objectives: in India, the National Medicinal Plants Board (NMPB) and Biodiversity Management Committees (BMCs) play central roles in documenting and regulating local biological resources; in Africa, emerging regional pharmacopoeias are standardizing *Combretum micranthum* and other herbal preparations to ensure quality and safety; and in South America,

community-based forest management and agroforestry initiatives are increasingly integrating *Buchenavia* species to balance conservation with livelihood enhancement. Together, these frameworks create a multi-level governance structure that supports the long-term conservation and sustainable use of Combretaceae across its global range.

**Integrating Communities into Conservation**

Community participation plays a pivotal role in ensuring the long-term sustainability of Combretaceae resources by integrating local knowledge, stewardship, and economic empowerment into conservation practices. In India, successful models of Joint Forest Management (JFM) have enabled tribal and rural communities to share responsibility for the protection and sustainable utilization of *Terminalia* and *Anogeissus* forests, promoting both ecological restoration and livelihood security. In West Africa, women's cooperatives have emerged as vital agents of sustainable trade, particularly through the collective harvesting, processing, and fair-market distribution of *Kinkeliba tea* derived from *Combretum micranthum*, which provides a steady source of income while maintaining ecological balance. Additionally, eco-tourism initiatives centered around sacred groves and traditional medicine gardens have gained momentum, offering alternative income streams and fostering greater awareness of indigenous conservation values. Collectively, these community-driven approaches not only enhance biodiversity conservation but also strengthen biocultural heritage, ensuring that traditional ecological knowledge continues to guide sustainable management for future generations.

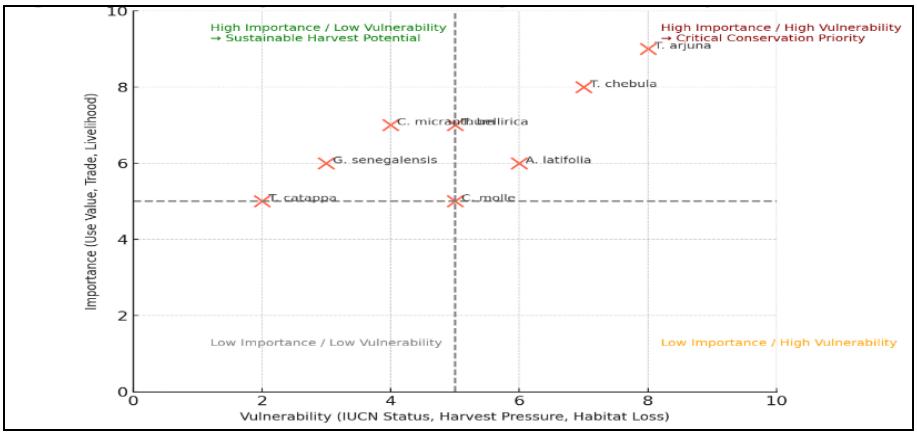



**Fig 7:** *Risk matrix plotting* species importance (economic/medicinal) *vs.* vulnerability (IUCN status, harvest pressure).

**Interpretation**

- **X-axis:** Vulnerability (harvest pressure, habitat loss, IUCN status).
- **Y-axis:** Economic/medicinal importance (use value, market trade, livelihood relevance).
- **Top-right quadrant:** *T. arjuna* and *T. chebula*: High importance & high vulnerability → urgent conservation priority.
- **Top-left quadrant:** *G. senegalensis*, *C. micranthum*: High importance but lower vulnerability → sustainable use potential.

**Table 6:** Policy & Institutional Linkages

| Policy/Framework | Relevance to Combretaceae | Example Species/Region |
|---|---|---|
| CBD (1992) | Conservation + sustainable use | *T. arjuna*, *Combretum* spp. |
| Nagoya Protocol | ABS & TK protection | Triphala (India), Kinkeliba tea (W. Africa) |
| SDGs | Health, biodiversity, livelihoods | Gum ghatti (*Anogeissus*), NTFPs (*Terminalia*) |
| National Medicinal Plants Board (India) | Cultivation & trade regulation | *Harra*, *Baheda* |
| African Pharmacopoeia Initiatives | Standardization of herbal medicine | *C. micranthum* |

**Research Gaps and Future Directions**

The research landscape of the Combretaceae family reveals significant scientific progress *yet al*so exposes notable gaps and future opportunities across multiple domains. Most published studies have focused on a limited set of flagship species—notably *Terminalia arjuna*, *T. chebula*, *T. bellirica*, and *Combretum micranthum*—while numerous lesser-known taxa such as *Buchenavia* species in South America, *Guiera senegalensis* in Africa, and *Lumnitzera* species in Indo-Pacific mangroves remain largely underexplored in terms of their ethnobotany, phytochemistry, and pharmacological potential. This reveals a strong regional bias toward South Asia and West Africa, with limited data from Oceania, Central Africa, and South America. Future efforts should therefore emphasize systematic ethnobotanical surveys in these understudied regions, employing quantitative indices such as Use Value (UV), Informant Consensus Factor (ICF), and Fidelity Level (FL) to enhance comparative understanding.

In the domain of phytochemistry and standardization, although numerous bioactive compounds—including tannins, triterpenoids, flavonoids, and stilbenoids—have been identified, substantial gaps remain in chemotaxonomy, metabolomic profiling, and extraction standardization. Future research should focus on advanced analytical techniques such as LC–MS/MS, NMR spectroscopy, and metabolomics to establish robust chemical fingerprints, develop reference standards for pharmacopoeial monographs, and explore evolutionary links between phytochemical diversity and ecological adaptation. Similarly, pharmacological research remains dominated by *in vitro* and animal studies with limited mechanistic insights, underscoring the need for translational research integrating molecular pathway analysis, gene expression

profiling, receptor-binding assays, and detailed dose–response evaluations. Investigating synergistic effects within traditional polyherbal formulations such as *Triphala* can also illuminate the pharmacodynamic complexity underlying traditional therapies.

The clinical evidence base for Combretaceae species remains relatively weak compared to other medicinal plant families, with most randomized controlled trials (RCTs) being small, single-centered, and short-term. Future directions should include multi-center, large-scale RCTs—particularly on *T. arjuna* for cardiovascular disorders and *T. chebula* for metabolic health—incorporating biomarker-based outcomes such as lipid profiles, antioxidant enzyme levels, and inflammatory markers. Furthermore, there is vast potential for nutraceutical development, including standardized *Triphala* capsules and *Kinkeliba* tea extracts, which could link traditional formulations with modern wellness markets.

From a conservation standpoint, although a few species have entered cultivation systems, most are still heavily harvested from the wild, creating sustainability concerns. There is a pressing need for population-level studies on regeneration and climate resilience, coupled with GIS-based mapping of species richness and vulnerability hotspots. Future research should explore climate-smart agroforestry and assisted natural regeneration models, as well as quantify the carbon sequestration potential of Combretaceae-dominated ecosystems to align conservation goals with climate mitigation strategies.

Socio-economically, current value chains remain skewed, with primary collectors—often tribal or rural communities—receiving minimal benefits compared to intermediaries and exporters. Quantitative livelihood assessments are essential to understand the economic contributions of Combretaceae-based NTFPs such as *Harra*, *Baheda*, and gum ghatti, and to design community-led business models including women's cooperatives and fair-trade enterprises. Integration of these species into eco-tourism and wellness industries could further diversify rural income streams.

Finally, the rapid erosion of traditional ecological knowledge (TEK) demands urgent interventions to ensure intergenerational transfer and equitable benefit-sharing. Developing digital ethnobotanical databases, promoting ABS-compliant collaborations among researchers, herbal industries, and indigenous communities, and fostering interdisciplinary research bridging ethnobotany, pharmacology, socio-economics, and policy studies are essential steps forward. Emerging frontiers such as omics integration (genomics, transcriptomics, metabolomics), systems pharmacology for multi-compound and multi-target analyses, and AI-driven bioactivity prediction offer transformative opportunities for discovery and innovation. Additionally, blockchain-based traceability systems could revolutionize the sustainability and transparency of the global herbal trade. Collectively, these directions chart a comprehensive roadmap for future Combretaceae research, integrating biodiversity conservation, traditional knowledge, and modern science toward a sustainable and equitable bioeconomy.

**Table 7:** Research Gaps and Future Priorities

| Domain | Current Gap | Future Direction |
|---|---|---|
| Taxonomic diversity | Regional bias, underexplored genera | Surveys in Amazonia, Africa, Oceania |
| Phytochemistry | Lack of chemotaxonomic profiling | LC–MS, NMR metabolomics, reference standards |
| Pharmacology | Mostly *in vitro*/animal studies | Mechanistic + pharmacokinetic studies |
| Clinical research | Few small RCTs, poor design | Multi-centered, biomarker-based RCTs |
| Conservation | Inadequate population studies | GIS mapping, climate-smart regeneration |
| Value chains | Low benefit to collectors | Cooperative models, fair-trade certification |
| TEK integration | Knowledge erosion, weak ABS | Digital databases, ABS-compliant collaborations |

## Conclusion

The family Combretaceae, with nearly 20 genera and over 600 species distributed across tropical and subtropical regions, represents a unique intersection of biodiversity, culture, and medicine. From the *Terminalia* species of South Asia to *Combretum* in Africa and *Buchenavia* in South America, members of this family provide critical ecosystem services, sustain rural livelihoods, and form the backbone of numerous traditional healthcare systems. This review synthesized global evidence on taxonomic diversity, ethnomedicinal applications, phytochemistry, pharmacology, clinical validation, and value chains. Findings demonstrate that species such as *Terminalia arjuna*, *T. chebula*, and *Combretum micranthum* hold well-documented ethnomedicinal and pharmacological significance, supported by emerging clinical trials. Phytoconstituents including hydrolyzable tannins, flavonoids, triterpenoids, and stilbenoids underpin a wide range of biological activities — from antioxidant and cardioprotective to antimicrobial and anticancer. Importantly, combretastatins represent one of the few natural product classes from this family that have advanced into oncology clinical trials, highlighting the translational potential of Combretaceae-derived compounds.At the same time, the review underscores critical gaps and challenges: geographic biases in research, underexplored species, lack of standardized protocols, limited large-scale clinical evidence, and growing conservation threats from overharvesting, habitat loss, and climate change. The uneven distribution of benefits within value chains further emphasizes the need for community-centered, fair-trade, and ABS-compliant approaches. Looking forward, integrating modern omics tools, pharmacological validation, GIS-based conservation planning, and socio-economic analysis will be key to unlocking the full potential of this plant family. Equally vital is the recognition and protection of traditional ecological knowledge, ensuring that indigenous communities are active stakeholders in future research and benefit-sharing mechanisms. In conclusion, Combretaceae stands as a cornerstone bio-cultural resource, bridging traditional medicine and modern pharmacology while supporting rural economies and biodiversity

conservation. Strengthening interdisciplinary collaboration, fostering sustainable value chains, and expanding rigorous clinical research will not only safeguard this heritage but also contribute to global health, sustainable development, and climate resilience.

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