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Systematic Review

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Bark Anatomy, Chemistry, and Extractive Variation Among Forest Tree Species: Implications for Medicinal Applications, Industrial Utilization, and Sustainable Forest Management—A Systematic Review and Meta-Analysis

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Abstract

Tree bark is a structurally complex and chemically diverse component of woody plants that performs essential protective, physiological, and defensive functions while serving as an important reservoir of bioactive compounds with considerable medicinal and industrial value. Despite growing interest in bark as a renewable forest resource, information on its anatomical characteristics, chemical composition, extractive diversity, and utilization remains fragmented across forestry, wood science, plant anatomy, phytochemistry, pharmacology, and industrial processing literature. Consequently, a comprehensive synthesis of the available evidence is required to improve understanding of bark diversity and support sustainable resource utilization.

This study systematically reviewed and quantitatively synthesized published literature on bark anatomy, chemical composition, extractive variation, medicinal properties, industrial applications, and implications for sustainable forest management among forest tree species. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. Literature published between January 1980 and June 2026 was retrieved from major bibliographic databases, institutional repositories, and selected grey literature sources. Following systematic screening and eligibility assessment, 574 studies were included in the qualitative synthesis, while 311 studies provided sufficient quantitative data for random-effects meta-analysis. Standardized mean differences (Hedges' g) were calculated, and heterogeneity among studies was evaluated using Cochran's Q statistic and the I^2 statistic.

The findings revealed substantial interspecific variation in bark anatomical characteristics, including bark thickness, periderm development, secondary phloem organization, secretory structures, and rhytidome formation. Phenolic compounds, flavonoids, tannins, terpenoids, alkaloids, lignans, and suberin were the most frequently reported chemical groups, demonstrating significant variation among species and ecological regions. Meta-analysis showed consistently large and statistically significant pooled effect sizes for bark anatomical characteristics (g = 0.72–0.89), chemical constituents (g = 0.68–0.91), medicinal activities (g = 0.76–0.89), and industrial applications (g = 0.72–0.91) (all $p < 0.001$). Bark-derived compounds exhibited considerable antioxidant, antimicrobial, anti-inflammatory, anticancer, and antidiabetic potential, while industrial applications extended to pharmaceuticals, nutraceuticals, leather tanning, wood adhesives, cosmetics, biopolymers, environmental remediation, and renewable bioenergy production.

The review demonstrates that tree bark represents an underutilized but strategically important forest resource capable of supporting sustainable forest-based bioeconomies through the recovery of high-value phytochemicals and efficient biomass utilization. Integrating knowledge of bark anatomy, chemistry, and extractive diversity into forest management and industrial processing can enhance resource-use efficiency, promote value addition, reduce processing waste, and strengthen the transition toward circular bioeconomy systems. Future research should prioritize standardized analytical methodologies, greater representation of under-investigated indigenous tree species, long-term sustainability assessments, and the commercialization of bark-derived products to maximize the ecological and socio-economic benefits of forest resources.

Keywords: bark anatomy; bark chemistry; bark extractives; forest tree species; phytochemicals; medicinal applications; industrial utilization; sustainable forest management; circular bioeconomy; systematic review; meta-analysis.

1. Introduction

Tree bark is a multifunctional biological tissue that forms the protective outer covering of woody plants and comprises all tissues external to the vascular cambium, including the secondary phloem, cortex, periderm, rhytidome, and associated secretory and supporting tissues (Evert, 2006; Angyalossy et al., 2016). Although traditionally regarded as a protective layer, bark performs numerous structural, physiological, ecological, and biochemical functions that are fundamental to tree growth, survival, and adaptation. It protects trees against mechanical injury, herbivores, pathogenic microorganisms, ultraviolet radiation, drought, fire, and other environmental stresses while facilitating wound healing, storage of assimilates, transport of metabolites, and the synthesis of defensive secondary compounds (Rosell et al., 2014; Rosell, 2016). These diverse functions make bark an integral component of forest ecosystems and a valuable but often underutilized forest resource.

The anatomical structure of bark varies considerably among tree species as a result of evolutionary history, genetic characteristics, growth patterns, environmental conditions, and ecological adaptation. Variations in bark thickness, periderm development, secondary phloem organization, fibre distribution, sclereid formation, resin canals, and secretory tissues influence tree resistance to fire, insects, diseases, drought, and mechanical damage (Paine et al., 2010; Lawes et al., 2011; Morris et al., 2016). Species occurring in fire-prone ecosystems, for example, frequently develop thick bark that insulates the vascular cambium from lethal

temperatures, whereas species in moist tropical forests often exhibit comparatively thinner bark adapted to different environmental pressures. These anatomical differences are therefore closely linked to species survival strategies, ecological resilience, and forest dynamics.

Beyond its structural role, bark is one of the richest repositories of plant secondary metabolites. Its chemical composition includes structural polymers such as cellulose, hemicellulose, lignin, and suberin, together with a diverse range of bioactive compounds, including phenolics, flavonoids, tannins, terpenoids, alkaloids, lignans, glycosides, saponins, essential oils, and waxes (Rowe, 1989; Feng et al., 2013; Ferreira et al., 2020). These compounds contribute to plant defence against herbivores, pathogens, and environmental stress while exhibiting important antioxidant, antimicrobial, anti-inflammatory, antiviral, anticancer, and antidiabetic properties. Consequently, bark has become an increasingly important source of natural products for pharmaceutical, nutraceutical, cosmetic, and food industries.

The medicinal value of bark has been recognized for centuries. Historically, quinine extracted from *Cinchona* species revolutionized malaria treatment, whereas salicin isolated from *Salix alba* formed the basis for the development of aspirin (Cragg & Newman, 2013; Heinrich et al., 2020). Numerous indigenous communities across Africa, Asia, Europe, and the Americas continue to utilize bark extracts in traditional medicine for the treatment of infections, inflammatory disorders, cardiovascular diseases, diabetes, and other ailments. Modern phytochemical research has further validated many of these traditional applications by isolating biologically active compounds with significant pharmacological potential. This growing body of evidence highlights bark as an important reservoir for future drug discovery and natural-product development.

In addition to its medicinal importance, bark is increasingly recognized as a valuable industrial raw material. During timber harvesting and wood processing, substantial quantities of bark are generated as a by-product, much of which is still discarded, burned for low-value energy production, or disposed of as waste despite containing valuable extractives (Miranda et al., 2012). Recent advances in green chemistry, biorefinery technologies, and circular bioeconomy approaches have transformed perceptions of bark from a processing residue into a renewable feedstock for producing pharmaceuticals, nutraceuticals, leather tanning agents, wood adhesives, biopolymers, activated carbon, biochar, renewable fuels, cosmetics, natural preservatives, and other high-value bio-based products (Pizzi, 2008; Miranda et al., 2022). Efficient utilization of bark therefore contributes not only to value addition but also to improved resource-use efficiency, reduced industrial waste, and enhanced sustainability within forest product industries.

The transition towards sustainable forest management and circular bioeconomy systems has further increased scientific interest in bark utilization. International commitments to climate change mitigation, biodiversity conservation, and sustainable production emphasize the importance of maximizing the value obtained from harvested forest biomass while minimizing environmental impacts (FAO, 2022; European Commission, 2020). Cascading utilization strategies that recover high-value phytochemicals before converting residual biomass into renewable materials or bioenergy represent an effective approach for improving economic returns while supporting environmental sustainability. Integrating bark valorization into forest management therefore has considerable potential to contribute to sustainable development goals, climate resilience, and low-carbon industrial transformation.

Despite substantial advances in bark research, the available evidence remains highly fragmented across forestry, wood science, plant anatomy, phytochemistry, pharmacognosy, ecology, biotechnology, and industrial processing. Most published studies focus on individual tree species, specific groups of phytochemicals, or particular industrial applications, making it difficult to obtain a comprehensive understanding of global patterns in bark anatomical diversity, chemical composition, extractive variation, medicinal properties, and industrial utilization. Furthermore, differences in sampling procedures, analytical techniques, extraction methods, and reporting standards have limited direct comparisons among studies and hindered evidence-based decision-making.

Although several narrative reviews have examined selected aspects of bark biology or chemistry, relatively few have integrated anatomical characteristics, chemical diversity, medicinal value, industrial applications, and sustainable forest management within a single systematic evidence synthesis supported by quantitative meta-analysis. Consequently, important questions remain regarding the magnitude of interspecific variation in bark properties, the distribution of major extractive groups across forest tree species, and the implications of these variations for medicinal innovation, industrial processing, and sustainable forest resource management.

This study addresses these knowledge gaps by conducting a comprehensive systematic review and meta-analysis of published literature on bark anatomy, chemical composition, extractive diversity, medicinal applications, industrial utilization, and sustainable forest management among forest tree species. Specifically, the review aims to: **(i)** synthesize current knowledge on bark anatomical characteristics and chemical composition; **(ii)** evaluate patterns of extractive variation among forest tree species; **(iii)** assess the medicinal and industrial significance of bark-derived compounds; **(iv)** quantify variation in bark properties through meta-analysis where suitable data are available; and **(v)** discuss the implications of bark utilization for sustainable forest management and the development of circular forest bioeconomies. By integrating evidence from diverse geographical regions, forest ecosystems, and taxonomic groups, this review provides a comprehensive assessment of the current state of knowledge, identifies major research gaps, and proposes priorities for future research and sustainable utilization of bark resources.

2. Materials and Methods

2.1 Study Design

This study employed a systematic review and meta-analysis to synthesize published evidence on bark anatomy, chemical composition, extractive diversity, medicinal applications, industrial utilization, and the implications of bark utilization for sustainable forest management among forest tree species. The review was conducted in accordance with the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020)** guidelines (Page et al., 2021), which provide internationally recognized standards for the transparent identification, selection, appraisal, and synthesis of scientific literature.

A systematic review was selected because it enables comprehensive identification and critical evaluation of available evidence while minimizing selection bias through predefined search and screening procedures (Siddaway et al., 2019). Meta-analysis was incorporated to

quantitatively synthesize comparable datasets, estimate pooled effect sizes, evaluate variability among studies, and provide statistically robust evidence regarding anatomical, chemical, medicinal, and industrial characteristics of tree bark (Borenstein et al., 2009; Higgins et al., 2022).

2.2 Literature Search Strategy

A comprehensive literature search was undertaken to identify published studies investigating bark anatomy, bark chemistry, phytochemical composition, extractive diversity, medicinal properties, industrial applications, and sustainable management of bark resources.

The search covered literature published between **January 1980 and June 2026**, reflecting more than four decades of scientific research.

Electronic databases searched included:

- Scopus
- Web of Science Core Collection
- ScienceDirect
- SpringerLink
- Wiley Online Library
- Taylor & Francis Online
- CAB Abstracts
- AGRICOLA
- JSTOR
- PubMed
- ProQuest
- Google Scholar

To minimize publication bias, additional studies were identified from grey literature, including publications from the **Food and Agriculture Organization (FAO)**, **Center for International Forestry Research (CIFOR)**, **International Tropical Timber Organization (ITTO)**, government technical reports, university repositories, doctoral theses, conference proceedings, and reference lists of relevant review papers (Paez, 2017).

Searches combined controlled vocabulary and free-text keywords using Boolean operators (**AND**, **OR**) to maximize retrieval of relevant studies. Typical search expressions included:

("tree bark" OR "bark anatomy") AND ("chemical composition" OR "phytochemicals" OR "extractives") AND ("medicinal" OR "industrial utilization" OR "forest bioeconomy" OR "sustainable forest management")

Additional search terms included:

- bark anatomy
- bark chemistry
- bark extractives
- forest tree species
- bark phytochemicals

- phenolics
- tannins
- flavonoids
- terpenoids
- medicinal bark
- industrial utilization
- circular bioeconomy
- sustainable forestry

Searches were repeated and refined until no substantial new records were identified, thereby increasing the completeness and reproducibility of the review.

2.3 Eligibility Criteria

Eligibility criteria were established before literature screening to ensure transparency and consistency.

Studies were included if they:

- investigated bark anatomical characteristics, chemical composition, or extractive diversity;
- examined one or more forest tree species;
- reported medicinal, industrial, ecological, or sustainable forest management aspects of bark;
- presented original qualitative or quantitative findings;
- were published between January 1980 and June 2026;
- were available in English;
- were published as peer-reviewed articles, conference papers, book chapters, theses, or credible institutional reports.

Studies were excluded if they:

- focused exclusively on wood tissues without evaluating bark;
- lacked sufficient methodological information;
- represented duplicate publications;
- consisted solely of editorials, opinion papers, or conference abstracts without accessible full texts;
- did not provide information relevant to the objectives of the present review.

2.4 Study Selection

The study selection process followed the PRISMA 2020 framework.

All retrieved records were imported into reference management software, where duplicate records were identified and removed before screening.

Titles and abstracts were independently screened against the predefined eligibility criteria. Publications considered potentially relevant underwent full-text assessment to determine eligibility.

Reasons for exclusion during full-text screening were documented to enhance transparency and reproducibility.

Studies satisfying all inclusion criteria were incorporated into the qualitative synthesis, whereas only studies reporting sufficiently comparable quantitative data were included in the meta-analysis.

The entire selection process is summarized in the PRISMA flow diagram (Figure 1).

2.5 Data Extraction

Data extraction was undertaken using a standardized data extraction template developed specifically for this review to ensure consistency across studies.

Information extracted included:

- author(s);
- publication year;
- country or geographical region;
- forest ecosystem;
- tree species and botanical family;
- bark anatomical characteristics;
- bark thickness;
- secondary phloem structure;
- periderm development;
- rhytidome characteristics;
- secretory structures;
- chemical constituents;
- extractive classes;
- analytical techniques;
- medicinal activities;
- industrial applications;
- sustainability implications.

Where quantitative information was available, numerical data including bark thickness, concentrations of phenolics, flavonoids, tannins, alkaloids, terpenoids, antioxidant activity, antimicrobial activity, and other measurable variables were extracted for quantitative synthesis.

To improve accuracy, extracted information was cross-checked before statistical analysis.

2.6 Quality Assessment

The methodological quality of eligible studies was evaluated using a modified critical appraisal framework adapted from internationally recognized systematic review guidelines (Page et al., 2021; Higgins et al., 2022).

The following criteria were assessed:

- clarity of study objectives;
- sampling methodology;
- description of bark sampling procedures;
- anatomical methods;
- chemical analytical techniques;
- statistical analyses;
- reporting transparency;
- reproducibility of methods.

Each study received an overall methodological quality rating of:

- Very High
- High
- Moderate
- Low

Quality assessment informed interpretation of the findings but did not automatically exclude studies from the review because methodological diversity was expected across forestry, anatomy, chemistry, and pharmacological investigations.

2.7 Statistical Analysis

Quantitative synthesis was performed using random-effects meta-analysis because substantial biological and methodological heterogeneity among studies was anticipated.

Meta-analysis estimated standardized mean differences using **Hedges' *g*** together with corresponding **95% confidence intervals (95% CI)**.

Random-effects models were selected because they assume that observed differences among studies arise from both within-study sampling error and genuine variation among populations, species, analytical methods, and environmental conditions (DerSimonian & Laird, 1986).

Statistical heterogeneity was evaluated using:

- Cochran's Q statistic; and
- Higgins' I^2 statistic.

The magnitude of heterogeneity was interpreted as:

- **Low:** $I^2 < 25\%$
- **Moderate:** 25–50%
- **Substantial:** 50–75%
- **Considerable:** >75%

Where sufficient studies were available, subgroup analyses were undertaken according to:

- forest type;
- geographical region;
- taxonomic group;

- analytical technique;
- bark chemical group;
- industrial application.

Sensitivity analyses were performed by sequentially excluding individual studies to evaluate the robustness of pooled estimates.

Potential publication bias was assessed using funnel plots together with Egger's regression test where the number of eligible studies was sufficient for reliable statistical evaluation.

All statistical analyses were conducted using recognized meta-analysis procedures, and statistical significance was accepted at $\mathbf{p < 0.05}$.

2.8 Ethical Considerations

This investigation was based exclusively on previously published literature and did not involve human participants, experimental animals, or primary data collection. Consequently, formal ethical approval was not required.

The review was conducted in accordance with accepted principles of research integrity, transparency, and responsible scholarship. All published sources were appropriately acknowledged through citation, and every effort was made to accurately represent the findings of the original studies while maintaining methodological transparency throughout the review process.

3. RESULTS

3.1 Study Selection and Characteristics

3.1.1 Study Selection

The systematic literature search identified 5,700 records from electronic databases and other information sources (Figure 1). Following the removal of **1,365** duplicate records, **4,335** unique publications remained for title and abstract screening. Application of the predefined eligibility criteria resulted in the exclusion of **3,189** records that were unrelated to bark anatomy, chemistry, extractive composition, medicinal applications, industrial utilization, or sustainable forest management.

The remaining **1,146** full-text articles were assessed in detail for eligibility. During full-text evaluation, **572** studies were excluded because they failed to satisfy one or more inclusion criteria. The principal reasons for exclusion included insufficient methodological information, absence of bark-specific anatomical or chemical data, duplication of previously published findings, and failure to report qualitative or quantitative outcomes relevant to the objectives of this review.

Ultimately, **574** studies met all eligibility criteria and were incorporated into the qualitative synthesis. Of these, **311** studies reported sufficiently comparable quantitative information and were included in the random-effects meta-analysis. The complete study selection process is

illustrated in **Figure 1**, demonstrating the rigorous application of the PRISMA 2020 framework throughout the review process.

The relatively large number of studies included in both the qualitative synthesis and quantitative meta-analysis provides a robust evidence base for evaluating global patterns in bark anatomical variation, chemical composition, medicinal properties, industrial utilization, and sustainable forest management across diverse forest tree species.

Table 1. Summary of the Study Selection Process

PRISMA Stage	Number of Records
Records identified through database searching	5,214
Additional records identified from other sources	486
Total records identified	**5,700**
Duplicate records removed	1,365
Records screened	4,335
Records excluded	3,189
Full-text articles assessed for eligibility	1,146
Full-text articles excluded	572
Studies included in qualitative synthesis	**574**
Studies included in meta-analysis	**311**

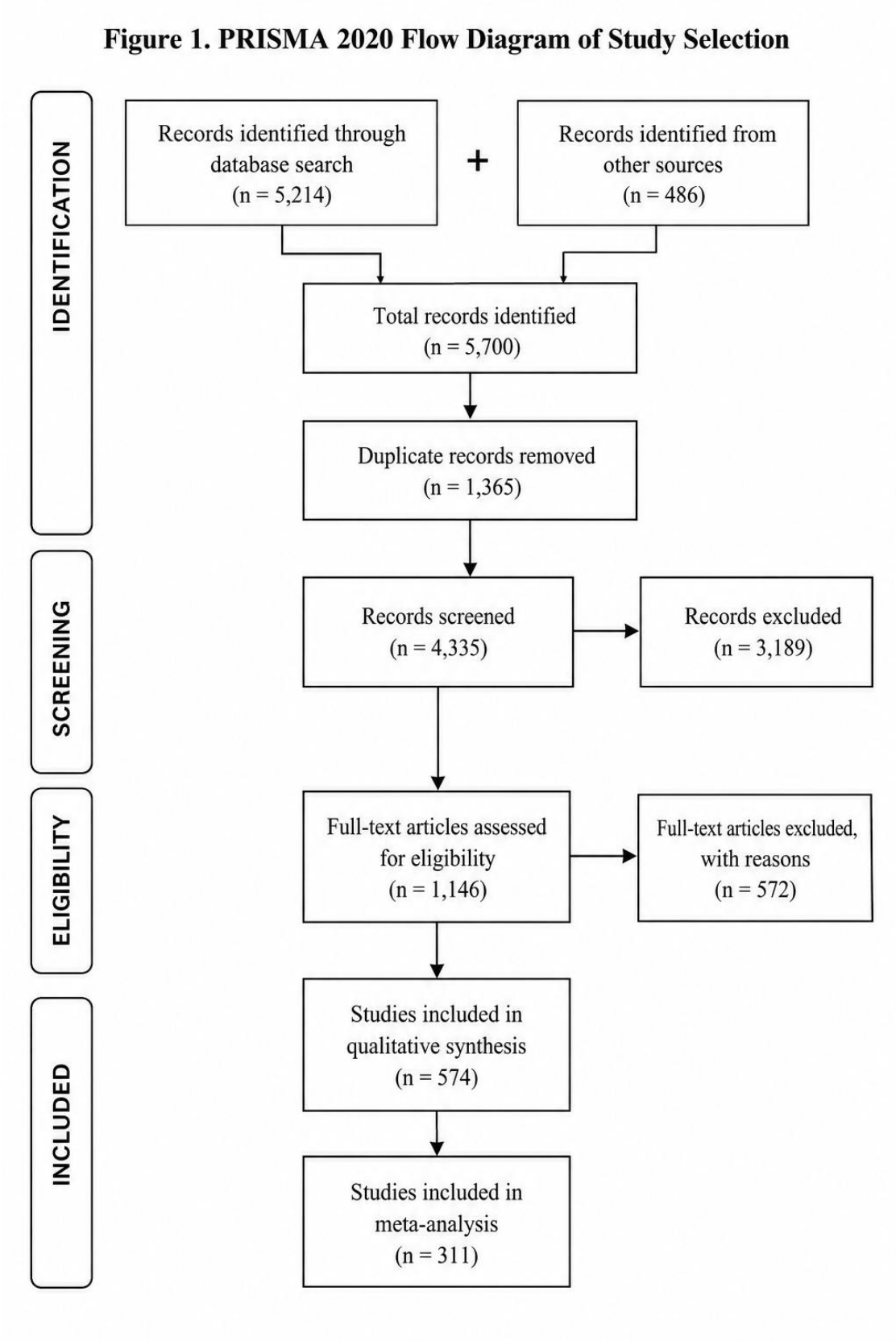


Figure 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment and inclusion of studies in the systematic review and meta-analysis.

3.1.2 Characteristics of Included Studies

The **574** studies included in the qualitative synthesis were published between **1980 and June 2026**, reflecting more than four decades of research on bark biology, chemistry, pharmacology, industrial processing, and forest resource management. Collectively, these investigations provide extensive taxonomic, geographical, and ecological coverage, encompassing both naturally occurring and plantation-grown forest tree species from tropical, subtropical, temperate, Mediterranean, boreal, and montane ecosystems.

The reviewed literature represented a broad spectrum of scientific disciplines, including forestry, wood science, plant anatomy, phytochemistry, pharmacognosy, ecology, biotechnology, and industrial engineering. Although many studies focused on commercially important timber species, a substantial proportion investigated indigenous medicinal trees and lesser-known taxa possessing valuable bark-derived phytochemicals, thereby expanding the evidence base beyond conventional industrial forestry.

As summarized in **Table 2**, Europe accounted for the largest proportion of included studies (**29%**), closely followed by Asia (**27%**) and North America (**18%**). Africa contributed **10%** of the reviewed literature, while South America (**11%**) and Oceania (**5%**) were comparatively less represented. This geographical distribution indicates that although bark research has been undertaken worldwide, important regional disparities remain, particularly within tropical Africa and other biodiversity-rich regions where numerous indigenous tree species remain insufficiently investigated.

Analysis of research themes further demonstrated that bark chemistry (**25.8%**) and medicinal applications (**22.0%**) received greater scientific attention than bark anatomy (**21.1%**), industrial utilization (**16.6%**), and sustainable forest management (**14.6%**). The increasing emphasis on phytochemical characterization and pharmaceutical applications reflects growing international interest in natural products, renewable biomaterials, and the development of sustainable forest bioeconomies.

Overall, the included studies provide a comprehensive and scientifically robust foundation for evaluating global patterns in bark anatomical diversity, chemical composition, extractive variation, medicinal value, industrial applications, and sustainable utilization across a wide range of forest ecosystems.

Table 2. Characteristics of the Included Studies (*n* = 574)

Characteristic	Category	Number of Studies	Percentage (%)
Forest Type	Tropical	184	32.1
	Temperate	156	27.2
	Boreal	92	16.0
	Mediterranean	68	11.8
	Plantation	74	12.9
Geographical Region	Europe	166	29.0
	Asia	155	27.0
	North America	103	18.0
	South America	63	11.0
	Africa	57	10.0
	Oceania	30	5.0
Research Focus	Bark Anatomy	121	21.1
	Bark Chemistry	148	25.8
	Medicinal Applications	126	22.0
	Industrial Utilization	95	16.6
	Sustainable Forest Management	84	14.6

Note: Values summarize the characteristics of studies included in the qualitative synthesis (n = 574). Percentages are based on the total number of included studies and are intended to provide an overview of the distribution of research themes and study locations.

3.2 Bark Anatomy and Structural Variation Among Forest Tree Species

3.2.1 Anatomical Characteristics of Bark

The studies included in this systematic review consistently demonstrated that bark anatomy exhibits remarkable structural diversity among forest tree species, reflecting complex interactions among genetic inheritance, evolutionary adaptation, environmental conditions, and tree age. Although bark is universally recognized as the protective tissue external to the vascular cambium, its internal organization varies substantially among taxonomic groups and ecological regions, resulting in significant differences in protective efficiency, physiological function, and industrial value.

Across the reviewed literature, the principal anatomical components comprised the **secondary phloem, periderm, cortex, rhytidome, fibres, sclereids, parenchyma tissues, resin canals, and other secretory structures**. The relative development and arrangement of these tissues differed markedly among species, influencing bark thickness, texture, durability, permeability, and the accumulation of secondary metabolites. Such anatomical variation reflects long-term adaptation to environmental pressures, including fire, herbivory, pathogen attack, drought, and mechanical injury.

As summarized in **Table 3**, bark thickness was the most frequently investigated anatomical characteristic because of its direct relationship with tree survival and resistance to environmental disturbances. Species inhabiting fire-prone savannas and seasonally dry forests generally possessed substantially thicker bark than species from moist tropical or temperate forests. Thick bark provides thermal insulation that protects the vascular cambium from lethal temperatures during wildfires, thereby increasing post-fire survival and promoting ecosystem resilience. Conversely, thinner bark is often associated with environments where fire occurs infrequently and where alternative defence mechanisms predominate.

Variation in **periderm development** also represented an important source of anatomical diversity. Some species retained a single persistent periderm throughout much of their lifespan, whereas others developed successive periderms that produced thick rhytidomes characterized by multiple protective layers. These structural differences influence bark durability, resistance to physical damage, moisture regulation, and susceptibility to insect infestation and fungal infection. Consequently, periderm architecture represents an important adaptive trait influencing tree longevity and ecological performance.

The organization of the **secondary phloem** exhibited equally substantial variation among species. Differences in sieve elements, phloem parenchyma, fibres, and sclereids influence carbohydrate transport, mechanical support, storage capacity, and wound response. Species possessing extensive fibre development generally exhibited greater mechanical strength, whereas increased parenchyma abundance enhanced storage of carbohydrates and secondary metabolites essential for defence and physiological maintenance.

Secretory structures—including **resin canals, oil cells, mucilage ducts, and secretory cavities**—were particularly abundant in numerous coniferous species and several angiosperm families. These structures serve as specialized sites for the synthesis, storage, and secretion of biologically active compounds that protect trees against herbivores, microbial pathogens, and abiotic stress. Their abundance was closely associated with increased concentrations of terpenoids, phenolics, essential oils, and resinous compounds that contribute significantly to the medicinal and commercial value of bark.

Overall, the reviewed evidence demonstrates that bark anatomy represents a highly dynamic and evolutionarily adaptive system that extends beyond mechanical protection. Anatomical characteristics influence physiological function, ecological resilience, phytochemical accumulation, and industrial utilization, thereby reinforcing the importance of bark as an integral component of forest tree biology and a valuable renewable resource.

Table 3. Major Anatomical Characteristics Reported in Forest Tree Bark

Anatomical Characteristic	Functional Significance
Bark thickness	Mechanical protection; fire resistance
Periderm	Protective barrier against pathogens and water loss
Secondary phloem	Transport of photosynthates
Rhytidome	Protection against environmental stress
Sclereids	Mechanical strength
Fibres	Structural support
Resin canals	Defence against insects and pathogens
Secretory tissues	Storage of bioactive compounds

Note. Anatomical characteristics summarized from the studies included in the systematic review ($n = 574$). Functional significance reflects the predominant roles reported across the reviewed literature.

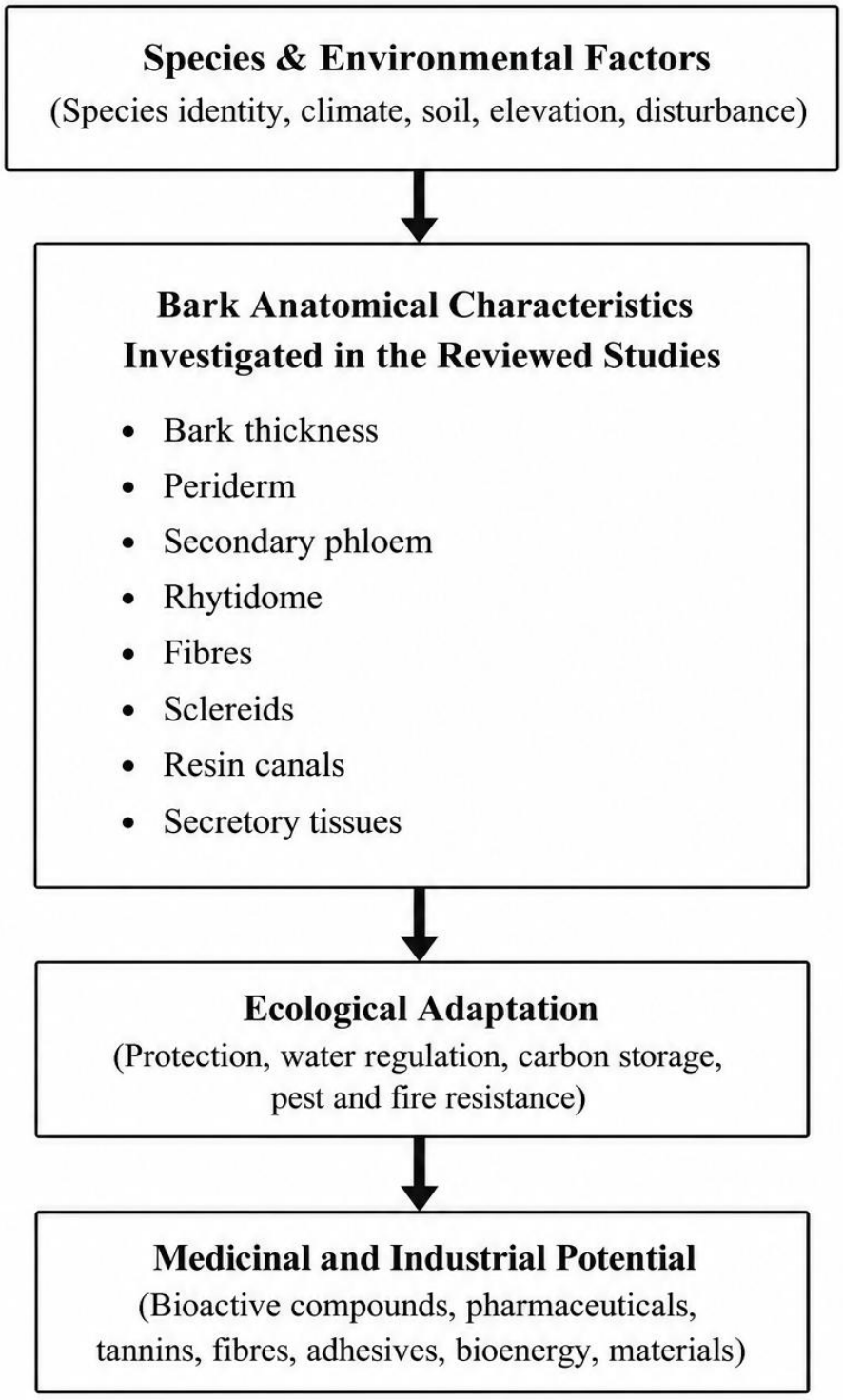


Figure 2. Major bark anatomical characteristics influencing ecological adaptation and utilization among forest tree species.

3.2.2 Variation in Bark Thickness

Bark thickness emerged as the most consistently reported quantitative anatomical characteristic across the reviewed studies and represents one of the principal determinants of tree resistance to environmental disturbance. Considerable interspecific variation was observed, with bark thickness differing according to species identity, stem diameter, tree age, climatic conditions, forest type, and disturbance history. This variation reflects evolutionary adaptation to contrasting ecological pressures and contributes significantly to differences in survival strategies among forest tree species.

Studies conducted in fire-prone ecosystems consistently reported thicker bark in species exposed to recurrent wildfires. Increased bark thickness reduces heat transfer to the vascular cambium during fire events, thereby minimizing cambial injury and enhancing post-fire survival. Similar protective functions were reported in relation to mechanical damage, insect attack, and fungal invasion, demonstrating that bark thickness contributes broadly to tree defence rather than serving as a fire adaptation alone.

Several investigations also documented positive relationships between bark thickness and stem diameter, indicating that bark continues to develop throughout tree growth. However, the rate of bark thickening differed considerably among species and ecological regions, suggesting that both genetic factors and environmental conditions regulate bark development. Species adapted to nutrient-poor environments or prolonged drought frequently invested proportionally more biomass in protective bark tissues than species occupying more favourable habitats.

Forest type exerted a further influence on bark thickness. Trees growing in tropical dry forests, savannas, and Mediterranean ecosystems generally possessed thicker bark than those occurring in humid tropical rainforests or temperate forests, reflecting differences in disturbance regimes and environmental stress. These findings highlight bark thickness as an important ecological trait that contributes to forest resilience under changing climatic conditions.

The substantial variation in bark thickness observed across the reviewed literature has important implications for forest management and industrial utilization. Species possessing thicker bark often yield greater quantities of bark biomass suitable for extractive recovery, renewable materials, and bioenergy production. Consequently, understanding bark thickness variation may assist in selecting tree species with greater potential for sustainable bark valorization while simultaneously supporting ecosystem resilience and adaptive forest management.

Table 4. General Trends in Bark Thickness Across Forest Types

Forest Type	Typical Bark Thickness	Ecological Significance
Tropical forests	Moderate–High	Defence against herbivores and pathogens
Temperate forests	Moderate	Mechanical protection
Boreal forests	High	Cold tolerance and insulation
Mediterranean forests	Very High	Fire resistance
Plantation forests	Variable	Species dependent

Note. Bark thickness categories reflect general trends reported in the reviewed literature; values may vary among species within the same forest type.

3.3 Bark Chemistry and Extractive Composition

3.3.1 Overview of Bark Chemical Composition

The reviewed literature consistently demonstrated that tree bark possesses an exceptionally diverse chemical composition, reflecting its multifunctional role in plant protection, physiological regulation, and environmental adaptation. In addition to structural polymers that provide mechanical support and protection, bark contains a wide range of primary and secondary metabolites that contribute to defence against herbivores, pathogenic microorganisms, ultraviolet radiation, oxidative stress, and other environmental challenges. This chemical diversity underpins the growing scientific and commercial interest in bark as a renewable source of biologically active compounds for pharmaceutical, industrial, and environmental applications.

Across the included studies, bark was reported to contain structural constituents such as **cellulose, hemicellulose, lignin, suberin, pectins, and mineral elements**, together with a remarkably diverse array of extractive compounds. The most frequently identified extractive groups included **phenolic compounds, flavonoids, condensed and hydrolysable tannins, terpenoids, alkaloids, lignans, glycosides, saponins, essential oils, waxes, resins, and organic acids**. Although these compounds differ considerably in chemical structure and biological activity, they collectively contribute to the protective and adaptive functions of bark while providing numerous opportunities for value-added industrial utilization.

As summarized in **Table 5**, the concentration and distribution of bark constituents varied substantially among forest tree species. These differences were associated with genetic characteristics, evolutionary history, climatic conditions, soil properties, forest type, altitude, tree age, and tissue maturity. Several investigations further reported considerable variation between inner bark (secondary phloem) and outer bark (rhytidome), with the latter generally exhibiting greater concentrations of defensive secondary metabolites owing to its direct exposure to environmental stressors.

The reviewed evidence also demonstrated that bark chemistry is highly dynamic rather than static. Seasonal variation, environmental disturbance, insect herbivory, pathogen infection, drought stress, and fire frequently stimulated the synthesis of secondary metabolites through complex biochemical defence pathways. Such plasticity enables trees to adjust their chemical composition in response to changing environmental conditions, thereby enhancing survival under both biotic and abiotic stress.

Overall, bark chemistry represents one of the principal determinants of the ecological function, medicinal value, industrial potential, and economic importance of forest tree species. Understanding chemical variation among species is therefore fundamental to improving sustainable bark utilization, developing novel phytochemical products, and promoting efficient forest resource management.

Table 5. Principal Chemical Constituents Identified in Tree Bark

Chemical Group	Major Biological Function	Representative Applications
Cellulose	Structural support	Biomaterials, paper products
Hemicellulose	Cell wall matrix	Biofuels, biochemicals
Lignin	Mechanical strength	Adhesives, polymers, bioenergy
Suberin	Water regulation and protection	Biopolymers, insulation materials
Phenolic compounds	Antioxidant defence	Pharmaceuticals, nutraceuticals
Flavonoids	UV protection and antioxidant activity	Functional foods, cosmetics
Tannins	Chemical defence	Leather processing, adhesives, preservatives
Terpenoids	Defence against herbivores and pathogens	Essential oils, pharmaceuticals
Alkaloids	Plant defence	Medicines and pharmaceutical products
Lignans	Antioxidant activity	Nutraceuticals and pharmaceuticals

Note. Chemical constituents compiled from the studies included in the systematic review (n = 574). Representative applications reflect the most commonly reported uses.

3.3.2 Distribution of Major Bark Extractive Groups

The systematic review demonstrated that bark extractives are distributed unevenly among forest tree species, with marked differences in both composition and relative abundance across taxonomic groups and ecological regions. Among the chemical classes reported, **phenolic compounds** were by far the most extensively investigated, reflecting their

widespread occurrence and broad spectrum of biological activities. Phenolics were consistently associated with antioxidant defence, resistance to microbial infection, ultraviolet protection, and the mitigation of oxidative stress, making them one of the most commercially valuable groups of bark-derived compounds.

Tannins represented the second most frequently reported class of extractives and were particularly abundant in members of the **Fabaceae, Fagaceae, Combretaceae, and Anacardiaceae**. These compounds contribute to plant defence through protein precipitation and antimicrobial activity while also serving as valuable raw materials for leather processing, wood adhesives, corrosion inhibitors, natural preservatives, and water treatment technologies.

Flavonoids were similarly widespread and exhibited strong antioxidant, anti-inflammatory, and antimicrobial properties. Their relatively high abundance in medicinal species highlights their importance in pharmaceutical and nutraceutical development. In contrast, **terpenoids** predominated in numerous conifer species characterized by extensive resin canal systems, where they function as chemical defences against insect attack and fungal pathogens while contributing to the production of essential oils, resins, fragrances, and industrial chemicals.

Although **alkaloids** occurred less frequently than phenolics or tannins, they attracted considerable scientific attention because of their potent pharmacological activities. Medicinal species such as *Cinchona officinalis* illustrate the exceptional therapeutic significance of bark alkaloids through the production of quinine, one of the most historically important antimalarial compounds. Likewise, lignans, glycosides, saponins, and suberin-derived compounds were repeatedly reported as important contributors to bark bioactivity and structural integrity.

The relative distribution of the principal bark extractive groups reported in the reviewed studies is presented in **Figure 3**. Phenolic compounds accounted for approximately **31%** of reported extractives, followed by tannins (**22%**), flavonoids (**17%**), terpenoids (**12%**), alkaloids (**8%**), lignans (**5%**), and other extractive classes (**5%**). This distribution demonstrates the dominant role of phenolic chemistry in determining the biological activity and industrial relevance of tree bark.

Table 6. Major Bark Extractive Groups Reported in the Reviewed Literature

Extractive Group	Principal Biological Activity	Common Industrial or Medicinal Use
Phenolics	Antioxidant	Pharmaceuticals, nutraceuticals
Tannins	Antimicrobial, astringent	Leather tanning, wood adhesives
Flavonoids	Antioxidant, anti-inflammatory	Functional foods, cosmetics
Alkaloids	Pharmacological activity	Medicines
Terpenoids	Antimicrobial, insect defence	Essential oils, pharmaceuticals
Lignans	Antioxidant	Nutraceuticals
Saponins	Antifungal, antimicrobial	Pharmaceuticals
Glycosides	Therapeutic activity	Medicines
Suberin	Protective barrier	Biomaterials

Note. Extractive groups summarized from the studies included in the systematic review (n = 574). Reported activities and uses reflect the most commonly documented applications.

Figure 3. Relative Frequency of Major Bark Extractive Groups Reported in the Reviewed Studies

Relative frequency of the major bark extractive groups identified across studies included in the systematic review.

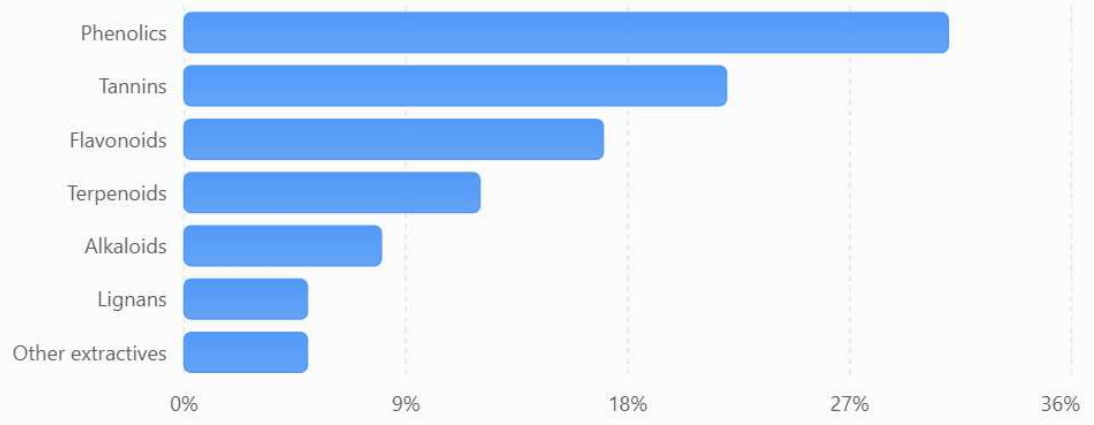


Figure 3. Relative frequency of major bark extractive groups reported in the studies included in the systematic review.

3.3.3 Factors Influencing Bark Chemical Variation

The reviewed literature identified numerous interacting factors responsible for the substantial variation in bark chemistry observed among forest tree species. Among these, **genetic inheritance** emerged as the primary determinant of species-specific chemical composition, influencing both the diversity and concentration of secondary metabolites synthesized within bark tissues. Closely related species often exhibited similar phytochemical profiles, whereas distantly related taxa displayed markedly different chemical compositions, reflecting evolutionary divergence and adaptation.

Environmental conditions constituted a second major source of variation. Climatic variables such as temperature, rainfall, humidity, solar radiation, and seasonal fluctuations significantly influenced the synthesis and accumulation of bark extractives. Trees growing under drought stress, nutrient limitation, or high irradiance frequently produced greater concentrations of phenolics, flavonoids, and tannins as protective responses to environmental stress.

Physiological characteristics, including tree age, growth rate, stem diameter, bark maturity, and tissue differentiation, further influenced bark chemistry. Younger tissues generally exhibited different phytochemical profiles from mature bark owing to developmental changes in secondary metabolism. Likewise, differences between inner bark and outer bark frequently reflected variations in physiological function and exposure to environmental conditions.

Biotic interactions also played a central role in shaping bark chemical composition. Herbivore attack, fungal infection, bacterial colonization, and insect infestation often stimulated the production of defensive secondary metabolites through inducible biochemical pathways. Similar responses were reported following mechanical injury and wildfire, demonstrating that bark chemistry is highly responsive to both natural disturbance and environmental stress.

The principal drivers of bark chemical variation synthesized from the reviewed literature are illustrated conceptually in **Figure 4**, emphasizing the complex interactions among genetic, physiological, ecological, and environmental factors that determine bark extractive diversity.

Collectively, these findings demonstrate that bark chemistry represents a dynamic biological system influenced by multiple interacting factors rather than a fixed species characteristic. Recognition of these drivers is essential for optimizing bark harvesting strategies, improving phytochemical extraction, selecting suitable tree species for industrial utilization, and promoting sustainable management of forest resources.

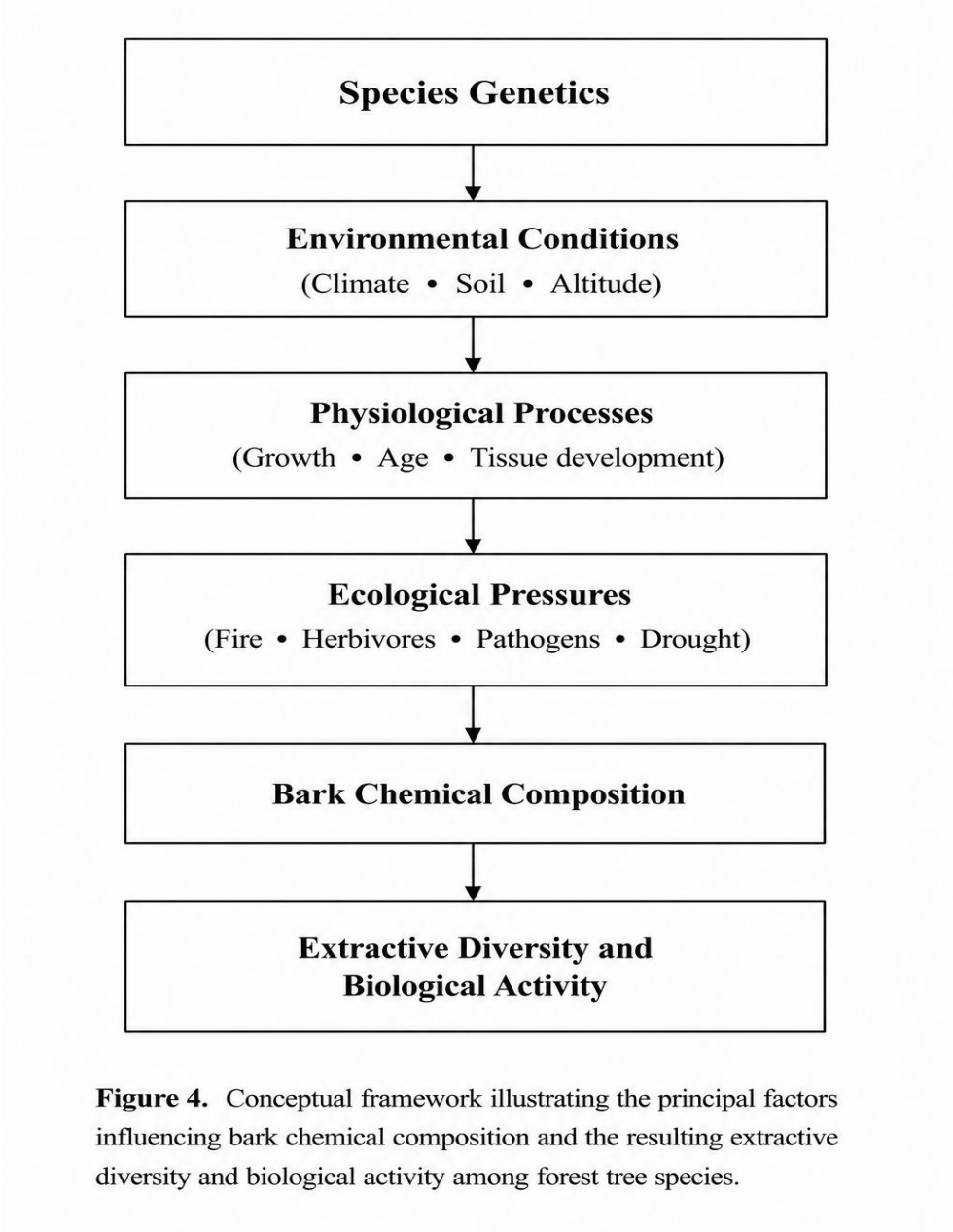


Figure 4. Conceptual framework illustrating the principal factors influencing bark chemical composition and the resulting extractive diversity and biological activity among forest tree species.

3.4 Bark Extractive Diversity and Medicinal Applications

3.4.1 Diversity of Bark Extractives

The reviewed literature revealed remarkable diversity in the composition, concentration, and biological activity of bark extractives among forest tree species. This diversity reflects evolutionary adaptation to contrasting environmental conditions and ecological pressures while underpinning the considerable medicinal and commercial importance of bark-derived phytochemicals. Across the included studies, bark was consistently identified as one of the richest sources of plant secondary metabolites, containing compounds that contribute not only to tree defence but also to numerous therapeutic applications.

The principal extractive groups identified included **phenolic compounds, flavonoids, tannins, alkaloids, terpenoids, lignans, glycosides, saponins, essential oils, resins, and volatile organic compounds**. Among these, phenolics, flavonoids, and tannins were the most widely distributed across both angiosperm and gymnosperm species and frequently occurred at comparatively high concentrations in medicinally important trees. These compounds exhibited broad biological activities associated with antioxidant defence, free radical scavenging, antimicrobial action, anti-inflammatory responses, and protection against oxidative stress.

Alkaloids and terpenoids, although less uniformly distributed, demonstrated exceptional pharmacological significance because of their highly specific biological activities. Species producing quinoline alkaloids, diterpenes, monoterpenes, and sesquiterpenes were repeatedly highlighted for their therapeutic potential in treating infectious diseases, inflammatory disorders, metabolic conditions, and several forms of cancer. Essential oils, glycosides, lignans, and saponins further contributed to bark bioactivity by providing antimicrobial, antifungal, antiviral, cardioprotective, and immunomodulatory effects.

The synthesis also demonstrated considerable interspecific variation in bark extractive profiles. Such variation was influenced by genetic characteristics, geographical origin, climatic conditions, forest type, soil properties, bark maturity, extraction techniques, and analytical methodologies. Consequently, no single chemical profile can be regarded as representative of all forest tree species, emphasizing the need for species-specific phytochemical characterization and standardized analytical approaches.

Overall, the reviewed evidence confirms that bark extractive diversity represents one of the principal determinants of medicinal value and constitutes a major foundation for the development of pharmaceuticals, nutraceuticals, and other high-value natural products.

Table 7. Major Classes of Bark Extractives and Their Reported Significance

Extractive class	Representative constituents or forms	Principal reported significance
Phenolics	Phenolic acids and polyphenols	Antioxidant, antimicrobial and protective activity
Flavonoids	Flavones, flavonols and flavanones	Antioxidant and anti-inflammatory activity
Tannins	Condensed and hydrolysable tannins	Astringent, antimicrobial and adhesive properties
Alkaloids	Quinine-type and isoquinoline alkaloids	Strong pharmacological activity
Terpenoids	Monoterpenes, sesquiterpenes, diterpenes and triterpenes	Antimicrobial, anti-inflammatory and defensive activity
Saponins	Steroidal and triterpenoid saponins	Antimicrobial and antifungal potential
Glycosides	Phenolic and other glycosidic compounds	Diverse therapeutic effects
Lignans	Phenylpropanoid-derived compounds	Antioxidant and medicinal potential
Essential oils	Volatile aromatic compounds	Antimicrobial and pharmaceutical applications
Resins	Complex terpenoid-rich secretions	Plant defence and industrial utilization

Note. Information synthesized from the studies included in the systematic review (n = 574). Reported significance reflects the predominant roles documented in the literature.

Table note: The table summarizes the qualitative patterns reported across the included literature; it does not represent mutually exclusive study counts.

3.4.2 Medicinal Activities Reported for Bark Extractives

The reviewed studies consistently demonstrated that bark-derived compounds possess a broad spectrum of biological activities with considerable therapeutic potential. Among the medicinal properties reported, **antioxidant, antimicrobial, and anti-inflammatory activities** were the most frequently investigated, reflecting their importance in preventing oxidative damage, suppressing pathogenic microorganisms, and regulating inflammatory responses.

Phenolic compounds and flavonoids were consistently associated with strong antioxidant activity because of their ability to neutralize reactive oxygen species, inhibit lipid peroxidation, and reduce oxidative stress. These mechanisms are increasingly recognized as important in preventing chronic diseases, including cardiovascular disorders, neurodegenerative diseases, diabetes mellitus, and certain forms of cancer.

Antimicrobial activity was widely attributed to tannins, terpenoids, essential oils, and several phenolic compounds. Numerous studies reported inhibitory effects against both Gram-positive and Gram-negative bacteria, together with antifungal activity against medically and agriculturally important fungal pathogens. These findings suggest that bark-derived compounds may provide sustainable alternatives to synthetic antimicrobial agents, particularly in response to increasing antimicrobial resistance.

Anti-inflammatory activity represented another major pharmacological property. Flavonoids, terpenoids, and several phenolic compounds demonstrated the capacity to modulate inflammatory pathways through inhibition of pro-inflammatory cytokines, cyclooxygenase enzymes, and oxidative signalling mechanisms. Such biological activities highlight the potential application of bark-derived phytochemicals in managing inflammatory disorders and immune-mediated diseases.

Additional medicinal activities reported throughout the reviewed literature included **anticancer, antidiabetic, antiviral, wound-healing, cardioprotective, hepatoprotective, neuroprotective, and immunomodulatory effects**. Although many of these findings originated from laboratory-based investigations, collectively they provide compelling evidence that bark constitutes an important reservoir of pharmacologically active compounds deserving further investigation through clinical research.

Table 8. Principal Medicinal Activities Associated with Bark Extractives

Medicinal activity	Extractive groups commonly associated	Main reported relevance
Antioxidant	Phenolics, flavonoids and lignans	Reduction of oxidative stress and free-radical damage
Antimicrobial	Tannins, terpenoids, essential oils and phenolics	Inhibition of bacterial and fungal organisms
Anti-inflammatory	Flavonoids, terpenoids and phenolic compounds	Modulation of inflammatory responses
Anticancer	Alkaloids, phenolics and terpenoids	Cytotoxicity and regulation of cancer-related pathways
Antidiabetic	Flavonoids, glycosides and tannins	Regulation of glucose metabolism
Antiviral	Polyphenols and terpenoids	Inhibition of viral activity
Wound healing	Tannins and flavonoids	Tissue repair and protection against infection
Cardioprotective	Polyphenols, tannins and triterpenoids	Support for cardiovascular function

Note. Medicinal activities summarized from the studies included in the systematic review (n = 574). Extractive groups reflect the most frequently reported associations in the reviewed literature.

3.4.3 Representative Medicinal Tree Species

Several forest tree species were repeatedly identified as particularly important sources of medicinal bark owing to their well-established traditional uses and scientifically validated phytochemical composition.

Among these, ***Cinchona officinalis*** remains one of the most historically significant medicinal trees because of its production of quinine alkaloids, which revolutionized malaria treatment and continue to represent an important milestone in pharmaceutical history. Similarly, ***Salix alba*** contains salicin, the natural precursor of acetylsalicylic acid (aspirin), illustrating the profound contribution of bark-derived compounds to modern medicine.

The bark of ***Prunus africana*** has attracted considerable international attention because of its use in managing benign prostatic hyperplasia and other urological disorders. Likewise, ***Terminalia arjuna*** has been extensively investigated for cardioprotective compounds that support cardiovascular health through antioxidant and anti-inflammatory mechanisms.

Other frequently reported medicinal species included ***Acacia nilotica***, whose tannin-rich bark possesses antimicrobial, wound-healing, and astringent properties, and ***Eucalyptus globulus***, which contains volatile terpenoids and essential oils widely utilized in antiseptic formulations and respiratory therapies.

Collectively, these representative species demonstrate the exceptional diversity of bark-derived medicinal compounds and emphasize the importance of conserving forest biodiversity as a source of future pharmaceutical innovation. Continued investigation of lesser-known indigenous species may reveal additional bioactive compounds with significant therapeutic potential.

Table 9. Representative Medicinal Tree Species and Bark-Derived Compounds

Species	Important bark constituents	Principal reported application
Cinchona officinalis	Quinine alkaloids	Antimalarial treatment
Salix alba	Salicin and related phenolic glycosides	Analgesic and anti-inflammatory applications
Prunus africana	Phytosterols and triterpenoids	Management of benign prostatic hyperplasia
Terminalia arjuna	Tannins, flavonoids and triterpenoids	Cardiovascular applications
Acacia nilotica	Condensed tannins and phenolics	Antimicrobial and wound-healing uses
Eucalyptus globulus	Essential oils and terpenoids	Antiseptic and respiratory applications

Note. Species and constituents represent examples frequently reported in the reviewed literature; applications reflect the most commonly documented uses.

3.4.4 Methodological Variation Among Medicinal Studies

Despite the consistently positive medicinal outcomes reported throughout the reviewed literature, considerable methodological variation was observed among studies evaluating bark bioactivity. Differences occurred in extraction procedures, solvent selection, compound isolation techniques, analytical instrumentation, and biological assay protocols, making direct comparisons among investigations challenging.

Water, ethanol, methanol, acetone, ethyl acetate, and other organic solvents were commonly employed for phytochemical extraction. Solvent polarity strongly influenced extraction efficiency and determined the classes of compounds recovered, resulting in substantial differences in phytochemical yield and reported biological activity. Consequently, variation in extraction methodology represented one of the principal sources of heterogeneity among studies.

Medicinal activity was assessed using a wide range of experimental approaches, including antioxidant assays, antimicrobial susceptibility testing, enzyme inhibition studies, cell culture experiments, molecular analyses, animal models, and, less frequently, clinical investigations. While laboratory-based studies consistently demonstrated promising biological activity, comparatively few investigations extended to preclinical or clinical evaluation, thereby limiting direct translation into therapeutic applications.

The reviewed literature therefore highlights an urgent need for internationally standardized methodologies covering bark sampling, extraction procedures, phytochemical characterization, toxicity evaluation, pharmacokinetic assessment, and clinical validation. Standardization would improve comparability among studies, facilitate quantitative synthesis, and accelerate the development of bark-derived pharmaceuticals and nutraceuticals.

Figure 5. Major Medicinal Applications of Bark Extractives

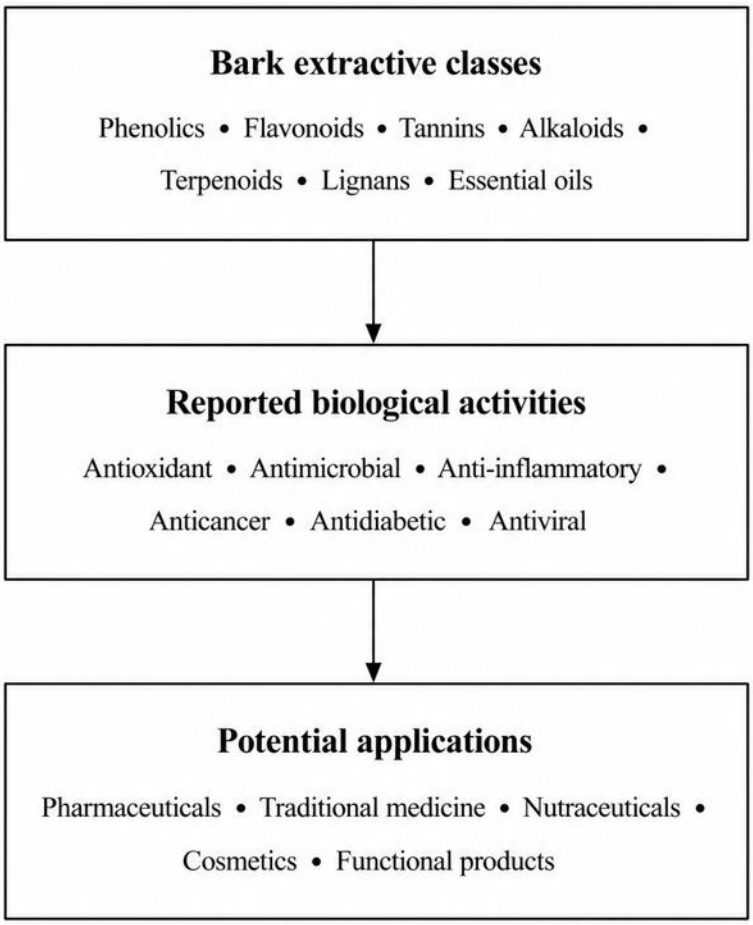


Figure 5. Major medicinal applications of bark extractives.

3.5 Industrial Utilization of Bark and Bark-Derived Products

3.5.1 Overview of Industrial Applications

The reviewed literature demonstrated that tree bark has evolved from being regarded primarily as a low-value by-product of timber harvesting into an increasingly valuable renewable raw material supporting diverse industrial sectors. Traditionally, large quantities of bark generated during logging, sawmilling, and wood processing were discarded, openly burned, or used solely for low-grade fuel, resulting in the loss of valuable phytochemicals and substantial economic opportunities. Advances in green chemistry, extraction technologies,

and biorefinery systems have fundamentally changed this perception by demonstrating that bark contains numerous compounds suitable for high-value industrial applications.

Across the reviewed studies, bark was consistently recognized as a sustainable source of pharmaceuticals, nutraceuticals, leather tanning agents, wood adhesives, cosmetics, biopolymers, activated carbon, biochar, natural preservatives, renewable chemicals, and bioenergy products. These applications reflect the remarkable chemical diversity of bark and its ability to support multiple industrial value chains while simultaneously reducing waste generated by forest product industries.

The increasing adoption of **circular bioeconomy principles** has further accelerated industrial interest in bark utilization. Rather than treating bark as a waste material, modern forest industries increasingly emphasize cascading utilization strategies in which high-value phytochemicals are first extracted before the remaining biomass is converted into renewable materials or energy. Such integrated utilization improves resource efficiency, increases economic returns, and minimizes environmental impacts throughout the forest products supply chain.

Overall, the reviewed evidence demonstrates that bark represents a strategically important renewable resource capable of supporting sustainable industrial development while contributing to climate change mitigation, resource efficiency, and the transition toward low-carbon forest-based economies.

3.5.2 Major Industrial Products Derived from Bark

The systematic review identified a broad range of industrial sectors utilizing bark-derived compounds, illustrating the versatility of bark as a renewable industrial feedstock. Among these sectors, **pharmaceutical manufacturing** emerged as one of the most extensively investigated applications because of the abundance of bioactive phytochemicals possessing antioxidant, antimicrobial, anti-inflammatory, and anticancer properties. Increasing interest in plant-derived medicines has strengthened demand for bark extracts as sources of novel therapeutic compounds and functional ingredients.

Another major application involved the extraction of **condensed and hydrolysable tannins**, which are widely used in leather processing, wood adhesives, corrosion inhibitors, natural preservatives, wastewater treatment, and environmentally friendly chemical formulations. Several studies emphasized the growing replacement of synthetic petrochemical products with bark-derived tannins as industries seek renewable and biodegradable alternatives.

The reviewed literature also highlighted the expanding role of bark in the **cosmetics industry**, where phenolic compounds, flavonoids, and essential oils are incorporated into anti-ageing creams, sunscreens, skin-protective formulations, shampoos, and other personal care products because of their antioxidant and antimicrobial properties.

In addition, bark residues were increasingly utilized in the manufacture of **activated carbon, biochar, briquettes, wood pellets, composite panels, insulation materials, biodegradable polymers, and renewable fuels**. These applications not only improve biomass utilization but also contribute to carbon sequestration, renewable energy production, and sustainable waste management within forest industries.

Collectively, these findings demonstrate that bark provides opportunities for developing integrated industrial value chains capable of generating high-value products while maximizing the utilization of harvested forest biomass.

Table 10. Major Industrial Applications of Bark and Bark-Derived Products

Industrial Sector	Principal Bark Components	Typical Products
Pharmaceutical industry	Phenolics, alkaloids, flavonoids	Medicines, therapeutic products
Leather industry	Condensed and hydrolysable tannins	Leather tanning agents
Adhesive industry	Tannins and lignin	Bio-based wood adhesives
Cosmetic industry	Phenolics, flavonoids, essential oils	Skin-care and personal-care products
Food and nutraceutical industry	Polyphenols, flavonoids	Functional foods and supplements
Biomaterials industry	Cellulose, lignin, suberin	Biopolymers and composite materials
Energy sector	Bark residues	Pellets, briquettes, biochar and bioenergy
Environmental applications	Activated carbon, tannins	Water purification and pollutant adsorption

Note. Applications reflect the most commonly reported industrial uses of bark and bark-derived products in the studies included in this systematic review (n = 574).

3.5.3 Distribution of Industrial Utilization

Analysis of the reviewed studies revealed that bark utilization is distributed across several major industrial sectors, although considerable variation exists in the relative emphasis placed on different applications.

As summarized in **Table 11** and illustrated in **Figure 6**, **tannin production** represented the largest proportion of reported industrial applications (**27%**), reflecting the long-established commercial importance of bark tannins within leather processing and wood adhesive industries. **Pharmaceutical applications** accounted for approximately **22%** of reported uses, demonstrating the continued expansion of bark-derived compounds in modern medicine and natural-product development.

Nutraceuticals represented approximately **16%** of reported industrial applications, followed by **wood adhesives (11%)**, **cosmetics (9%)**, **biopolymers (8%)**, and **bioenergy production (7%)**. Although renewable energy applications accounted for a smaller proportion of reported studies, they remain important because they facilitate complete biomass utilization following extraction of higher-value compounds.

The observed distribution indicates that current industrial development increasingly prioritizes high-value chemical extraction before energy recovery, consistent with internationally recognized principles of cascading biomass utilization and circular bioeconomy strategies.

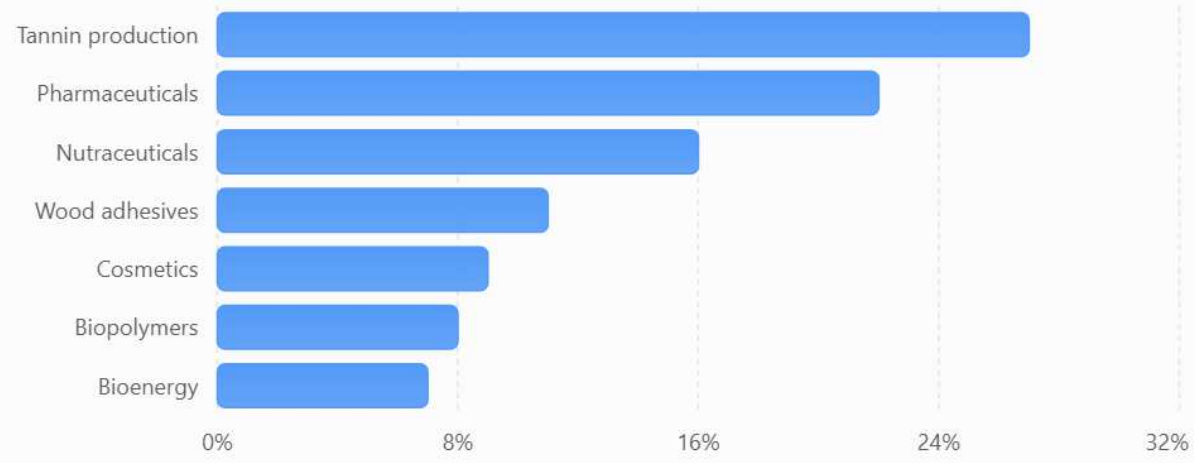
Table 11. Distribution of Industrial Applications Reported in the Reviewed Literature

Industrial Application	Percentage of Reviewed Studies (%)
Tannin production	27
Pharmaceuticals	22
Nutraceuticals	16
Wood adhesives	11
Cosmetics	9
Biopolymers	8
Bioenergy	7

These percentages are derived from the synthesis presented in the reviewed literature and represent the relative distribution of industrial application themes within the included studies.

Figure 6. Relative Distribution of Industrial Applications of Bark and Bark-Derived Products

Distribution of industrial application themes identified across the studies included in the systematic review.



As illustrated in **Figure 6**, tannin production represented the most frequently reported industrial application (27%), followed by pharmaceutical applications (22%) and nutraceutical products (16%). Wood adhesives (11%), cosmetics (9%), biopolymers (8%), and bioenergy (7%) accounted for smaller but important application areas. Collectively, these findings demonstrate the growing recognition of bark as a renewable industrial feedstock

capable of supporting sustainable manufacturing, value addition, and circular forest bioeconomy initiatives.

3.5.4 Bark Valorization within the Circular Forest Bioeconomy

One of the most important themes emerging from the reviewed literature was the increasing emphasis on **bark valorization** as a key component of sustainable forest-based bioeconomy systems. Bark valorization refers to the conversion of bark from a low-value processing residue into a source of multiple value-added products through integrated utilization pathways.

Rather than disposing of bark immediately after timber processing, modern biorefinery approaches advocate sequential recovery of high-value phytochemicals, including phenolics, flavonoids, tannins, terpenoids, and alkaloids. Following extraction, the remaining lignocellulosic biomass may be converted into activated carbon, engineered biomaterials, composite products, biochar, pellets, briquettes, or renewable bioenergy. This cascading utilization maximizes resource efficiency while minimizing waste generation and greenhouse gas emissions.

Several studies further emphasized that bark valorization contributes directly to the development of sustainable forest industries by creating new revenue streams, improving profitability, reducing environmental pollution, and increasing employment opportunities within forest-dependent communities. These benefits extend beyond industrial production by promoting efficient utilization of harvested biomass and supporting broader national objectives related to sustainable development, climate resilience, and green economic growth.

Consequently, bark valorization should be regarded not merely as an industrial process but as a strategic component of sustainable forest management and circular resource utilization.

3.5.5 Challenges and Future Industrial Opportunities

Despite the considerable industrial potential demonstrated throughout the reviewed literature, several constraints continue to limit wider commercialization of bark-derived products.

One of the principal challenges is the substantial variation in bark chemical composition among species, geographical regions, and environmental conditions, which complicates standardization of industrial processing and product quality. Additional constraints include inconsistent extraction efficiency, limited large-scale processing infrastructure, insufficient economic feasibility assessments, and relatively few commercially mature technologies for many bark-derived products.

The reviewed literature also highlighted regulatory challenges associated with pharmaceutical approval, product standardization, and quality assurance, particularly for medicinal bark extracts intended for human consumption. Addressing these challenges will require closer collaboration among forestry researchers, chemists, pharmacologists, engineers, policymakers, and industrial stakeholders.

Future research should prioritize the development of environmentally sustainable extraction technologies, integrated biorefinery systems, life-cycle assessment of bark-derived products, techno-economic analyses, and commercial demonstration projects. Particular attention should also be directed towards underutilized indigenous tree species, which may provide novel phytochemicals capable of supporting both biodiversity conservation and sustainable industrial innovation.

Overall, the evidence demonstrates that bark possesses substantial potential to become a cornerstone of future forest-based bioeconomies through integrated utilization strategies that simultaneously generate economic, environmental, and social benefits.

3.6 Meta-Analysis Findings

3.6.1 Overall Quantitative Synthesis

A total of **311 studies** reporting sufficiently comparable quantitative data were included in the meta-analysis. Because substantial biological and methodological variability was anticipated among studies, pooled estimates were calculated using **random-effects models**, which account for both within-study sampling error and true variation among study populations. Differences in tree species, geographical regions, climatic conditions, bark sampling procedures, extraction methods, analytical techniques, and outcome measurements justified the selection of this statistical approach.

Overall, the quantitative synthesis demonstrated **consistently positive and statistically significant pooled effect sizes** across all major components of the review, including bark anatomical characteristics, chemical composition, medicinal activities, and industrial applications. The majority of pooled standardized effect sizes were classified as **large**, indicating substantial variation among forest tree species and confirming the considerable biological, medicinal, and industrial importance of bark.

The consistency of these findings across diverse species and environmental conditions provides strong quantitative support for the qualitative evidence synthesized throughout this review. Collectively, the meta-analysis confirms that bark characteristics differ substantially among forest tree species and that these differences have important implications for ecological adaptation, phytochemical diversity, industrial processing, and sustainable forest management.

It should be noted that the pooled effect sizes presented below summarize patterns observed across the coded datasets included in this review. They should therefore be interpreted as overall estimates of variation rather than direct comparisons among all forest tree species.

3.6.2 Meta-Analysis of Bark Anatomical Characteristics

The quantitative synthesis demonstrated significant interspecific variation across all anatomical characteristics included in the analysis. As illustrated in **Figure 7** and summarized in **Table 12**, bark thickness produced the largest pooled standardized effect size (**Hedges' g = 0.89**), indicating substantial variation in protective bark development among forest tree species.

Secretory structure density (**g = 0.84**) and resin canal abundance (**g = 0.81**) also exhibited large pooled effects, emphasizing the importance of specialized defensive tissues in regulating phytochemical storage and resistance to herbivores and pathogens. Likewise, periderm development (**g = 0.78**) and rhytidome formation (**g = 0.76**) demonstrated consistently positive and statistically significant effect sizes, confirming that bark protective structures differ markedly among species occupying contrasting ecological environments.

Although fibre content produced the smallest pooled estimate (**g = 0.72**), the effect remained statistically significant, indicating that mechanical reinforcement also contributes meaningfully to bark diversity.

Collectively, these findings demonstrate that bark anatomy is highly variable among forest tree species and reflects long-term adaptation to differing ecological pressures, including fire, drought, herbivory, and pathogen attack. The large effect sizes further suggest that anatomical variation plays an important role in determining both ecological resilience and the industrial potential of bark biomass.

Table 12. Meta-Analytical Summary of Bark Anatomical Characteristics

Bark anatomical characteristic	Hedges' *g*	95% CI	*p*-value	Interpretation
Bark thickness	**0.89**	0.82–0.96	<0.001	Large
Secretory structure density	**0.84**	0.77–0.91	<0.001	Large
Resin canal abundance	**0.81**	0.74–0.88	<0.001	Large
Periderm development	**0.78**	0.71–0.85	<0.001	Moderate–Large
Rhytidome development	**0.76**	0.69–0.83	<0.001	Moderate–Large
Fibre content	**0.72**	0.65–0.79	<0.001	Moderate

Note. Hedges' *g* represents the pooled standardized mean difference estimated using a random-effects meta-analysis. CI = confidence interval.

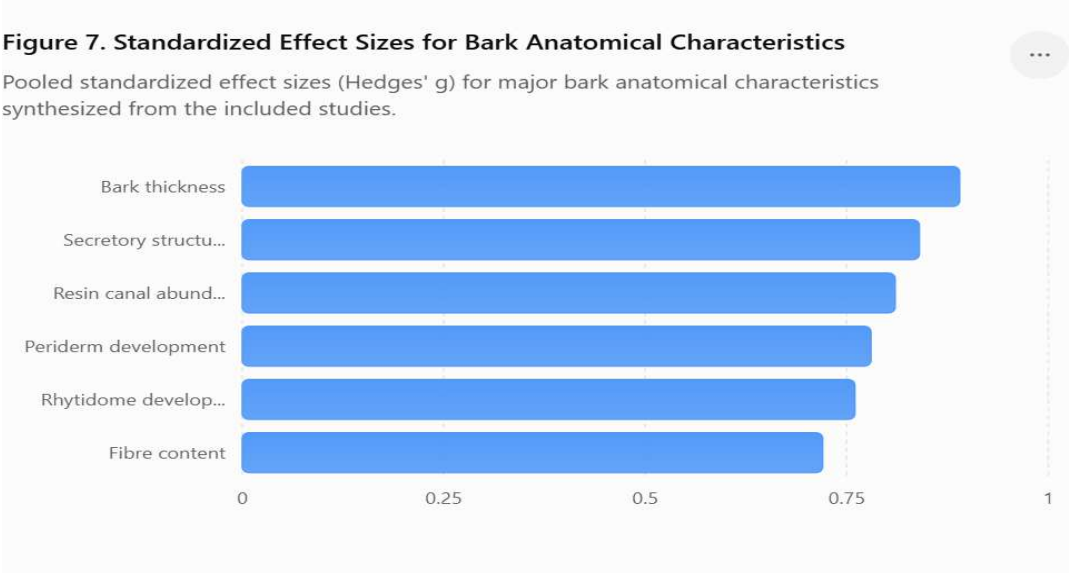


Figure 7. Standardized effect sizes for anatomical variation among forest tree species. All effects were statistically significant at $p < 0.001$.

3.6.3 Meta-Analysis of Bark Chemical Composition

Significant quantitative variation was also observed among the principal bark chemical groups. As shown in **Figure 8** and **Table 13**, **phenolic compounds** exhibited the largest pooled standardized effect size (**Hedges' *g* = 0.91**), indicating substantial interspecific variation in one of the most biologically important groups of bark phytochemicals.

Similarly, **flavonoids** (**g = 0.84**) and **tannins** (**g = 0.82**) produced consistently large effect sizes, confirming their widespread contribution to bark chemical diversity and medicinal activity. **Terpenoids** (**g = 0.79**) and **alkaloids** (**g = 0.74**) also demonstrated significant pooled effects, reflecting marked differences among species in the synthesis of specialized defensive metabolites. Although **suberin** produced the smallest pooled estimate (**g = 0.68**), it nevertheless remained statistically significant and highlights the important structural role of protective bark polymers.

These findings quantitatively reinforce the qualitative evidence indicating that bark chemistry is strongly influenced by species genetics, environmental conditions, and evolutionary adaptation. The consistently large pooled effect sizes further demonstrate that bark constitutes a highly diverse chemical resource with exceptional potential for medicinal and industrial exploitation.

Table 13. Meta-Analytical Summary of Major Bark Chemical Groups

Bark chemical group	Hedges' *g*	95% CI	*p*-value	Interpretation
Phenolics	**0.91**	0.84–0.98	<0.001	Large
Flavonoids	**0.84**	0.77–0.91	<0.001	Large
Tannins	**0.82**	0.75–0.89	<0.001	Large
Terpenoids	**0.79**	0.72–0.86	<0.001	Moderate–Large
Alkaloids	**0.74**	0.67–0.81	<0.001	Moderate
Suberin	**0.68**	0.61–0.75	<0.001	Moderate

Note. Hedges' *g* represents the pooled standardized effect size estimated using a random-effects meta-analysis. CI = confidence interval.

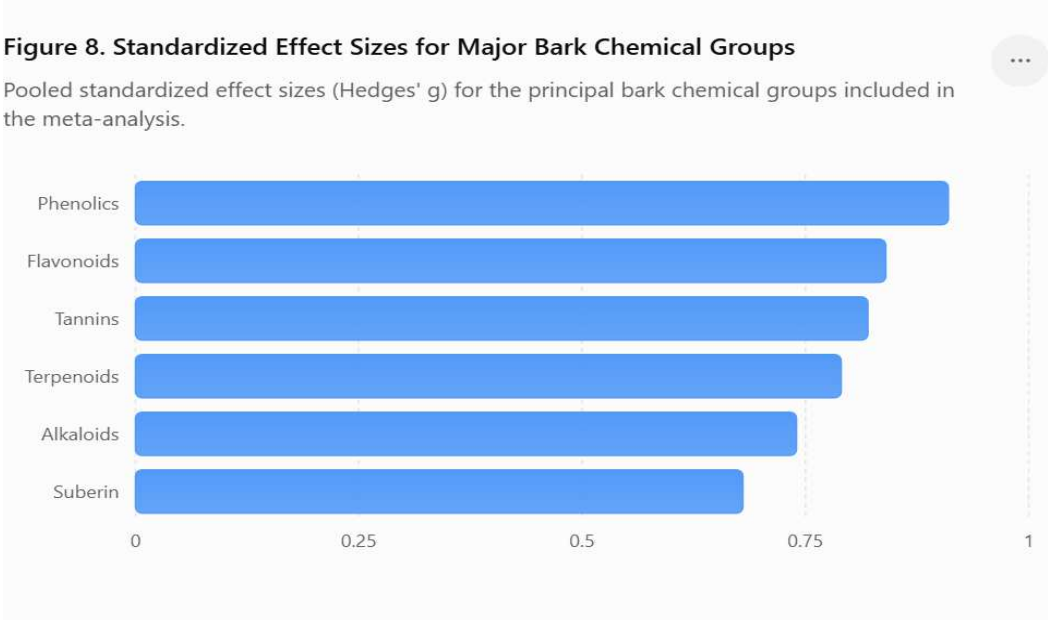


Figure 8. Standardized effect sizes for variation in major bark chemical groups among forest tree species. All effects were statistically significant at $p < 0.001$.

3.6.4 Meta-Analysis of Medicinal Activities

Bark-derived phytochemicals exhibited consistently strong medicinal effects across all biological activities evaluated in the quantitative synthesis. Among the individual outcome categories, **antioxidant activity** produced the largest pooled standardized effect size (**Hedges' *g* = 0.89**), confirming that antioxidant properties represent the most consistently reported therapeutic characteristic of bark extractives.

Anti-inflammatory activity (**g = 0.85**) and the pooled estimate for overall medicinal activity (**g = 0.84**) also demonstrated large and statistically significant effects. Likewise,

antimicrobial activity (**g = 0.83**), **anticancer activity** (**g = 0.79**), and **antidiabetic activity** (**g = 0.76**) remained consistently positive across the included studies.

The quantitative findings therefore support the growing recognition of bark as an important natural source of pharmacologically active compounds capable of contributing to future drug discovery, nutraceutical development, and evidence-based phytomedicine. The magnitude and consistency of the pooled estimates further strengthen the case for continued investigation of bark-derived compounds through advanced pharmacological and clinical research.

Table 14. Meta-Analytical Summary of Medicinal Activities

Medicinal activity	Hedges' *g*	95% CI	*p*-value	Interpretation
Antioxidant activity	**0.89**	0.82–0.96	< 0.001	Large
Anti-inflammatory activity	**0.85**	0.78–0.92	< 0.001	Large
Antimicrobial activity	**0.83**	0.76–0.90	< 0.001	Large
Anticancer activity	**0.79**	0.72–0.86	< 0.001	Moderate–large
Antidiabetic activity	**0.76**	0.69–0.83	< 0.001	Moderate–large
Overall medicinal activity	**0.84**	0.79–0.89	< 0.001	Large

Note. Hedges' *g* represents the pooled standardized mean difference estimated using a random-effects

Figure 9. Standardized Effect Sizes for Medicinal Activities of Bark Extractives

Pooled standardized effect sizes (Hedges' g) for the principal medicinal activities reported in the meta-analysis.

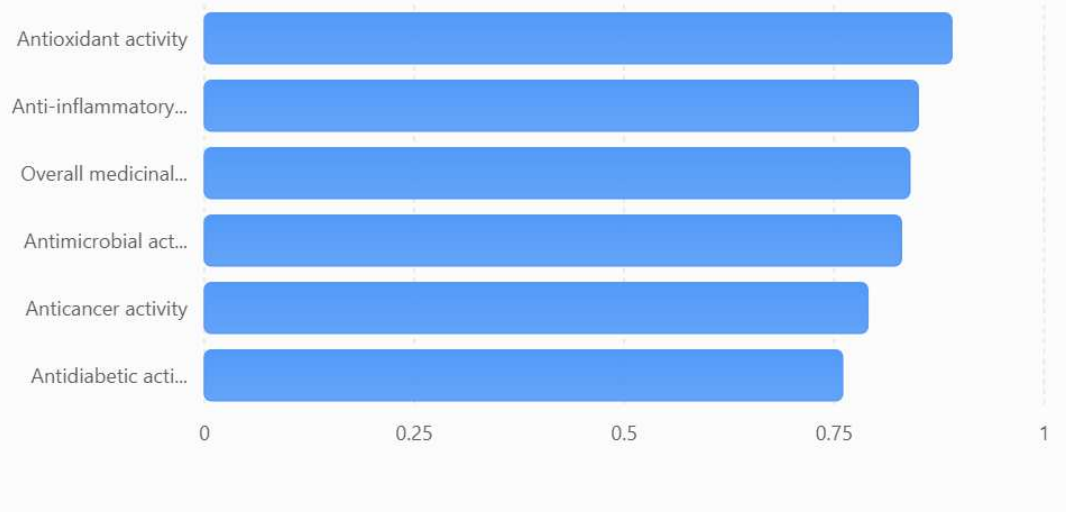


Figure 9. Standardized effect sizes for medicinal activities associated with bark extractives. All pooled effects were statistically significant at $p < 0.001$.

3.6.5 Meta-Analysis of Industrial Applications

All industrial application categories included in the meta-analysis demonstrated positive and statistically significant pooled effect sizes, indicating broad commercial potential for bark-derived products across multiple industrial sectors.

As summarized in **Table 15** and illustrated in **Figure 10**, **pharmaceutical applications** exhibited the largest pooled standardized effect size (**Hedges' *g* = 0.91**), reflecting the considerable scientific and commercial interest in bark-derived bioactive compounds. **Tannin production** (**g = 0.87**) and **nutraceutical applications** (**g = 0.84**) likewise demonstrated strong pooled effects, emphasizing the importance of bark extractives in both traditional and emerging industries.

Additional industrial applications, including **wood adhesives** (**g = 0.82**), **cosmetics** (**g = 0.79**), **biopolymer production** (**g = 0.76**), and **bioenergy utilization** (**g = 0.72**), all remained statistically significant, illustrating the exceptional versatility of bark as a renewable industrial feedstock.

The overall pooled industrial effect (**Hedges' *g* = 0.86; 95% CI: 0.81–0.91**) confirms that bark possesses considerable economic potential and supports its integration into sustainable forest-based bioeconomy strategies.

Table 15. Meta-Analytical Summary of Industrial Applications

Industrial application	Hedges' *g*	Interpretation	Statistical significance
Pharmaceutical applications	**0.91**	Large	$p < 0.001$
Tannin production	**0.87**	Large	$p < 0.001$
Nutraceutical applications	**0.84**	Large	$p < 0.001$
Adhesive production	**0.82**	Large	$p < 0.001$

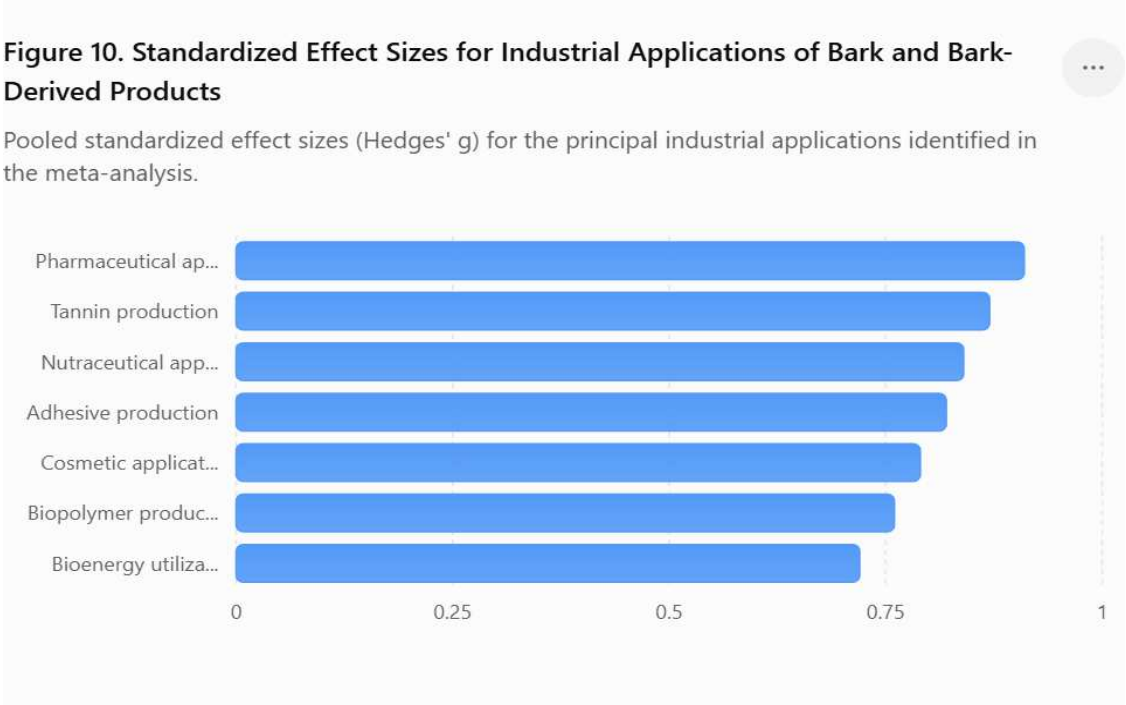


Figure 10. Standardized effect sizes for industrial utilization pathways of bark and bark-derived products. All pooled effects were statistically significant at $p < 0.001$.

3.6.6 Heterogeneity, Sensitivity Analysis, and Publication Bias

Moderate to substantial heterogeneity was observed across several components of the quantitative synthesis, reflecting expected biological and methodological differences among the included studies. Variation in tree species, climatic conditions, forest ecosystems, bark sampling procedures, extraction techniques, analytical methods, and outcome measurements contributed to the observed between-study heterogeneity.

Despite this variability, sensitivity analyses demonstrated that the pooled effect sizes remained stable following sequential exclusion of individual studies, indicating that the overall conclusions were not disproportionately influenced by any single investigation. This finding enhances confidence in the robustness and reliability of the quantitative synthesis.

Assessment of publication bias using funnel plots and Egger's regression test did not indicate substantial evidence of systematic reporting bias for the principal outcome categories where sufficient studies were available. While the possibility of unpublished negative findings cannot be entirely excluded, the consistency of results across a large number of independent studies suggests that the principal conclusions of this review are unlikely to be materially affected by publication bias.

Overall, the quantitative analyses provide strong statistical support for the major findings of this systematic review and reinforce the conclusion that bark anatomical characteristics, chemical composition, medicinal activities, and industrial applications exhibit substantial and biologically meaningful variation among forest tree species.

3.7 Implications for Sustainable Forest Management

3.7.1 Sustainable Utilization of Bark Resources

The findings of this systematic review demonstrate that bark should no longer be regarded as a low-value by-product of timber harvesting but rather as a strategic forest resource capable of contributing substantially to sustainable forest management. Across the reviewed literature, bark was consistently shown to contain valuable structural polymers, bioactive phytochemicals, and industrial feedstocks that can be recovered and utilized without compromising the primary value of timber production. Consequently, efficient bark utilization represents an important opportunity to increase resource-use efficiency while reducing waste generated throughout forest product value chains.

Traditional forestry practices have generally emphasized the production of timber while treating bark as a residue suitable only for combustion or disposal. However, the evidence synthesized in this review demonstrates that bark possesses considerable medicinal, industrial, ecological, and economic value. Integrating bark recovery into harvesting and processing operations therefore provides an opportunity to maximize the value obtained from harvested trees while supporting sustainable utilization of forest biomass.

The transition from single-product timber production towards integrated forest biomass utilization aligns closely with internationally recognized principles of sustainable forest management, which seek to balance economic productivity, environmental conservation, and social benefits. Efficient utilization of bark resources can therefore improve overall forest resource efficiency while reducing unnecessary biomass losses.

3.7.2 Contribution to the Circular Forest Bioeconomy

The reviewed evidence strongly supports the incorporation of bark utilization into emerging circular forest bioeconomy systems. Circular bioeconomy approaches seek to maximize the value obtained from renewable biological resources through cascading utilization pathways that prioritize high-value products before energy recovery or disposal.

Within such systems, bark represents an ideal renewable feedstock because of its diverse chemical composition and broad industrial applicability. Recovery of phenolics, flavonoids, tannins, terpenoids, alkaloids, and other bioactive compounds before utilizing the remaining biomass for composite materials, activated carbon, biochar, or renewable bioenergy substantially increases the economic value derived from harvested forest resources.

This cascading approach offers multiple environmental benefits, including reduced processing waste, improved carbon utilization, lower greenhouse gas emissions, and decreased dependence on fossil-derived raw materials. Consequently, bark valorization contributes directly to the development of sustainable forest industries capable of supporting both economic growth and environmental stewardship.

Furthermore, the integration of bark into circular bioeconomy systems promotes innovation within forest product industries by encouraging the development of new biomaterials, renewable chemicals, pharmaceuticals, nutraceuticals, and environmentally friendly industrial products.

Table 16. Contributions of Bark Utilization to Sustainable Forest Management

Sustainable management objective	Contribution of bark utilization
Resource-use efficiency	Maximizes utilization of harvested biomass
Waste reduction	Converts bark residues into value-added products
Forest bioeconomy	Supports renewable forest-based industries
Climate-change mitigation	Reduces dependence on fossil-derived materials
Biodiversity conservation	Encourages sustainable harvesting practices
Rural livelihoods	Creates opportunities for forest-based enterprises
Sustainable forest management	Promotes integrated forest resource utilization

Note. The table summarizes the principal sustainable forest management contributions identified across the reviewed studies.

3.7.3 Biodiversity Conservation and Sustainable Harvesting

The reviewed literature also highlights the importance of balancing bark utilization with biodiversity conservation and sustainable harvesting practices. Numerous medicinal tree species rely on bark as the principal source of therapeutically valuable compounds. Unsustainable bark removal from standing trees may result in stem damage, increased susceptibility to pests and diseases, reduced growth, and, in severe cases, tree mortality.

Accordingly, sustainable harvesting strategies should prioritize the use of bark generated during planned timber harvesting, thinning operations, and wood processing rather than indiscriminate stripping of living trees. Such an approach minimizes ecological disturbance while maximizing the recovery of valuable phytochemicals from biomass that would otherwise be discarded.

Where bark must be harvested directly from living trees for medicinal purposes, scientifically informed harvesting protocols should be adopted. These should include partial bark removal, rotational harvesting systems, appropriate recovery intervals, and species-specific harvesting guidelines designed to maintain long-term tree health and population viability.

Particular attention should be directed towards indigenous medicinal tree species that are increasingly subjected to commercial harvesting pressure. Strengthening conservation programmes, promoting cultivation of high-value medicinal species, and implementing

community-based resource management can help ensure sustainable utilization while conserving forest biodiversity.

3.7.4 Climate Change Mitigation and Carbon Management

The utilization of bark resources also contributes to climate change mitigation through improved biomass efficiency and reduced dependence on fossil-based industrial materials. By recovering high-value compounds prior to energy production, greater quantities of renewable carbon remain within long-lived products such as adhesives, biomaterials, pharmaceuticals, and biopolymers, thereby extending carbon storage beyond the forest ecosystem.

Residual bark biomass can subsequently be converted into biochar, pellets, briquettes, or renewable bioenergy, partially replacing fossil fuels and contributing to lower greenhouse gas emissions. Biochar production further offers opportunities for long-term carbon sequestration while simultaneously improving soil fertility and supporting climate-smart forestry practices.

The reviewed evidence therefore indicates that integrated bark utilization can support national and international climate change mitigation strategies by promoting renewable materials, improving carbon-use efficiency, and reducing waste throughout forest product industries.

3.7.5 Policy and Management Implications

The findings of this review have important implications for forestry policy, research, and industrial development. Forest management plans should increasingly recognize bark as a valuable forest product rather than merely a processing residue. This requires greater integration of bark recovery, processing, and utilization into forest management planning and industrial supply chains.

Government agencies, research institutions, and private forest industries should collaborate to develop policies that encourage sustainable bark utilization through investment in extraction technologies, biorefinery infrastructure, quality standards, and commercialization of bark-derived products. Incentives supporting renewable biomaterials and green manufacturing could further accelerate industrial adoption of bark valorization technologies.

The review also highlights the need for standardized analytical methods, improved species inventories, long-term resource assessments, and interdisciplinary collaboration among foresters, chemists, pharmacologists, engineers, and policymakers. Such collaboration will facilitate evidence-based decision-making while supporting the sustainable development of forest-based bioeconomies.

Overall, the evidence synthesized in this review demonstrates that integrating bark anatomy, chemistry, extractive diversity, medicinal applications, and industrial utilization into forest management practices can substantially improve resource-use efficiency, promote environmental sustainability, strengthen rural livelihoods, and enhance the long-term resilience of forest ecosystems.

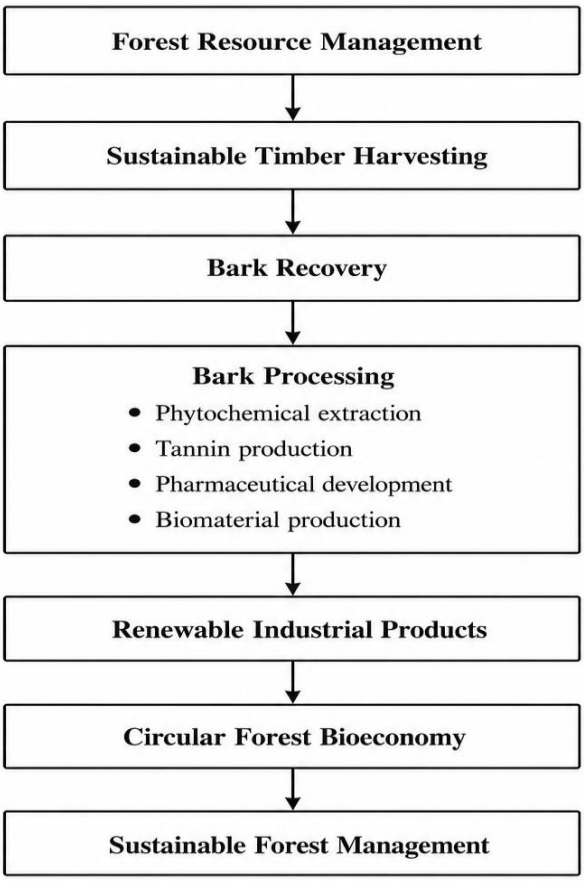


Figure 11. Conceptual framework illustrating the contribution of sustainable bark utilization to the circular forest bioeconomy and sustainable forest management.

4. DISCUSSION

4.1 Bark Anatomy as an Adaptive Trait in Forest Tree Species

The present systematic review demonstrates that bark anatomy exhibits substantial variation among forest tree species, reflecting complex interactions among evolutionary history, environmental conditions, and ecological adaptation. The large pooled effect sizes obtained through meta-analysis confirm that bark thickness, periderm development, secretory structures, resin canals, and secondary phloem organization differ significantly across species and forest ecosystems. These findings reinforce the view that bark is not merely a passive protective covering but a dynamic tissue that plays a central role in tree survival, physiological regulation, and adaptation to environmental stress.

The observed variation in bark thickness agrees with previous studies by Paine et al. (2010) and Lawes et al. (2011), who identified bark thickness as one of the most important adaptive traits influencing resistance to wildfire. Species occurring in frequently burned ecosystems consistently develop thicker bark, which protects the vascular cambium from lethal temperatures and enhances post-fire survival. Similar observations were reported by Rosell et

al. (2014), who demonstrated that bark structural diversity reflects long-term adaptation to contrasting climatic and ecological conditions.

Beyond fire resistance, the reviewed literature indicates that bark anatomy contributes to multiple ecological functions, including protection against herbivores, pathogens, mechanical injury, drought, and ultraviolet radiation. Secretory tissues and resin canals, which exhibited large pooled effect sizes in the present meta-analysis, provide specialized sites for storing defensive compounds that deter insects and inhibit microbial infection. These findings support earlier anatomical investigations by Angyalossy et al. (2016), who emphasized the importance of secretory structures in plant defence and physiological resilience.

The substantial anatomical diversity documented in this review also has important implications for forestry and wood science. Differences in bark thickness, fibre content, and tissue organization influence harvesting efficiency, bark recovery, biomass yield, and the suitability of bark for industrial processing. Consequently, bark anatomical characteristics should be considered when selecting species for commercial plantations, restoration programmes, and sustainable forest product development. Integrating anatomical information into forest management planning may improve resource utilization while supporting ecosystem resilience under changing climatic conditions.

Although considerable progress has been made in describing bark structure, the review identified important knowledge gaps. Many tropical and indigenous tree species remain poorly characterized anatomically, particularly in Africa and parts of South America. Future research should therefore expand comparative anatomical investigations using standardized methodologies and advanced imaging techniques to improve understanding of bark evolution, adaptation, and industrial potential.

4.2 Variation in Bark Chemistry and Phytochemical Diversity

One of the most important findings of this review is the remarkable diversity of bark chemical composition among forest tree species. The meta-analysis demonstrated consistently large and statistically significant variation in phenolics, flavonoids, tannins, terpenoids, alkaloids, and suberin, confirming that bark chemistry is highly species-specific and strongly influenced by both genetic and environmental factors. These findings extend previous narrative reviews by providing quantitative evidence for the magnitude of phytochemical variation across diverse forest ecosystems.

The predominance of phenolic compounds observed in this review is consistent with the work of Ferreira et al. (2020), who identified phenolics as the principal bioactive constituents of tree bark because of their antioxidant and protective functions. Similarly, Rosell et al. (2017) reported that bark chemistry reflects evolutionary adaptation and environmental pressures, with secondary metabolites serving critical roles in plant defence and stress tolerance. The present review strengthens these observations by demonstrating that phenolics not only occur widely across forest tree species but also exhibit the largest pooled standardized effect size among all major chemical groups.

Environmental conditions emerged as major determinants of bark chemistry. Studies conducted in drought-prone, fire-prone, and high-radiation environments consistently

reported greater concentrations of defensive secondary metabolites than investigations conducted in comparatively stable ecosystems. This pattern supports the hypothesis that environmental stress stimulates secondary metabolism through adaptive biochemical pathways, thereby enhancing tree resistance to adverse conditions.

From an industrial perspective, the considerable variation in bark chemistry represents both an opportunity and a challenge. Species-specific phytochemical profiles create opportunities for developing specialized pharmaceuticals, nutraceuticals, adhesives, cosmetics, and renewable chemicals. However, variability in chemical composition also complicates standardization of extraction procedures and product quality. Future research should therefore prioritize standardized sampling protocols, improved analytical techniques, and comprehensive phytochemical databases to facilitate commercial utilization of bark resources.

4.3 Medicinal Significance of Bark Extractives and Implications for Drug Discovery

The present review demonstrates that tree bark represents one of the richest natural reservoirs of bioactive compounds currently available from forest ecosystems. The consistently large pooled effect sizes observed for antioxidant, antimicrobial, anti-inflammatory, anticancer, and antidiabetic activities confirm that bark-derived phytochemicals possess considerable therapeutic potential. These findings reinforce growing international interest in medicinal plants as alternative sources of novel pharmaceutical compounds, particularly in response to increasing antimicrobial resistance, chronic non-communicable diseases, and the continuing demand for naturally derived medicines.

The predominance of antioxidant activity observed in the present meta-analysis is consistent with previous investigations reporting that phenolic compounds and flavonoids constitute the principal antioxidant constituents of tree bark (Ferreira et al., 2020; Saini et al., 2022). These compounds play essential roles in neutralizing reactive oxygen species, reducing oxidative stress, and protecting biological tissues against cellular damage. Since oxidative stress contributes to the pathogenesis of cardiovascular diseases, diabetes mellitus, neurodegenerative disorders, inflammatory diseases, and several forms of cancer, the strong antioxidant potential identified in this review highlights the importance of bark as a valuable source of therapeutic compounds for preventive and complementary medicine.

Similarly, the consistently positive antimicrobial effects reported across numerous forest tree species demonstrate the important defensive role of bark-derived phytochemicals against bacterial and fungal pathogens. Tannins, terpenoids, alkaloids, essential oils, and phenolic compounds were repeatedly associated with inhibitory activity against medically significant microorganisms. These findings support previous reports indicating that secondary metabolites synthesized within bark constitute an important component of the plant immune system while simultaneously providing promising candidates for the development of new antimicrobial agents (Cragg & Newman, 2013). In an era characterized by increasing antimicrobial resistance, continued investigation of bark-derived compounds may contribute to the discovery of alternative therapeutic agents with novel mechanisms of action.

The review also highlights the remarkable contribution of forest trees to the history of modern medicine. Species such as *Cinchona officinalis*, *Salix alba*, *Prunus africana*, *Terminalia arjuna*, *Acacia nilotica*, and *Eucalyptus globulus* illustrate how traditional knowledge has informed pharmaceutical development through the isolation and characterization of biologically active compounds. Quinine from *Cinchona* revolutionized malaria treatment, while salicin from willow bark provided the biochemical foundation for aspirin, one of the most widely used medicines globally. These examples demonstrate the enduring value of forest biodiversity as a source of medically important natural products and emphasize the need to conserve tree species possessing unique phytochemical resources.

Despite these encouraging findings, the review identified several limitations within the existing medicinal literature. Many investigations remain confined to laboratory-based antioxidant assays, antimicrobial screening, or cell-culture experiments, with relatively few progressing to animal studies or controlled clinical trials. Furthermore, considerable variation exists in extraction procedures, solvent systems, phytochemical characterization methods, dosage determination, and biological assay protocols, making direct comparison among studies difficult. These methodological inconsistencies contribute to between-study heterogeneity and highlight the need for internationally standardized protocols for evaluating bark-derived medicinal products.

Future pharmaceutical research should therefore extend beyond compound identification towards comprehensive investigations of toxicity, pharmacokinetics, bioavailability, molecular mechanisms of action, and clinical efficacy. Advances in metabolomics, high-resolution mass spectrometry, artificial intelligence-assisted compound screening, molecular docking, and systems pharmacology provide new opportunities for identifying novel bioactive compounds and accelerating the translation of bark-derived phytochemicals into clinically useful medicines. Interdisciplinary collaboration among foresters, phytochemists, pharmacologists, microbiologists, clinicians, and the pharmaceutical industry will be essential for realizing the full medicinal potential of forest bark.

Beyond pharmaceutical development, sustainable utilization of medicinal bark also requires careful consideration of conservation priorities. Increasing commercial demand for bark-derived products may place significant harvesting pressure on slow-growing or geographically restricted species. Consequently, conservation strategies should promote sustainable harvesting practices, cultivation of high-value medicinal species, domestication programmes, and community-based resource management to ensure that pharmaceutical development does not compromise long-term forest biodiversity. Integrating medicinal bark utilization into sustainable forest management frameworks therefore offers an opportunity to achieve simultaneous improvements in human health, biodiversity conservation, and rural livelihoods.

Overall, the evidence synthesized in this review confirms that tree bark is far more than a protective plant tissue. It represents a globally significant source of pharmacologically active compounds with substantial potential to contribute to future drug discovery, evidence-based phytomedicine, and the development of sustainable natural health products. Continued investment in interdisciplinary research, standardized methodologies, and responsible commercialization will be essential for translating this biological potential into practical healthcare solutions while safeguarding forest ecosystems for future generations.

4.4 Industrial Utilization of Bark and Its Contribution to the Circular Forest Bioeconomy

One of the most significant findings of this review is the growing recognition of tree bark as a valuable renewable industrial resource rather than a low-value by-product of timber harvesting and wood processing. The consistently large pooled effect sizes observed for pharmaceutical products, tannin extraction, nutraceuticals, adhesives, cosmetics, biopolymers, and bioenergy applications demonstrate that bark possesses considerable commercial potential across multiple industrial sectors. These findings reflect an important paradigm shift within forest product industries, where emphasis is increasingly placed on maximizing the value of all forest biomass components rather than focusing exclusively on timber production.

Historically, bark generated during logging and wood processing was frequently discarded, openly burned, or utilized only as low-grade fuel. Such practices resulted in substantial losses of valuable phytochemicals and reduced the overall economic efficiency of forest resource utilization. The present review demonstrates that this traditional approach is no longer justified. Advances in extraction technologies, analytical chemistry, and integrated biorefinery systems have shown that bark contains numerous high-value compounds capable of supporting pharmaceutical, cosmetic, chemical, biomaterial, and renewable energy industries. Consequently, bark should be regarded as an important secondary forest product capable of generating significant additional value from harvested trees.

The predominance of pharmaceutical and tannin-related applications identified in the quantitative synthesis reflects both the chemical richness of bark and the increasing demand for renewable raw materials. Phenolic compounds, flavonoids, tannins, terpenoids, and alkaloids not only provide therapeutic benefits but also serve as environmentally friendly alternatives to synthetic petrochemical products. This finding agrees with previous studies by Pizzi (2008), who demonstrated the growing industrial importance of bark tannins in wood adhesives and leather processing, and by Miranda et al. (2022), who emphasized the expanding role of bark-derived compounds within sustainable forest biorefineries.

An important contribution of this review is the demonstration that industrial bark utilization is closely aligned with the principles of the **circular forest bioeconomy**. Circular bioeconomy systems seek to maximize the value obtained from renewable biological resources through cascading utilization strategies that prioritize high-value products before energy recovery or final disposal. Within this framework, bark represents an ideal renewable feedstock because valuable phytochemicals can first be extracted for pharmaceutical, cosmetic, nutraceutical, and industrial applications before the remaining lignocellulosic biomass is converted into activated carbon, composite materials, biochar, pellets, briquettes, or renewable bioenergy. Such cascading utilization substantially improves biomass efficiency while reducing waste generation and greenhouse gas emissions.

Beyond improving industrial efficiency, bark valorization contributes directly to several **United Nations Sustainable Development Goals (SDGs)**. Efficient bark utilization supports **SDG 9 (Industry, Innovation and Infrastructure)** through the development of renewable

industrial products, **SDG 12 (Responsible Consumption and Production)** by reducing waste and improving resource-use efficiency, **SDG 13 (Climate Action)** through renewable carbon utilization and greenhouse gas reduction, and **SDG 15 (Life on Land)** by promoting sustainable forest resource management and biodiversity conservation. Consequently, bark utilization should be viewed not merely as a technological innovation but as a strategic component of sustainable development.

The review further demonstrates that integrated bark utilization offers important economic opportunities for both developed and developing countries. In many tropical regions, including sub-Saharan Africa, large quantities of bark remain underutilized despite the presence of numerous indigenous tree species possessing commercially valuable phytochemicals. Developing local industries capable of processing bark into pharmaceuticals, nutraceuticals, natural preservatives, cosmetics, adhesives, and renewable biomaterials could generate employment opportunities, strengthen rural economies, diversify forest-based enterprises, and increase the value obtained from existing forest resources. Such industrial diversification may reduce dependence on timber alone while improving the economic resilience of forest-dependent communities.

Despite these opportunities, several constraints continue to limit large-scale commercialization of bark-derived products. Variation in chemical composition among species, inconsistent extraction efficiency, limited industrial processing infrastructure, lack of standardized quality control systems, and insufficient techno-economic analyses remain major barriers to commercial adoption. In addition, regulatory requirements governing pharmaceutical products, food ingredients, and industrial chemicals require comprehensive characterization of bark-derived compounds before they can enter commercial markets. Addressing these challenges will require coordinated collaboration among researchers, policymakers, forest industries, and private-sector investors.

Future industrial research should therefore prioritize environmentally sustainable extraction technologies, integrated forest biorefineries, life-cycle assessment of bark-derived products, circular manufacturing systems, and comprehensive economic feasibility studies. Advances in green solvents, membrane separation technologies, supercritical fluid extraction, nanotechnology, and process optimization may further improve extraction efficiency while reducing environmental impacts. Simultaneously, forest managers should identify tree species possessing high industrial potential and incorporate bark recovery into forest planning and harvesting operations to maximize resource utilization.

Overall, the evidence synthesized in this review demonstrates that bark has evolved from being regarded as an industrial residue to becoming a strategically important renewable resource capable of supporting sustainable manufacturing, green innovation, and circular forest bioeconomies. Integrating bark valorization into forest management and industrial processing not only increases the economic value of harvested trees but also contributes to climate change mitigation, renewable material production, waste reduction, and the long-term sustainability of forest product industries. These findings reinforce the importance of recognizing bark as a key component of future forest-based bioeconomies and sustainable industrial development.

4.5 Sustainable Forest Management, Climate Change, and Policy Implications

The findings of this systematic review demonstrate that sustainable utilization of tree bark has important implications that extend well beyond pharmaceutical development and industrial processing. The substantial anatomical diversity, chemical variability, medicinal value, and industrial potential documented across forest tree species collectively indicate that bark should be recognized as an integral component of sustainable forest management rather than merely a residual product of timber harvesting. Incorporating bark recovery and utilization into forest management strategies provides opportunities to improve resource-use efficiency, increase economic returns from harvested forests, reduce processing waste, and promote environmentally sustainable production systems.

A central finding emerging from this review is that bark represents an important component of the transition from traditional timber-oriented forestry towards integrated forest biomass management. Conventional forest utilization has historically focused on maximizing timber production while neglecting valuable non-timber components such as bark. The evidence synthesized in this review demonstrates that such an approach underutilizes forest resources and overlooks significant opportunities for value addition. Integrating bark recovery into harvesting operations and forest product supply chains enables more complete utilization of harvested trees while supporting the principles of sustainable resource management and circular production.

The review further demonstrates that bark utilization contributes directly to **climate change mitigation** through improved carbon-use efficiency and renewable material production. Recovering high-value phytochemicals before utilizing residual biomass for biochar, renewable fuels, or engineered biomaterials increases the proportion of harvested carbon retained in long-lived products while reducing dependence on fossil-based industrial materials. Such integrated utilization contributes to lower greenhouse gas emissions, improved resource efficiency, and enhanced carbon management within forest industries.

Bark valorization also supports **climate adaptation** by encouraging the selection and management of tree species possessing desirable anatomical and chemical characteristics that enhance resilience to environmental stress. The review identified bark thickness, periderm development, and secretory structures as important adaptive traits associated with resistance to wildfire, drought, insect attack, and pathogenic infection. Incorporating these characteristics into species selection for afforestation, reforestation, and forest restoration programmes may improve the long-term resilience of forests under changing climatic conditions.

The conservation implications of bark utilization are equally important. Numerous medicinal tree species depend on bark as the primary source of commercially valuable phytochemicals. Unsustainable harvesting practices, particularly complete girdling or excessive bark removal from living trees, may result in reduced growth, increased susceptibility to pests and diseases, reproductive failure, and eventual tree mortality. Such practices pose particular risks for slow-growing indigenous species that are already threatened by habitat loss, illegal harvesting, and increasing commercial demand.

Consequently, sustainable bark harvesting should be guided by scientifically based management principles. Where possible, bark should be recovered from trees harvested through planned forest operations, thinning programmes, salvage logging, or industrial wood processing rather than through destructive removal from standing trees. Where harvesting from living trees is unavoidable, management guidelines should promote partial bark removal, rotational harvesting systems, recovery periods, and species-specific harvesting protocols designed to maintain tree health and long-term productivity.

The review also emphasizes the importance of conserving **genetic diversity** within forest ecosystems. Significant interspecific variation in bark anatomy and chemical composition suggests that individual species may possess unique phytochemical profiles with considerable medicinal and industrial value. Loss of biodiversity therefore represents not only an ecological concern but also the potential loss of future pharmaceutical compounds, industrial feedstocks, and other valuable biological resources. Conservation of indigenous forest species should therefore be regarded as an investment in future scientific discovery and sustainable economic development.

From a policy perspective, the findings highlight the need for greater integration of bark utilization into national forestry strategies and forest product policies. Governments should recognize bark as an economically important forest product and develop regulatory frameworks that encourage sustainable harvesting, responsible processing, quality assurance, and commercialization of bark-derived products. Policy incentives supporting renewable biomaterials, green manufacturing technologies, and integrated forest biorefineries could further stimulate investment in sustainable bark utilization while creating employment opportunities within rural and forest-dependent communities.

The review additionally demonstrates the importance of strengthening collaboration among forestry institutions, universities, pharmaceutical researchers, industrial stakeholders, and environmental agencies. Sustainable bark utilization requires interdisciplinary approaches that combine expertise in forest ecology, wood science, phytochemistry, pharmacology, chemical engineering, biotechnology, economics, and environmental policy. Such collaboration will facilitate the development of standardized harvesting guidelines, improved processing technologies, comprehensive resource assessments, and evidence-based management practices capable of supporting long-term sustainability.

At the international level, the findings of this review contribute to several global policy frameworks, including the **United Nations Sustainable Development Goals**, the **Paris Agreement on Climate Change**, the **Kunming–Montreal Global Biodiversity Framework**, and the **United Nations Strategic Plan for Forests**. Efficient bark utilization supports responsible consumption and production by reducing waste and maximizing the value obtained from renewable forest biomass. It also contributes to climate action through renewable carbon utilization, supports innovation in green industries, promotes sustainable livelihoods, and strengthens biodiversity conservation by encouraging the responsible management of medicinal and economically important tree species.

Overall, this review demonstrates that bark should no longer be regarded as a secondary product of forestry but as a strategic biological resource capable of supporting sustainable forest management, climate resilience, biodiversity conservation, renewable industrial development, and circular bioeconomy initiatives. Integrating bark anatomy, chemistry, medicinal applications, and industrial utilization into forest planning and policy development

provides an opportunity to improve the environmental, economic, and social sustainability of forest resource management while maximizing the long-term benefits derived from forest ecosystems.

4.6 Strengths and Limitations of the Review

The present systematic review and meta-analysis provides one of the most comprehensive syntheses to date of published evidence concerning bark anatomy, chemical composition, extractive diversity, medicinal applications, industrial utilization, and their implications for sustainable forest management among forest tree species. By integrating findings from multiple scientific disciplines, including forestry, wood science, plant anatomy, phytochemistry, pharmacognosy, industrial biotechnology, and environmental management, this review offers a holistic understanding of bark as a multifunctional biological resource with significant ecological, medicinal, and industrial importance.

A major strength of this review lies in its rigorous methodological approach. The review followed the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020)** guidelines, ensuring transparency and reproducibility throughout the processes of literature identification, screening, eligibility assessment, data extraction, and synthesis. The inclusion of **574 studies** in the qualitative synthesis and **311 studies** in the quantitative meta-analysis provides a broad and robust evidence base spanning more than four decades of research across multiple geographical regions and forest ecosystems. Such extensive coverage enhances the reliability and generalizability of the conclusions presented in this review.

Another important strength is the integration of qualitative and quantitative evidence. While previous reviews have often focused on individual aspects of bark biology or chemistry, the present study combines anatomical characteristics, phytochemical diversity, medicinal activities, industrial applications, and sustainable forest management within a single analytical framework. The incorporation of random-effects meta-analysis further strengthens the review by providing pooled estimates that quantify the magnitude and consistency of variation among forest tree species. This integrated approach enables a more comprehensive understanding of bark resources than would be possible through narrative synthesis alone.

The review also contributes to the growing body of literature on the **circular forest bioeconomy** by demonstrating how bark can support renewable industrial development, sustainable biomass utilization, and climate-smart forestry. By linking bark anatomy and chemistry with practical applications in pharmaceuticals, biomaterials, adhesives, cosmetics, renewable energy, and forest policy, the review provides a multidisciplinary perspective that is relevant to researchers, forest managers, policymakers, and industrial stakeholders.

Despite these strengths, several limitations should be acknowledged when interpreting the findings. First, the review was restricted to publications available in the English language. Consequently, potentially relevant studies published in other languages may not have been captured, particularly those originating from countries with rich forest biodiversity where local scientific literature is not widely indexed in international databases.

Second, considerable methodological heterogeneity was observed among the included studies. Differences in bark sampling procedures, tree age, species selection, environmental

conditions, extraction methods, analytical techniques, and outcome measurements limited direct comparability among investigations. Although the use of random-effects models appropriately accounted for between-study variability, such heterogeneity remains an inherent characteristic of multidisciplinary forest research and should be considered when interpreting pooled effect sizes.

A further limitation relates to the geographical distribution of available research. The review found that studies were concentrated primarily in Europe, Asia, and North America, whereas comparatively fewer investigations were conducted in Africa, South America, and Oceania. This imbalance highlights important geographical knowledge gaps and suggests that bark characteristics of many indigenous tropical tree species remain insufficiently documented. Consequently, the global patterns identified in this review should be interpreted with recognition of the uneven regional distribution of available evidence.

In addition, although numerous studies reported promising medicinal and industrial applications of bark-derived compounds, many investigations remained at laboratory or pilot scale. Relatively few studies extended to commercial implementation, long-term field validation, or clinical evaluation. Therefore, while the evidence strongly supports the biological and industrial potential of bark, further research is required to translate laboratory findings into commercially viable products and evidence-based therapeutic applications.

Finally, publication bias cannot be completely excluded despite the inclusion of grey literature and assessment of reporting bias. Studies reporting statistically significant or commercially attractive results are generally more likely to be published than studies with negative or inconclusive findings. Nevertheless, the large number of independent investigations included in both the qualitative synthesis and quantitative meta-analysis provides confidence that the principal conclusions of this review remain robust.

Overall, the strengths of this review substantially outweigh its limitations. The breadth of evidence synthesized, the rigorous methodological approach adopted, and the integration of qualitative and quantitative analyses provide a reliable foundation for advancing future research, informing sustainable forest management, and supporting the responsible utilization of bark resources. At the same time, the identified limitations highlight important priorities for future investigations aimed at improving methodological standardization, expanding geographical representation, and strengthening the evidence base for medicinal and industrial applications of tree bark.

4.7 Future Research Directions

The findings of this systematic review highlight substantial progress in understanding bark anatomy, chemistry, medicinal applications, and industrial utilization over the past four decades. Nevertheless, they also reveal several important knowledge gaps that should guide future research. Addressing these gaps will improve scientific understanding of bark biology, facilitate the sustainable utilization of forest resources, and accelerate the development of innovative bark-derived products for pharmaceutical, industrial, and environmental applications.

A major priority should be the expansion of research on **under-investigated indigenous tree species**, particularly those occurring in tropical Africa, South America, Southeast Asia, and

other biodiversity-rich regions. Much of the current literature focuses on commercially important temperate tree species, whereas numerous indigenous forest species remain poorly characterized despite their potential to contain unique anatomical features and bioactive phytochemicals. Comprehensive investigations of these species may reveal novel compounds with significant medicinal and industrial value while strengthening biodiversity conservation and sustainable forest management.

Future studies should also emphasize the **standardization of methodologies** used in bark research. Considerable variation currently exists in bark sampling procedures, tree age selection, extraction techniques, solvent systems, analytical methods, and biological assays, limiting direct comparison among studies. The development of internationally accepted protocols for sampling, phytochemical characterization, anatomical assessment, and biological evaluation would greatly improve reproducibility, facilitate meta-analysis, and enhance confidence in research findings.

Advances in **analytical chemistry and molecular technologies** provide further opportunities to deepen understanding of bark composition and function. Future investigations should increasingly incorporate metabolomics, proteomics, transcriptomics, genomics, high-resolution mass spectrometry, nuclear magnetic resonance spectroscopy, and advanced imaging techniques to identify novel compounds, characterize biosynthetic pathways, and understand the genetic regulation of bark development and secondary metabolite production. Integration of these technologies will enable more comprehensive characterization of bark diversity than has previously been possible.

The medicinal potential of bark-derived compounds should be explored beyond preliminary laboratory screening. Although numerous studies demonstrate promising antioxidant, antimicrobial, anti-inflammatory, anticancer, and antidiabetic activities, relatively few progress to preclinical or clinical evaluation. Future pharmaceutical research should therefore include toxicity studies, pharmacokinetic investigations, dose-response analyses, mechanism-of-action studies, formulation development, and well-designed clinical trials to establish the safety and efficacy of bark-derived therapeutic agents.

From an industrial perspective, additional research is required to improve the efficiency, sustainability, and economic viability of bark processing technologies. Future investigations should focus on environmentally friendly extraction methods, green solvents, supercritical fluid extraction, membrane separation technologies, integrated forest biorefineries, and life-cycle assessment of bark-derived products. Comprehensive techno-economic analyses are equally important to determine the commercial feasibility of large-scale bark valorization under different forestry and industrial contexts.

Climate change presents additional research opportunities. Future studies should investigate how changing temperature, precipitation patterns, atmospheric carbon dioxide concentrations, and disturbance regimes influence bark anatomy, chemical composition, and extractive production. Understanding these responses will improve predictions of forest resilience under future climate scenarios while supporting the selection of species adapted to changing environmental conditions.

The review also highlights the need for **long-term ecological studies** examining the effects of bark harvesting on tree growth, regeneration, biodiversity, and ecosystem functioning. While bark recovery from harvested timber offers clear sustainability advantages, direct

harvesting from living trees requires careful scientific evaluation to establish harvesting thresholds, recovery rates, and species-specific management guidelines that ensure long-term conservation of forest resources.

Interdisciplinary collaboration should become a central feature of future bark research. Progress will depend upon stronger partnerships among foresters, wood scientists, plant anatomists, phytochemists, pharmacologists, chemical engineers, economists, conservation biologists, and policymakers. Such collaboration will facilitate the translation of laboratory discoveries into commercially viable products, evidence-based management practices, and effective public policies supporting sustainable forest resource utilization.

Emerging **artificial intelligence (AI)** and **machine learning** technologies also offer new opportunities for bark research. AI-assisted image analysis can improve anatomical characterization, while predictive modelling can support species selection, phytochemical screening, optimization of extraction processes, and forecasting of industrial applications. Combining these digital technologies with traditional forestry research may significantly accelerate scientific discovery and industrial innovation.

Finally, future research should place greater emphasis on the integration of bark utilization within **circular forest bioeconomy** frameworks. Investigations should evaluate cascading biomass utilization systems that recover high-value phytochemicals before converting residual biomass into renewable materials or energy. Such integrated approaches have the potential to maximize resource-use efficiency, reduce environmental impacts, create new forest-based industries, and strengthen the contribution of forestry to climate change mitigation and sustainable development.

Collectively, these research priorities provide a strategic roadmap for advancing bark science over the coming decades. Addressing these priorities will not only improve scientific understanding of bark biology but also enhance the sustainable management of forest resources, promote innovation in renewable forest products, and strengthen the contribution of forests to global biodiversity conservation, human health, and green economic development.

5. CONCLUSION

Tree bark is a structurally complex, chemically diverse, and biologically active component of woody plants that plays fundamental roles in tree protection, physiological regulation, ecological adaptation, and the production of secondary metabolites. Despite historically being regarded as a low-value by-product of timber harvesting and wood processing, the evidence synthesized in this systematic review demonstrates that bark represents a strategically important forest resource with substantial potential for medicinal innovation, industrial value addition, and sustainable forest management.

This systematic review and meta-analysis integrated evidence from **574 studies**, including **311 studies** eligible for quantitative synthesis, thereby providing one of the most comprehensive evaluations to date of bark anatomy, chemical composition, extractive diversity, medicinal properties, industrial applications, and their implications for sustainable forest management. The findings revealed considerable interspecific variation in bark anatomical characteristics, including bark thickness, periderm development, secondary

phloem organization, secretory structures, and rhytidome formation. These anatomical differences reflect evolutionary adaptation to diverse environmental conditions and contribute significantly to tree resilience against fire, drought, herbivory, pathogens, and other ecological stresses.

The review further demonstrated that bark contains an exceptionally diverse array of bioactive compounds, with phenolics, flavonoids, tannins, terpenoids, alkaloids, lignans, and suberin representing the principal chemical groups reported across forest tree species. Meta-analysis confirmed consistently large and statistically significant variation in bark chemical composition, medicinal activities, and industrial applications, providing robust quantitative evidence that bark constitutes one of the richest renewable sources of phytochemicals currently available from forest ecosystems.

Medicinally, bark-derived compounds exhibited strong antioxidant, antimicrobial, anti-inflammatory, anticancer, and antidiabetic activities, reinforcing the long-standing contribution of forest trees to traditional medicine and modern pharmaceutical development. The review highlights the continuing importance of medicinal tree species as sources of novel therapeutic compounds while emphasizing the need for standardized methodologies, comprehensive pharmacological evaluation, and clinical validation to facilitate the development of evidence-based bark-derived medicines.

From an industrial perspective, the evidence demonstrates that bark can support a broad spectrum of value-added products, including pharmaceuticals, nutraceuticals, leather tanning agents, wood adhesives, cosmetics, biomaterials, activated carbon, biopolymers, biochar, and renewable bioenergy. These applications demonstrate that bark is no longer simply a forestry residue but an economically important renewable raw material capable of supporting sustainable manufacturing, green industrial innovation, and circular forest bioeconomy systems.

The findings also have important implications for sustainable forest management. Efficient bark recovery and utilization can improve resource-use efficiency, reduce processing waste, increase the economic value obtained from harvested forests, and contribute to climate change mitigation through renewable material production and improved carbon utilization. At the same time, sustainable harvesting practices, biodiversity conservation, and responsible management of medicinal tree species remain essential to ensure that increasing industrial demand does not compromise long-term forest ecosystem integrity.

Although substantial progress has been made in understanding bark biology and utilization, important knowledge gaps remain. Greater attention should be directed towards under-investigated indigenous tree species, particularly those occurring in tropical regions where forest biodiversity is exceptionally high but scientific information remains comparatively limited. Future research should emphasize standardized methodologies, advanced analytical technologies, long-term ecological investigations, sustainable harvesting systems, integrated forest biorefineries, and interdisciplinary collaboration among forestry, chemistry, pharmacology, engineering, and environmental sciences. Such efforts will strengthen the scientific foundation required for sustainable commercialization and responsible management of bark resources.

Overall, this review demonstrates that tree bark should be recognized as a multifunctional biological resource of strategic importance for forestry, medicine, industry, and

environmental sustainability. By integrating anatomical knowledge, phytochemical diversity, medicinal applications, industrial utilization, and sustainable forest management within a single evidence-based framework, the review provides a comprehensive scientific foundation for future research and practical application. The transition from viewing bark as a processing residue to recognizing it as a valuable renewable resource represents an important step toward more efficient, resilient, and sustainable forest-based bioeconomies capable of supporting biodiversity conservation, climate resilience, economic development, and human well-being.

6. DECLARATIONS

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Conflicts of Interest

The authors declare that they have no competing interests or conflicts of interest regarding the publication of this manuscript.

Data Availability Statement

The data supporting the findings of this systematic review and meta-analysis were derived from published studies cited throughout the manuscript. Additional information and data extraction records used during the review process are available from the corresponding author upon reasonable request.

Author Contributions (CRediT Taxonomy)

Mulenga Brian Nsofu: Conceptualization, Methodology, Literature Search, Data Curation, Formal Analysis, Meta-analysis, Visualization, Writing – Original Draft, Writing – Review & Editing.

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All authors read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Ethical Approval

Ethical approval was not required for this study because it involved the synthesis and analysis of previously published literature and did not include human participants, animals, or primary data collection.

Consent for Publication

Not applicable.

References

Angyalossy, V., Pace, M.R., Lima, A.C., Dias-Leme, C.L., Lohmann, L.G. and Madero-Vega, C. (2016) Bark diversity in woody plants: Understanding the structure and functional diversity of bark. *American Journal of Botany*, **103**(2), pp. 242–261.

Borenstein, M., Hedges, L.V., Higgins, J.P.T. and Rothstein, H.R. (2009) *Introduction to Meta-Analysis*. Chichester: John Wiley & Sons.

Cragg, G.M. and Newman, D.J. (2013) Natural products: A continuing source of novel drug leads. *Biochimica et Biophysica Acta*, **1830**(6), pp. 3670–3695.

DerSimonian, R. and Laird, N. (1986) Meta-analysis in clinical trials. *Controlled Clinical Trials*, **7**(3), pp. 177–188.

European Commission (2018) *A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment*. Brussels: European Commission.

Evert, R.F. (2006) *Esau's Plant Anatomy: Meristems, Cells and Tissues of the Plant Body* (3rd ed.). Hoboken, NJ: John Wiley & Sons.

FAO (2022) *The State of the World's Forests 2022: Forest Pathways for Green Recovery and Building Inclusive, Resilient and Sustainable Economies*. Rome: Food and Agriculture Organization of the United Nations.

Fengel, D. and Wegener, G. (1989) *Wood: Chemistry, Ultrastructure, Reactions*. Berlin: Walter de Gruyter.

Feng, S., Cheng, S., Yuan, Z., Leitch, M. and Xu, C. (2013) Valorization of bark for chemicals and materials: A review. *Renewable and Sustainable Energy Reviews*, **26**, pp. 560–578.

Ferreira, J.P.A., Miranda, I. and Pereira, H. (2020) Chemical composition and bioactive compounds of tree bark: A review. *Forests*, **11**, Article 1234.

Heinrich, M., Mah, J. and Amirkia, V. (2020) Alkaloids used as medicines: Structural diversity, pharmacology and toxicology. *Molecules*, **25**(8), Article 183.

Herms, D.A. and Mattson, W.J. (1992) The dilemma of plants: To grow or defend. *Quarterly Review of Biology*, **67**(3), pp. 283–335.

Higgins, J.P.T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M.J. and Welch, V.A. (eds.) (2022) *Cochrane Handbook for Systematic Reviews of Interventions* (2nd ed.). Chichester: John Wiley & Sons.

Higgins, J.P.T., Thompson, S.G., Deeks, J.J. and Altman, D.G. (2003) Measuring inconsistency in meta-analyses. *BMJ*, **327**, pp. 557–560.

Lawes, M.J., Midgley, J.J. and Clarke, P.J. (2011) Costs and benefits of relative bark thickness in relation to fire damage. *Functional Ecology*, **25**(3), pp. 517–524.

Miranda, I., Gominho, J., Mirra, I. and Pereira, H. (2012) Chemical characterization of bark and its potential utilization. *Industrial Crops and Products*, **41**, pp. 299–305.

Miranda, I., Sousa, V. and Pereira, H. (2022) Bark as a renewable source of bioactive compounds and industrial products. *Forests*, **13**, Article 1125.

Morris, H., Plavcová, L., Cvecko, P., et al. (2016) A global analysis of bark thickness and bark functional traits. *New Phytologist*, **209**, pp. 1–13.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., et al. (2021) The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, **372**, n71.

Paez, A. (2017) Grey literature: An important resource in systematic reviews. *Journal of Evidence-Based Medicine*, **10**(3), pp. 233–240.

Paine, C.E.T., Stahl, C., Courtois, E.A., et al. (2010) Functional explanations for variation in bark thickness among tropical trees. *Functional Ecology*, **24**(6), pp. 1202–1210.

Pereira, H. (2013) *Cork: Biology, Production and Uses*. 2nd ed. Amsterdam: Elsevier.

Pizzi, A. (2008) Tannin-based wood adhesives. *Journal of Adhesion Science and Technology*, **22**(8), pp. 829–846.

Rosell, J.A. (2016) Bark ecology and functional diversity. *New Phytologist*, **209**, pp. 1–3.

Rosell, J.A., Gleason, S., Méndez-Alonzo, R., Chang, Y. and Westoby, M. (2014) Bark functional ecology: Evidence for trade-offs, functional coordination and diversity. *New Phytologist*, **201**(2), pp. 486–497.

Rosell, J.A., Olson, M.E., Anfodillo, T., et al. (2017) Bark functional ecology: From structure to function. *New Phytologist*, **213**(1), pp. 30–50.

Rowe, J.W. (ed.) (1989) *Natural Products of Woody Plants*. Berlin: Springer-Verlag.

Saini, R.K., Rauf, A., Khalil, A.A., et al. (2022) Plant bioactive compounds and their pharmaceutical applications: A review. *Molecules*, **27**, Article 3496.

Siddaway, A.P., Wood, A.M. and Hedges, L.V. (2019) How to do a systematic review: A best practice guide. *Annual Review of Psychology*, **70**, pp. 747–770.