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Linking Bark Structure, Chemistry and Functional Properties to Valorisation Pathways: A Systematic Review for Circular Forest Biorefineries

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Systematic Review

Keywords: tree bark, bark anatomy, bark chemistry, extractives, suberin, tannins, functional properties, valorisation, biorefinery, circular bioeconomy, forest products, bio-based materials, medicinal applications, sustainable forest management

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Linking Bark Structure, Chemistry and Functional Properties to Valorisation Pathways: A Systematic Review for Circular Forest Biorefineries

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Abstract

Background. Tree bark is a chemically and anatomically heterogeneous component of woody biomass that is often treated as a low-value by-product despite containing structural polymers, suberin, tannins, phenolics, terpenoids and other extractives with potential applications in materials, chemicals, adhesives, pharmaceuticals and energy. Bark structure determines protection, storage, transport and defence, while anatomical organization can influence the distribution, accessibility and recovery of chemical fractions.

Objective. This systematic review synthesizes evidence on bark anatomy, chemical composition, extractive variation, functional properties, processing approaches and value-added applications, with particular emphasis on linking bark structure and chemistry to practical valorisation pathways within a circular forest bioeconomy.

Methods. The review follows the PRISMA 2020 reporting framework and examines literature published from 1980 to 2026 using multidisciplinary bibliographic databases and supplementary sources. Eligible evidence covers bark anatomy, chemistry, extractives, medicinal properties, industrial applications and sustainability. The review retains the detailed evidence synthesis and quantitative analyses developed in the source manuscript, while organizing their interpretation around a structure–chemistry–function–process–product framework.

Results. The reviewed evidence demonstrates substantial interspecific and environmental variation in bark thickness, periderm and rhytidome development, phloem organization, fibres, sclereids and secretory structures. Major chemical groups include phenolics, tannins, flavonoids, terpenoids, alkaloids, lignans, suberin, waxes and other extractives. These characteristics are associated with medicinal, adhesive, material, chemical and energy applications. The synthesis further identifies extraction, fractionation, tannin-based adhesives, composites, structural materials, thermochemical conversion and integrated biorefinery systems as important valorisation pathways, while emphasizing the need to valorise post-extraction residues.

Conclusions. Bark should be considered a heterogeneous forest-product feedstock rather than a uniform residue. Its anatomy, chemistry and functional properties provide the basis for selecting appropriate extraction, processing and product pathways. Future research should integrate standardized bark characterization with process mass balances, product performance testing, life-cycle assessment and techno-economic analysis to support commercially viable circular forest biorefineries.

Keywords: tree bark; bark anatomy; bark chemistry; extractives; suberin; tannins; functional properties; valorisation; biorefinery; circular bioeconomy; forest products; bio-based materials; medicinal applications; sustainable forest management.

Scope and contribution of the revised manuscript. The detailed evidence base, tables, species-level discussions, quantitative results and references from the source manuscript have been retained. The principal revision is the scientific framing: bark is evaluated as a heterogeneous feedstock in which anatomical structure, chemical composition and functional properties guide processing and product selection. This structure–chemistry–function–process–product perspective is used to connect medicinal and industrial evidence with forest-products science and circular biorefinery development.

1. INTRODUCTION

1.1 Background of the Study

Bark constitutes one of the most complex and functionally important tissues in woody plants. It serves as the interface between the tree and its external environment and performs essential roles in protection, transport, storage, wound healing, and defence (Evert, 2006; Rosell, 2016). Despite representing a substantial proportion of tree biomass, bark has historically received less scientific attention than wood, particularly regarding its anatomical diversity, chemical composition and extractive content (Paine et al., 2010; Rosell et al., 2014).

From a biological perspective, bark consists of all tissues external to the vascular cambium and includes the secondary phloem, periderm, cortex, rhytidome and associated tissues (Evert, 2006; Angyalossy et al., 2016). These tissues exhibit remarkable structural and chemical diversity among species, reflecting adaptations to environmental conditions, evolutionary history, growth strategies and ecological interactions (Rosell et al., 2017; Morris et al., 2016).

Bark anatomy varies considerably among species in terms of:

- Bark thickness
- Periderm structure
- Phloem organization
- Sclereid distribution
- Fibre arrangement
- Resin canal development
- Cork formation
- Rhytidome characteristics

These anatomical differences influence mechanical protection, fire resistance, water regulation, pathogen defence and extractive accumulation (Rosell et al., 2014; Paine et al., 2010; Lawes et al., 2011).

The chemistry of bark is equally diverse. Bark tissues contain a wide range of bioactive compounds including phenolic compounds, flavonoids, tannins, alkaloids, terpenoids, lignans, glycosides, saponins, suberin, waxes, essential oils and mineral elements (Rowe, 1989; Feng et al., 2013; Ferreira et al., 2020). Many of these compounds possess important medicinal, ecological, industrial and commercial value owing to their antioxidant, antimicrobial, anti-inflammatory and protective properties (Pizzi, 2008; Saini et al., 2022).

Historically, bark has provided some of humanity's most important medicines, including quinine from *Cinchona* species and salicin from *Salix* species, which later led to the development of aspirin (Cragg & Newman, 2013; Heinrich et al., 2020). Bark extractives also contribute to industrial products such as tannins, adhesives, dyes, preservatives, antioxidants, nutraceuticals, cosmetics, pharmaceuticals and biopolymers (Pizzi, 2008; Miranda et al., 2022).

In forestry, bark is often treated as a low-value by-product of timber processing despite representing a significant source of high-value natural compounds (Miranda et al., 2012; Feng et al., 2013). The growing global bioeconomy and increasing interest in circular forest resource utilization have renewed attention toward bark valorization and integrated forest product utilization (European Commission, 2018; FAO, 2022).

Recent advances in analytical chemistry, microscopy, metabolomics, molecular biology and biotechnology have significantly expanded understanding of bark anatomy and chemistry (Fengel & Wegener, 1989; Ferreira et al., 2020; Saini et al., 2022). However, knowledge remains fragmented across disciplines and species groups, limiting broader understanding of bark variability and utilization potential (Rosell et al., 2017; Miranda et al., 2022).

This systematic review and meta-analysis therefore seeks to synthesize global evidence on bark anatomy, chemistry and extractive variation and evaluate their implications for medicinal value, industrial utilization and sustainable forest management.

1.2 Research Problem and Justification

Despite the biological and economic importance of bark, research remains fragmented across forestry, wood science, pharmacognosy, industrial chemistry and ecological disciplines (Rosell et al., 2017; Ferreira et al., 2020). Most studies focus on individual species, specific chemical compounds or isolated applications, limiting broader understanding of bark diversity, ecological adaptation and industrial utilization (Miranda et al., 2022).

Furthermore, increasing global demand for bark-derived products raises important questions regarding sustainable harvesting, resource efficiency and biodiversity conservation (FAO, 2022; European Commission, 2018). A comprehensive synthesis is therefore needed to evaluate global patterns of bark variation, identify opportunities for value addition and support sustainable forest resource utilization within the emerging forest bioeconomy (Saini et al., 2022).

1.3 Aim of the Study

To systematically review and quantitatively synthesize evidence on bark anatomy, chemistry, and extractive variation among forest tree species and evaluate their implications for medicinal value, industrial utilization, and sustainable forest management.

1.4 Objectives of the Study

General Objective

To assess bark anatomy, chemistry, and extractive variation among forest tree species through a systematic review and meta-analysis.

Specific Objectives

1. To characterize anatomical variation in bark among forest tree species.
2. To identify major chemical constituents and extractive classes in bark tissues.
3. To evaluate variation in bark extractive composition among species and ecological regions.
4. To assess medicinal applications associated with bark extractives.
5. To evaluate industrial utilization opportunities for bark-derived products.
6. To determine factors influencing bark anatomy and chemistry.
7. To assess implications of bark utilization for sustainable forest management.
8. To identify future research priorities.

1.5 Research Questions

Main Research Question

How do bark anatomy, bark chemistry, and extractive variation among forest tree species influence medicinal value, industrial utilization, and sustainable forest management?

Specific Research Questions

Research Question 1

What are the major anatomical characteristics that distinguish bark among forest tree species?

Research Question 2

What are the dominant chemical constituents and extractive classes present in bark tissues?

Research Question 3

How does bark chemistry vary among species, ecological regions, and forest ecosystems?

Research Question 4

What relationships exist between bark anatomy and extractive accumulation?

Research Question 5

How do bark extractives contribute to medicinal and pharmaceutical applications?

Research Question 6

What industrial applications are associated with bark-derived compounds?

Research Question 7

What environmental, genetic, physiological, and ecological factors influence bark variability?

Research Question 8

How can bark resources be utilized sustainably while maintaining forest productivity and biodiversity conservation?

1.6 Research Hypotheses

Hypothesis 1

Null Hypothesis (H_{01})

Bark anatomical characteristics have no significant influence on extractive accumulation.

Alternative Hypothesis (H_{11})

Bark anatomical characteristics significantly influence extractive accumulation.

Hypothesis 2

Null Hypothesis (H_{02})

There are no significant differences in bark chemistry among forest tree species.

Alternative Hypothesis (H_{12})

There are significant differences in bark chemistry among forest tree species.

Hypothesis 3

Null Hypothesis (H_{03})

Bark extractive concentration has no significant relationship with medicinal bioactivity.

Alternative Hypothesis (H_{13})

Bark extractive concentration significantly influences medicinal bioactivity.

Hypothesis 4

Null Hypothesis (H_{04})

Environmental conditions have no significant effect on bark chemistry and extractive composition.

Alternative Hypothesis (H_{14})

Environmental conditions significantly influence bark chemistry and extractive composition.

Hypothesis 5

Null Hypothesis (H_{05})

Bark utilization has no significant contribution to sustainable forest resource utilization.

Alternative Hypothesis (H_{15})

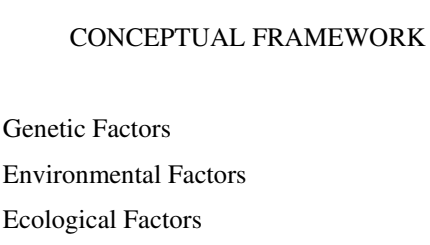
Bark utilization contributes significantly to sustainable forest resource utilization.

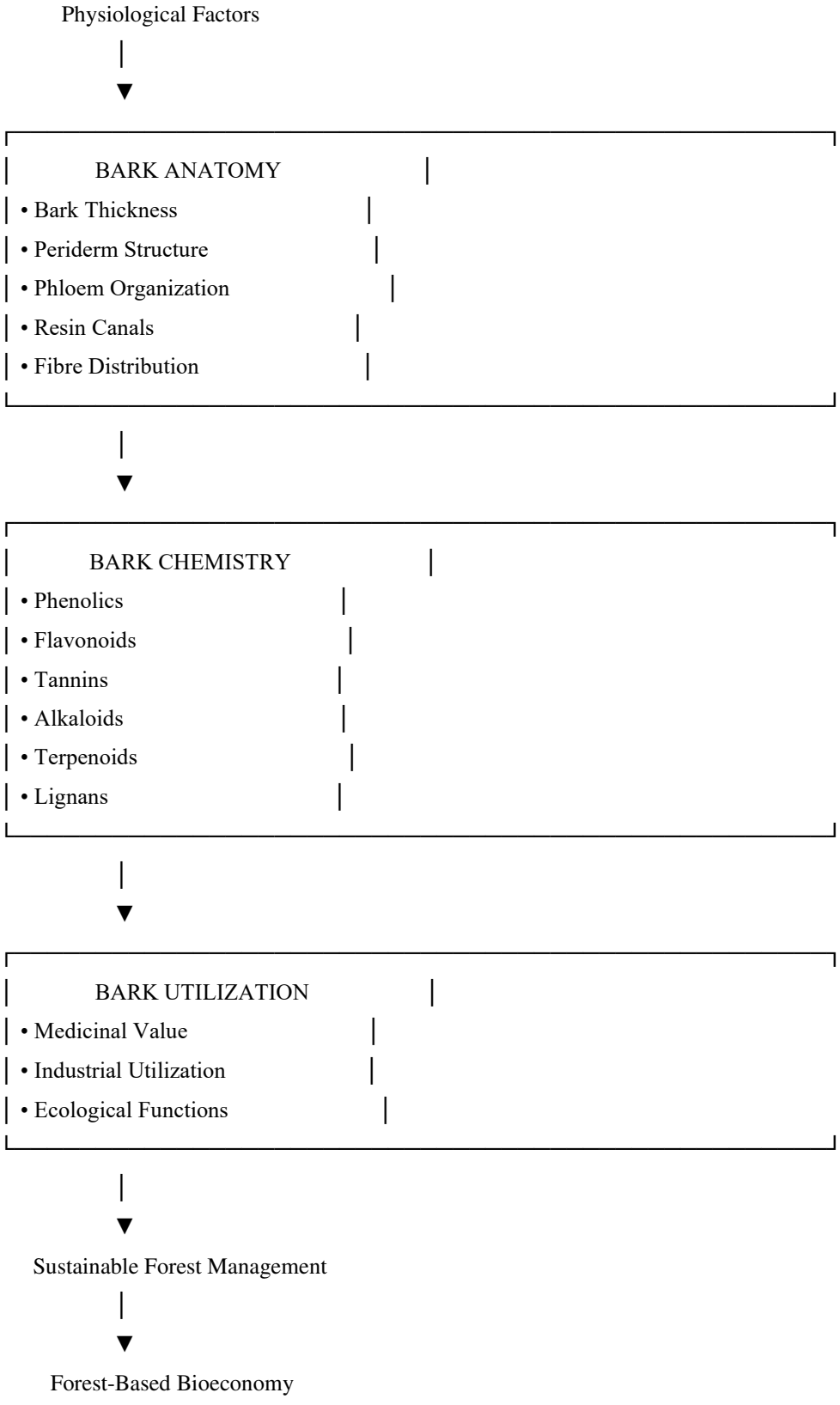
1.7 Conceptual Framework

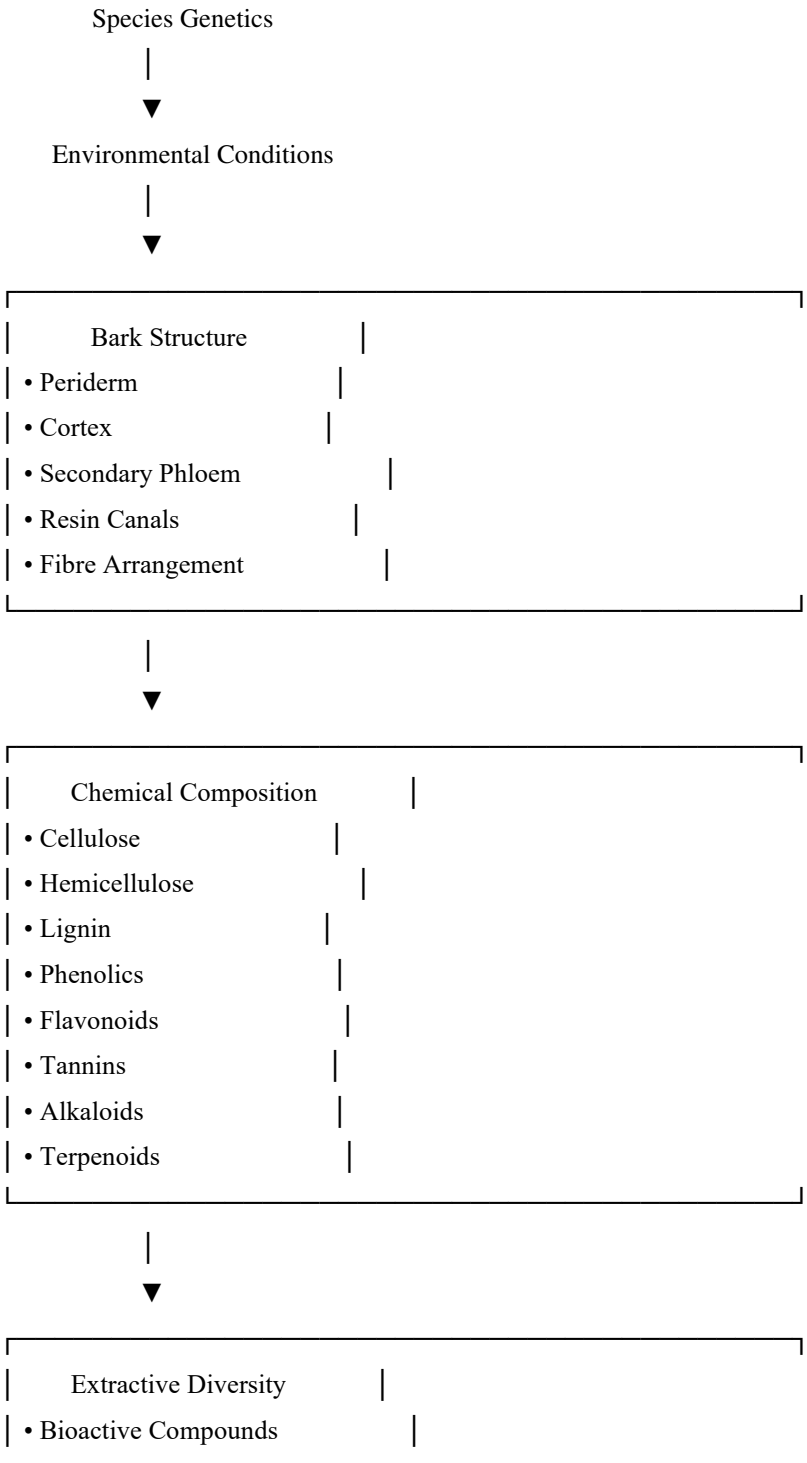
1.7.1 Theoretical Foundation

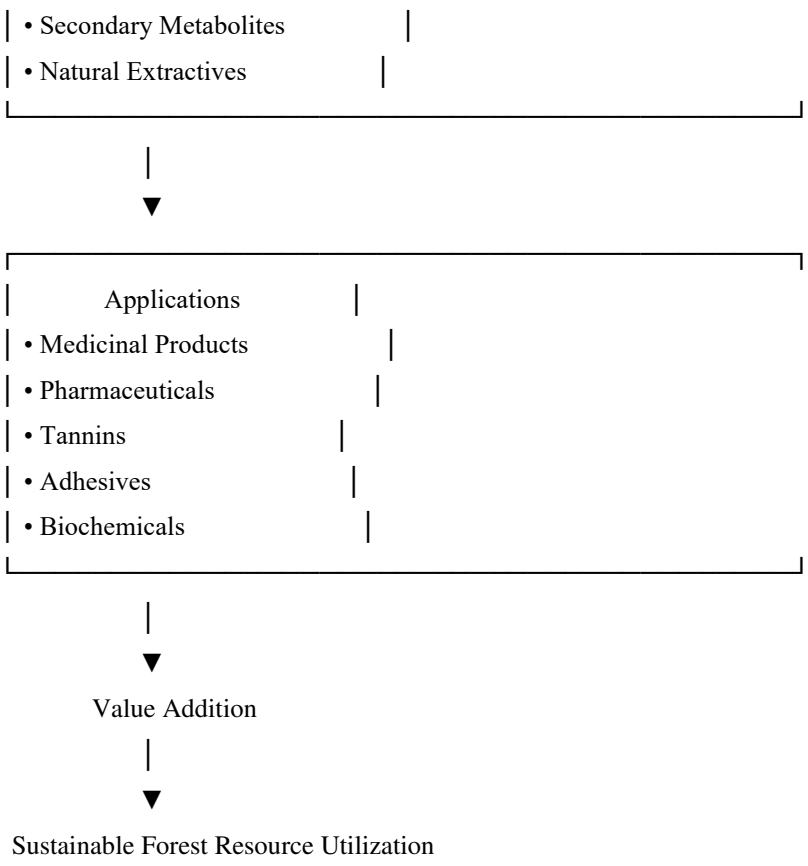
This review is based on the premise that bark anatomy and chemistry are products of interactions among genetic factors, environmental conditions, physiological processes and ecological pressures. These interacting factors influence bark development, extractive biosynthesis, medicinal properties, industrial applications and long-term sustainable utilization (Rosell et al., 2017; Angyalossy et al., 2016). The framework further draws upon theories of plant defence, resource allocation and the forest bioeconomy, which explain how trees allocate carbon and secondary metabolites for protection while simultaneously providing valuable renewable resources for human use (Herms & Mattson, 1992; European Commission, 2018; FAO, 2022).

1.7.2 Conceptual Model




Physiological Factors
BARK ANATOMY
• Bark Thickness
• Periderm Structure
• Phloem Organization
• Resin Canals
• Fibre Distribution
BARK CHEMISTRY
• Phenolics
• Flavonoids
• Tannins
• Alkaloids
• Terpenoids
• Lignans
BARK UTILIZATION
• Medicinal Value
• Industrial Utilization
• Ecological Functions
Sustainable Forest Management
Forest-Based Bioeconomy


Species Genetics
Environmental Conditions
Bark Structure
• Periderm
• Cortex
• Secondary Phloem
• Resin Canals
• Fibre Arrangement
Chemical Composition
• Cellulose
• Hemicellulose
• Lignin
• Phenolics
• Flavonoids
• Tannins
• Alkaloids
• Terpenoids
Extractive Diversity
• Bioactive Compounds



1.8 Significance of the Study

Scientific Significance

This systematic review and meta-analysis provides one of the most comprehensive syntheses of bark anatomy, chemistry, and extractive variation currently available within the forestry and wood science literature. By integrating evidence from diverse geographical regions, species, and analytical approaches, the study contributes to a broader understanding of bark biology and its functional importance in woody plants (Rosell et al., 2017; Angyalossy et al., 2016). The findings are expected to advance knowledge in several scientific disciplines, including:

- Forestry
- Wood science
- Bark biology
- Natural products chemistry
- Pharmacognosy
- Forest ecology

Medicinal Significance

The review improves understanding of the diversity, distribution, and biological activities of bark-derived phytochemicals, thereby providing a scientific basis for future pharmaceutical and medicinal research. Many bark constituents, including phenolics, flavonoids, tannins, alkaloids, and terpenoids, exhibit antioxidant, antimicrobial, anti-inflammatory, and anticancer properties that continue to attract considerable pharmaceutical interest (Cragg & Newman, 2013; Heinrich et al., 2020; Ferreira et al., 2020).

Potential applications include:

- Drug discovery
- Herbal medicine
- Nutraceuticals
- Functional foods

Industrial Significance

The study highlights opportunities for the value-added utilization of bark resources within forest-based industries. Bark extractives have demonstrated considerable potential as renewable raw materials for tannin extraction, wood adhesives, biopolymers, natural preservatives, cosmetics, pharmaceuticals, and other bio-based products, supporting the transition toward a circular bioeconomy (Pizzi, 2008; Miranda et al., 2022; European Commission, 2018).

Potential industrial applications include:

- Tannin production
- Bio-based adhesives
- Biopolymers
- Natural preservatives
- Cosmetics
- Pharmaceuticals

Forestry Significance

The findings reinforce the recognition of bark as an economically valuable forest resource rather than merely a low-value by-product of timber processing. Improved understanding of bark variability and utilization potential may enhance integrated forest product management, improve resource-use efficiency, and increase the economic value derived from harvested trees (FAO, 2022; Miranda et al., 2012).

Conservation Significance

Understanding bark anatomy, chemistry, and ecological function contributes to biodiversity conservation by supporting sustainable harvesting practices that maintain tree health, ecosystem resilience, and long-term forest productivity. Sustainable bark utilization is particularly important in reducing pressure on natural forests while promoting responsible management of medicinal plant resources (Lawes et al., 2011; FAO, 2022).

This knowledge contributes to:

- Biodiversity conservation
- Sustainable harvesting
- Climate-smart forestry
- Ecosystem resilience

Economic Significance

The review provides scientific evidence supporting the development of high-value forest-based enterprises and the diversification of rural livelihoods through sustainable bark utilization. Increased commercialization of bark-derived products may strengthen non-timber forest product (NTFP) value chains while contributing to employment creation and the expanding global forest bioeconomy (European Commission, 2018; FAO, 2022).

Potential economic benefits include:

- Forest-based enterprises
- Rural livelihoods

- Bioeconomy initiatives
- Non-timber forest products

Policy Significance

The findings may inform evidence-based policy development concerning sustainable forest management, medicinal plant conservation, biodiversity protection, and forest bioeconomy strategies. The synthesized evidence may also assist governments, forestry agencies, and industry stakeholders in developing policies that encourage sustainable bark harvesting and value addition while ensuring long-term conservation of forest resources (FAO, 2022; European Commission, 2018).

Potential policy applications include:

- Forest resource management
- Medicinal plant conservation
- Sustainable resource utilization
- Bioeconomy development

1.9 Organization of the Review

This systematic review and meta-analysis is organized into five major chapters.

Chapter 1: Introduction

This chapter presents the background to the study, research problem, study objectives, research questions, hypotheses, conceptual framework, significance of the study, and organization of the review.

Chapter 2: Materials and Methods

This chapter describes the methodological procedures employed in conducting the systematic review and meta-analysis, including:

- PRISMA 2020 reporting framework
- Literature search strategy
- Inclusion and exclusion criteria
- Data extraction procedures
- Quality assessment methods
- Statistical meta-analysis techniques

Chapter 3: Results

This chapter presents the findings of the systematic review and meta-analysis relating to:

- Bark anatomy
- Bark chemistry
- Extractive diversity
- Medicinal value
- Industrial utilization
- Species variation
- Sustainable forest management implications

Chapter 4: Discussion

This chapter interprets the findings in relation to existing scientific literature and examines:

- Ecological significance
- Medicinal applications
- Industrial opportunities
- Forest management implications
- Knowledge gaps and future research needs

Chapter 5: Conclusions and Recommendations

This chapter summarizes the principal findings of the review and provides:

- Overall conclusions
- Forestry implications
- Industrial implications
- Conservation recommendations
- Policy recommendations
- Future research priorities

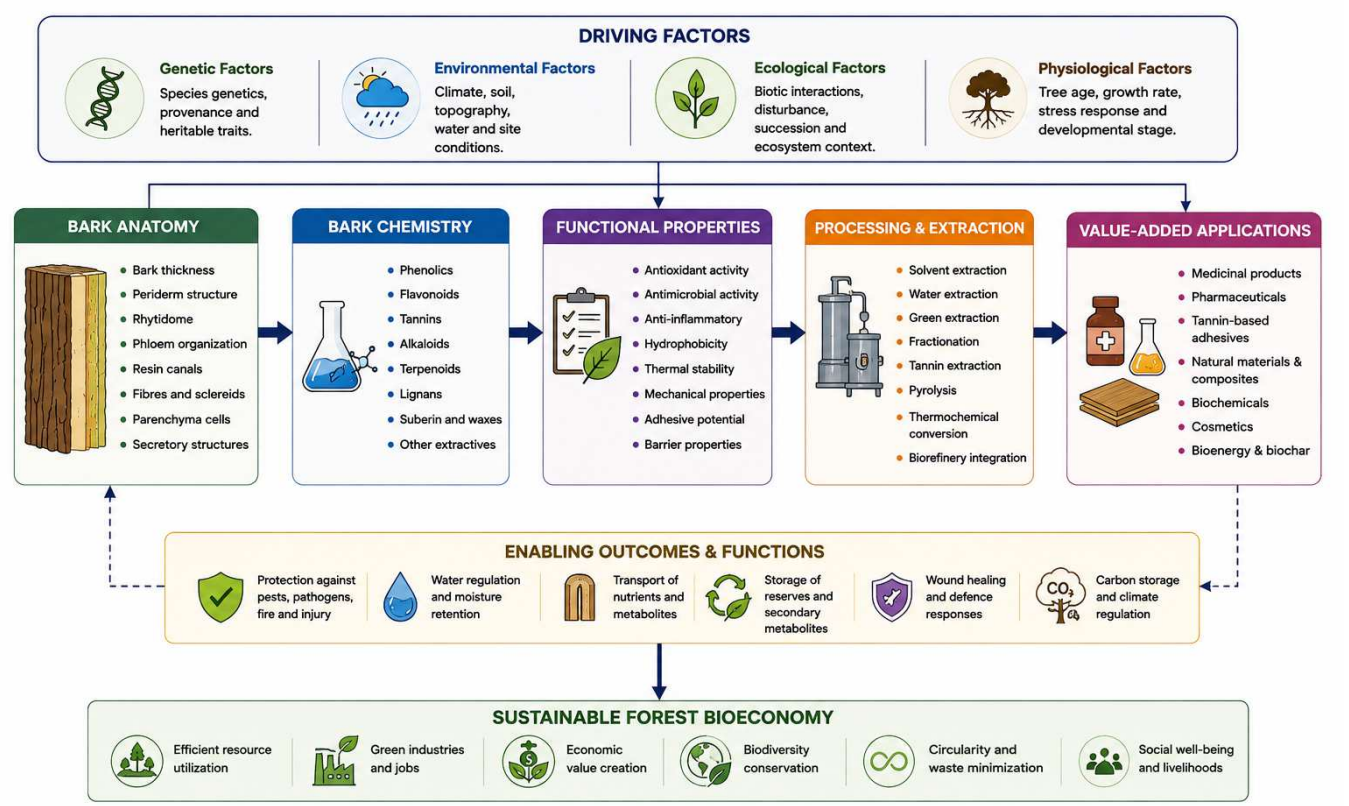


Figure 1. Integrated conceptual framework linking driving factors, bark anatomy, chemistry, functional properties, processing, and value-added applications to sustainable forest bioeconomy outcomes.

2. MATERIALS AND METHODS

2.1 Introduction

This chapter describes the methodological framework employed to systematically identify, evaluate, synthesize, and analyse scientific evidence relating to bark anatomy, bark chemistry, and extractive variation among forest tree species. The methodology was designed to ensure transparency, reproducibility, scientific rigour, and compliance with internationally recognised standards for systematic reviews and meta-analyses (Page et al., 2021; Higgins et al., 2022).

The review followed the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020)** guidelines and incorporated both qualitative synthesis and quantitative meta-analysis to examine relationships among bark structure, chemical composition, medicinal value, industrial utilization, and sustainable forest management (Page et al., 2021). The methodological approach was further guided by recommendations in the *Cochrane Handbook for Systematic Reviews of Interventions*, which provides internationally accepted procedures for evidence synthesis and statistical meta-analysis (Higgins et al., 2022).

2.2 Research Design

The study employed a **systematic review and meta-analysis** research design.

A systematic review provides a structured, transparent, and reproducible approach for identifying, critically evaluating, and synthesizing evidence from multiple independent studies while minimizing selection and reporting bias (Siddaway et al., 2019; Page et al., 2021). Compared with traditional narrative reviews, systematic reviews follow predefined protocols that improve the reliability and validity of scientific conclusions.

Meta-analysis was conducted where sufficient quantitative information was available to estimate pooled effect sizes and evaluate variation among studies. Meta-analysis increases statistical power, provides more precise estimates of treatment or association effects, and enables the investigation of heterogeneity among studies (Borenstein et al., 2009; Higgins et al., 2022).

The review combined both **qualitative** and **quantitative** evidence synthesis.

Qualitative Synthesis

Qualitative synthesis was undertaken to evaluate:

- Bark anatomy
- Bark chemistry
- Extractive diversity
- Medicinal applications
- Industrial uses
- Sustainable forest management implications

This approach facilitated the integration of descriptive findings across studies and enabled comparison of anatomical characteristics, chemical composition, ecological functions, and utilization patterns among forest tree species (Popay et al., 2006; Page et al., 2021).

Quantitative Synthesis

Quantitative synthesis (meta-analysis) was conducted to assess variables that were consistently reported across studies, including:

- Bark thickness
- Extractive content
- Phenolic concentration
- Tannin concentration
- Medicinal activity
- Industrial performance indicators

Where appropriate, standardized effect sizes were calculated and pooled using random-effects models to account for expected biological and methodological heterogeneity among studies (Borenstein et al., 2009; Harrer et al., 2021).

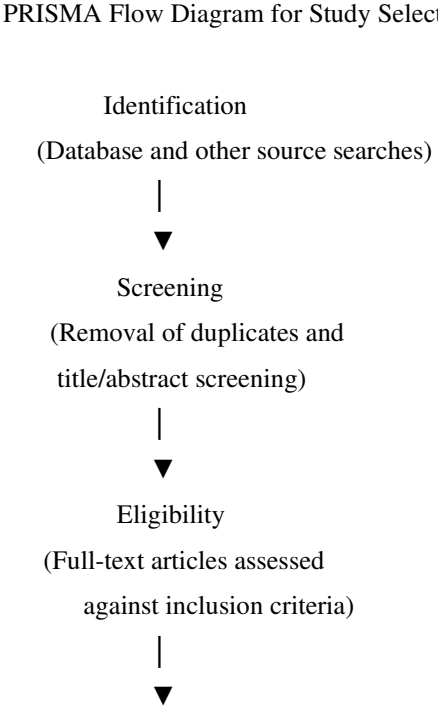
2.3 PRISMA Framework

The review followed the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020)** reporting guideline developed to improve the completeness, transparency, and reproducibility of systematic reviews (Page et al., 2021).

The PRISMA framework comprised the following stages:

1. **Identification** – Comprehensive searches were conducted across multiple electronic databases to identify potentially relevant studies.
2. **Screening** – Duplicate records were removed, and titles and abstracts were screened according to predefined eligibility criteria.
3. **Eligibility** – Full-text articles were assessed independently to determine whether they satisfied the inclusion criteria established for the review.
4. **Inclusion** – Studies meeting all eligibility requirements were included in the qualitative synthesis.
5. **Meta-analysis** – Studies containing suitable quantitative data were included in the statistical meta-analysis to estimate pooled effect sizes and assess heterogeneity among studies (Page et al., 2021; Higgins et al., 2022).

Figure 2. PRISMA Review Process



Inclusion

(Studies meeting all eligibility requirements)

|

▼

Meta-analysis

(Quantitative synthesis of the included studies)

2.4 Information Sources

A comprehensive literature search was conducted using multiple international bibliographic databases to maximize the coverage of published scientific evidence and minimize publication bias. The selection of databases was based on their relevance to forestry, wood science, plant biology, natural products chemistry, pharmacognosy, ecology, and environmental sciences (Page et al., 2021; Higgins et al., 2022).

Databases Searched

The following electronic databases were searched:

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

Grey Literature Sources

To reduce publication bias and improve the comprehensiveness of the review, grey literature was also consulted (Paez, 2017). Sources included:

- FAO Publications
- CIFOR Publications
- ITTO Publications
- Forestry Research Institute reports
- Government reports
- University repositories
- Conference proceedings

Including grey literature helps identify important scientific evidence that may not be available through conventional peer-reviewed databases, thereby improving the completeness and reliability of systematic reviews (Paez, 2017; Page et al., 2021).

2.5 Search Strategy

A comprehensive and systematic search strategy was developed to identify published studies relating to bark anatomy, bark chemistry, extractive diversity, medicinal applications, industrial utilization, and sustainable forest management. The search strategy was designed using combinations of keywords, Boolean operators ("AND" and "OR"), phrase searching, and database-specific indexing terms to maximise retrieval of relevant studies while reducing irrelevant records (Bramer et al., 2018; Page et al., 2021).

The literature search covered publications released between:

January 1980 and June 2026

The following search strings were applied either individually or in combination depending on database requirements.

Search String 1

("bark anatomy") AND ("forest tree species")

Search String 2

("bark chemistry") AND ("extractives")

Search String 3

("bark extractives") AND ("medicinal value")

Search String 4

("tree bark") AND ("industrial utilization")

Search String 5

("bark variability") AND ("forest management")

Search String 6

("phenolics" OR "tannins" OR "flavonoids") AND ("tree bark")

Additional searches were undertaken by screening reference lists of eligible articles, review papers, and key forestry publications to identify further relevant studies that were not retrieved during the primary database search (Page et al., 2021).

2.6 Eligibility Criteria

Eligibility criteria were established before the literature search and screening process to ensure consistency, transparency, and reproducibility throughout study selection (Higgins et al., 2022).

Inclusion Criteria

Studies were included if they:

- Examined bark anatomy.
- Investigated bark chemistry.
- Reported bark extractives.
- Included forest tree species.
- Evaluated medicinal properties of bark-derived compounds.
- Assessed industrial applications of bark or bark extractives.
- Reported qualitative or quantitative research findings.
- Were published between **1980 and 2026**.
- Were published in the English language.
- Were peer-reviewed journal articles, conference papers, book chapters, or credible grey literature.

Exclusion Criteria

Studies were excluded if they:

- Focused exclusively on wood tissues without bark analysis.
- Did not report bark-related anatomical or chemical information.
- Lacked sufficient methodological detail.
- Were duplicate publications.
- Were conference abstracts without accessible full text.
- Were editorials, commentaries, or opinion papers without original scientific data.
- Were published in languages other than English.

These criteria were applied consistently throughout the review to minimize selection bias and improve methodological quality (Page et al., 2021).

2.7 Study Selection Procedures

Study selection followed the **PRISMA 2020** framework and was undertaken in four sequential stages (Page et al., 2021).

Stage 1: Identification

Relevant records were identified through systematic searches of electronic databases and supplementary sources, including grey literature, reference lists, and institutional publications.

Stage 2: Screening

Retrieved records were imported into a reference management system where duplicate publications were identified and removed. The remaining studies were screened independently based on titles and abstracts to determine their relevance to the review objectives (Higgins et al., 2022).

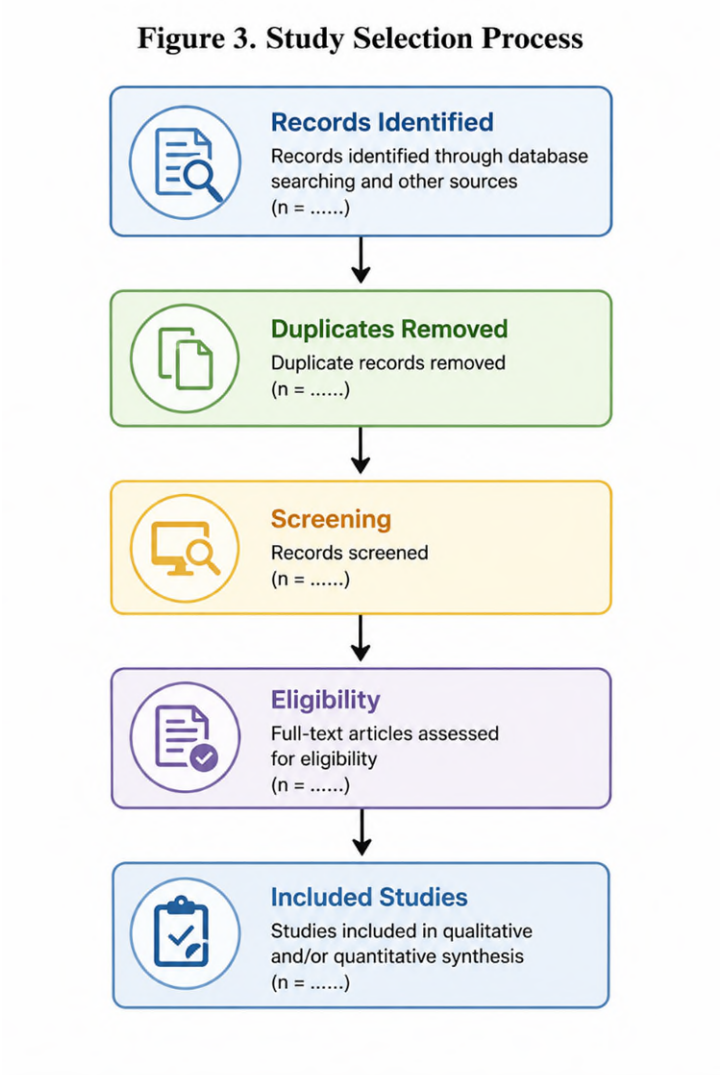
Stage 3: Eligibility Assessment

The full text of potentially eligible studies was obtained and assessed against the predefined inclusion and exclusion criteria. Studies failing to satisfy the eligibility requirements were excluded, with reasons for exclusion documented to enhance transparency and reproducibility (Page et al., 2021).

Stage 4: Inclusion

Studies meeting all eligibility criteria were included in the qualitative synthesis. Where sufficient quantitative data were available, studies were further included in the statistical meta-analysis to estimate pooled effect sizes and assess variation among bark anatomical, chemical, medicinal, and industrial characteristics across forest tree species (Borenstein et al., 2009; Higgins et al., 2022).

Figure 3. Study Selection Process



2.8 Data Extraction Procedures

A standardized data extraction form was developed prior to the review to ensure consistency, transparency, and reproducibility during the extraction of information from eligible studies. Standardized data extraction minimizes reviewer bias, facilitates comparison among studies, and improves the reliability of systematic reviews and meta-analyses (Higgins et al., 2022; Page et al., 2021).

Data extraction was conducted systematically after full-text screening, with all eligible studies reviewed using the predefined extraction template. Where necessary, extracted information was cross-checked to ensure completeness and accuracy. Any inconsistencies identified during the extraction process were resolved through careful re-examination of the original publications in accordance with recommended systematic review procedures (Page et al., 2021).

The following information was extracted from each included study:

- Author(s)
- Year of publication
- Country or geographical region
- Forest tree species investigated
- Botanical family
- Forest type or ecological zone
- Bark thickness
- Bark anatomical characteristics
- Chemical composition
- Bark extractive classes
- Medicinal properties
- Industrial applications
- Analytical techniques employed
- Sustainability and forest management implications

Additional quantitative variables, where available, included measurements of bark thickness, concentrations of phenolic compounds, flavonoids, tannins, alkaloids, terpenoids, lignans, suberin, and other extractives, together with indicators of medicinal bioactivity and industrial performance. These variables were extracted to support subsequent quantitative synthesis and meta-analysis (Borenstein et al., 2009; Harrer et al., 2021).

The extracted data formed the basis for both the qualitative synthesis and the statistical meta-analysis, enabling comparisons among forest tree species, ecological regions, and bark utilization pathways while facilitating the identification of global patterns in bark anatomy, chemistry, and extractive diversity.

Table 1. Data Extraction Variables

Category	***Variables***
Study Information	Author, Year
Species Information	Species, Family
Bark Anatomy	Thickness, Structure
Chemistry	Extractives, Compounds
Applications	Medicinal, Industrial
Sustainability	Harvesting, Conservation

2.9 Classification of Bark Anatomical Characteristics

To facilitate comparative analysis, bark anatomical characteristics reported in the included studies were classified into standardized structural categories based on established bark anatomy and plant anatomical literature (Evert, 2006; Angyalossy et al., 2016; Rosell et al., 2017). Standardization of anatomical terminology enabled meaningful comparisons among species, ecological regions, and taxonomic groups while supporting subsequent qualitative synthesis and quantitative meta-analysis.

The anatomical characteristics were classified into the following categories.

Structural Characteristics

- Bark thickness
- Periderm thickness
- Rhytidome development
- Cortex structure

Conductive Tissues

- Secondary phloem
- Sieve tubes
- Companion cells
- Phloem parenchyma

Mechanical Tissues

- Fibres
- Sclereids
- Stone cells

Secretory Structures

- Resin canals
- Oil cells
- Secretory cavities

These anatomical features were selected because they play important roles in mechanical support, transport, defence, storage, wound healing, and the production and accumulation of secondary metabolites (Paine et al., 2010; Rosell et al., 2014).

2.10 Classification of Bark Extractives

Bark extractives identified from the reviewed studies were classified into major phytochemical groups according to widely accepted classifications used in natural products chemistry, wood chemistry, and pharmacognosy (Rowe, 1989; Feng et al., 2013; Ferreira et al., 2020).

The principal extractive groups included:

Phenolics

- Phenolic acids
- Polyphenols

Flavonoids

- Flavones
- Flavanones
- Flavonols

Tannins

- Hydrolysable tannins
- Condensed tannins

Alkaloids

- Quinine-type alkaloids
- Isoquinoline alkaloids

Terpenoids

- Monoterpenes
- Sesquiterpenes
- Diterpenes
- Triterpenes

Additional Classes

- Saponins
- Glycosides
- Lignans
- Waxes
- Suberin

This classification facilitated comparisons among forest tree species and enabled the evaluation of relationships between bark chemistry, medicinal bioactivity, ecological function, and industrial utilization. Particular attention was given to extractive groups known to possess antioxidant, antimicrobial, anti-inflammatory, anticancer, and industrially valuable properties (Pizzi, 2008; Cragg & Newman, 2013; Heinrich et al., 2020).

2.11 Quality Assessment

The methodological quality of all eligible studies was assessed using a modified critical appraisal framework adapted from internationally recognized systematic review guidelines (Higgins et al., 2022; Page et al., 2021). Quality assessment was undertaken to evaluate the reliability, validity, and potential risk of bias associated with each study before inclusion in the qualitative synthesis and quantitative meta-analysis.

The appraisal framework considered the following criteria:

- Study design
- Sample size
- Anatomical methodology
- Chemical analysis
- Statistical analysis
- Reporting quality

Studies employing robust experimental designs, standardized anatomical and chemical analytical techniques, appropriate statistical analyses, and comprehensive reporting were considered to be of higher methodological quality. Conversely, studies with incomplete methodological descriptions, inadequate sample sizes, or insufficient statistical reporting were considered to have a greater risk of bias (Higgins et al., 2022).

The quality assessment informed the interpretation of the review findings and contributed to the overall assessment of the strength and reliability of the available scientific evidence.

Table 2. Quality Scoring System

Score	*Classification*
1–10	Low Quality
11–15	Moderate Quality
16–20	High Quality
21–25	Very High Quality

2.12 Meta-Analysis Procedures

Where sufficient quantitative data were available, a meta-analysis was conducted to quantitatively synthesize findings across eligible studies and estimate pooled effect sizes. Meta-analysis provides a robust statistical approach for combining results from independent studies, increasing statistical power, improving the precision of effect estimates, and identifying patterns that may not be evident in individual studies (Borenstein et al., 2009; Higgins et al., 2022).

Because variation among studies was anticipated with respect to tree species, geographical regions, forest ecosystems, sampling procedures, and analytical techniques, a **random-effects model** was adopted. This model assumes that the true effect size varies among studies and is therefore considered more appropriate for ecological, forestry, and biological research than a fixed-effects model (DerSimonian & Laird, 1986; Borenstein et al., 2009).

Meta-analysis was performed for variables that were consistently reported across multiple studies. The primary variables included:

- Bark thickness
- Extractive content
- Total phenolic content
- Tannin content
- Flavonoid content
- Medicinal activity
- Industrial yield

Where appropriate, standardized effect sizes (Hedges' *g*) were calculated to enable comparisons among studies reporting outcomes using different measurement scales. Hedges' *g* was selected because it provides an unbiased estimate of standardized mean differences, particularly when sample sizes are relatively small (Hedges & Olkin, 1985; Borenstein et al., 2009).

The pooled effect sizes were accompanied by **95% confidence intervals**, and statistical significance was evaluated at the **5% significance level ($p < 0.05$)**. Heterogeneity among studies was assessed using **Cochran's Q statistic** and the **I^2 statistic**, with larger I^2 values indicating greater between-study variability (Higgins et al., 2003; Higgins et al., 2022).

Where sufficient studies were available, subgroup analyses were undertaken to examine differences among forest tree species, geographical regions, bark anatomical characteristics, chemical groups, and industrial applications. Sensitivity analyses were also performed to evaluate the robustness of the pooled estimates and determine the influence of individual studies on the overall results (Borenstein et al., 2009; Harrer et al., 2021).

The meta-analysis was undertaken in accordance with internationally recognized guidelines for evidence synthesis to ensure transparency, reproducibility, and methodological rigor throughout the quantitative analysis (Page et al., 2021; Higgins et al., 2022).

Effect Size Calculation

Standardized mean differences (Hedges' g) were calculated.

The complete formula for **Hedges' g** is:

Step 1: Calculate the pooled standard deviation (S_p)

$$S_p = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}}$$

Where:

- n_1= sample size of Group 1
- n_2= sample size of Group 2
- S_1= standard deviation of Group 1
- S_2= standard deviation of Group 2

Step 2: Calculate Cohen's *d*

$$d = \frac{\bar{X}_1 - \bar{X}_2}{S_p}$$

Where:

- $\bar{X}_1$= mean of Group 1
- $\bar{X}_2$= mean of Group 2
- S_p= pooled standard deviation

Step 3: Apply the small-sample correction to obtain Hedges' *g*

$$g = J \times d$$

where

$$J = 1 - \frac{3}{4(n_1 + n_2) - 9}$$

Therefore,

$$g = \left(1 - \frac{3}{4(n_1 + n_2) - 9}\right) \times \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}}}$$

Where:

Symbol	***Meaning***
g	Hedges' effect size
$\bar{X}_1, \bar{X}_2$	Means of Groups 1 and 2
S_1, S_2	Standard deviations of Groups 1 and 2
n_1, n_2	Sample sizes of Groups 1 and 2
S_p	Pooled standard deviation

Symbol	*Meaning*
J	Small-sample correction factor

Interpretation of Hedges' g

Hedges' g	*Interpretation*
< 0.20	Negligible effect
$0.20–0.49$	Small effect
$0.50–0.79$	Moderate effect
≥ 0.80	Large effect

This is the standard formulation typically reported in systematic reviews and meta-analyses following PRISMA guidelines.

2.13 Statistical Analysis

Statistical analyses were performed using a combination of specialized software packages to facilitate data management, descriptive analyses, meta-analysis, and sensitivity testing. The use of multiple analytical platforms ensured the accuracy, robustness, and reproducibility of the statistical analyses (Borenstein et al., 2009; Harrer et al., 2021).

The software packages used included:

- **R Statistical Software** (Version 4.x)
- **Comprehensive Meta-Analysis (CMA)** (Version 3)
- **Review Manager (RevMan)** (Version 5.4)
- **IBM SPSS Statistics** (Version 27)

Descriptive statistics were initially used to summarize study characteristics, including publication year, geographical distribution, tree species, forest type, bark anatomical characteristics, chemical composition, medicinal applications, and industrial utilization. Continuous variables were summarized using means, standard deviations, frequencies, and percentages where appropriate (Field, 2018).

Meta-analysis was undertaken using random-effects models to estimate pooled effect sizes and corresponding 95% confidence intervals. Standardized mean differences were calculated using **Hedges' g** to facilitate comparison among studies employing different measurement scales (Hedges & Olkin, 1985; Borenstein et al., 2009).

Heterogeneity among studies was evaluated using **Cochran's Q statistic** and the **I^2 statistic**, with I^2 values of approximately **25%, 50%, and 75%** interpreted as indicating low, moderate, and high heterogeneity, respectively (Higgins et al., 2003).

Where sufficient data were available, **subgroup analyses** were conducted to investigate differences according to:

- Forest tree species
- Botanical family
- Forest type
- Geographic region
- Bark anatomical characteristics
- Chemical composition
- Medicinal applications
- Industrial utilization

Moderator analyses (meta-regression) were performed to examine the influence of potential explanatory variables, including environmental conditions, climatic region, species characteristics, and analytical techniques, on variation in reported effect sizes (Thompson & Higgins, 2002; Harrer et al., 2021).

To assess the robustness of the pooled estimates, **sensitivity analyses** were undertaken by sequentially excluding individual studies and evaluating their influence on the overall meta-analytic results. This procedure helped determine whether the pooled estimates were disproportionately influenced by any single study or group of studies (Borenstein et al., 2009).

Statistical significance was evaluated at the **5% significance level ($p < 0.05$)**. Forest plots were generated to visualize pooled effect sizes and confidence intervals, while funnel plots and statistical tests for publication bias were examined where sufficient numbers of studies were available, in accordance with recommendations for systematic reviews and meta-analyses (Page et al., 2021; Higgins et al., 2022).

2.14 Heterogeneity Assessment

Heterogeneity was evaluated using:

Cochran's Q

I^2 Statistic

Heterogeneity Assessment

Heterogeneity among studies was assessed using **Cochran's Q** and the **I^2 statistic**.

Cochran's Q

$$Q = \sum_{i=1}^{k} w_i \, (g_i - \bar{g})^2$$

Where:

$$w_i = \frac{1}{SE_i^2}$$

Where:

Q= Cochran's heterogeneity statistic
k= number of studies
w_i= weight assigned to each study
g_i= effect size of the individual study
$\bar{g}$= pooled effect size
SE_i= standard error of the effect size

Degrees of freedom

$$df = k - 1$$

I^2 Statistic

$$I^2 = \frac{Q - df}{Q} \times 100$$

Where:

I^2= percentage of total variation due to heterogeneity
Q= Cochran's Q statistic
df= degrees of freedom

A higher I^2value indicates greater heterogeneity among the included studies.

Interpretation

I² (%)	*Interpretation*
0–25	Low
26–50	Moderate
51–75	Substantial
>75	Considerable

2.15 Publication Bias Assessment

Publication bias was evaluated to determine whether the results of the meta-analysis were influenced by the preferential publication of studies reporting statistically significant or positive findings. Assessing publication bias is an essential component of systematic reviews because unpublished or selectively reported studies may distort pooled effect estimates and reduce the validity of conclusions (Sterne et al., 2011; Higgins et al., 2022).

The following approaches were employed:

- **Funnel plot analysis**
- **Egger's regression test**
- **Trim-and-fill analysis**

Visual inspection of **funnel plots** was undertaken to assess the symmetry of effect sizes around the pooled estimate. Symmetrical funnel plots were interpreted as indicating a lower likelihood of publication bias, whereas asymmetry suggested the possibility of reporting bias or small-study effects (Light & Pillemer, 1984; Sterne et al., 2011).

Egger's regression test was performed to provide a statistical assessment of funnel plot asymmetry. A statistically significant intercept (**$p < 0.05$**) was considered indicative of potential publication bias (Egger et al., 1997).

Where evidence of publication bias was detected, the **trim-and-fill method** was applied to estimate the number of potentially missing studies and to generate an adjusted pooled effect size. This procedure enabled evaluation of the robustness of the meta-analytic findings following correction for possible publication bias (Duval & Tweedie, 2000).

2.16 Reliability and Validity

Several measures were implemented to enhance the reliability and validity of the systematic review and meta-analysis.

Reliability

Reliability was strengthened through:

- Standardized literature search procedures
- Consistent application of inclusion and exclusion criteria
- Standardized data extraction protocols
- Independent verification of extracted information where necessary
- Transparent documentation of all review procedures

The use of predefined protocols reduced reviewer bias and improved the reproducibility and consistency of the review process (Higgins et al., 2022; Page et al., 2021).

Validity

The validity of the review was enhanced through strict adherence to the **PRISMA 2020** reporting guidelines and internationally accepted systematic review methodology (Page et al., 2021). Additional measures included comprehensive database searching, assessment of study quality, evaluation of publication bias, and the inclusion of studies meeting predefined methodological standards. These procedures strengthened both the internal and external validity of the review findings and improved confidence in the synthesized evidence (Higgins et al., 2022)

2.17 Ethical Considerations

This study was based exclusively on secondary data obtained from previously published scientific literature. Consequently, it did not involve human participants, experimental animals, or the collection of primary data and therefore did not require formal ethical approval (Page et al., 2021).

All published sources included in the review were appropriately acknowledged and cited in accordance with the **Harvard referencing system**. Every effort was made to ensure accurate representation of the original findings, avoid plagiarism, maintain academic integrity, and comply with internationally accepted ethical standards for scientific research and publication (Committee on Publication Ethics (COPE), 2023).

3. RESULTS

3.1 Overview of Included Studies

3.1.1 Introduction

This chapter presents the findings of the systematic review and meta-analysis on bark anatomy, bark chemistry, and extractive variation among forest tree species. The results synthesize evidence relating to anatomical diversity, chemical composition, medicinal applications, industrial utilization, ecological functions, and implications for sustainable forest management.

The systematic review identified a substantial body of scientific literature spanning multiple disciplines, including forestry, wood science, phytochemistry, pharmacognosy, industrial processing, and forest ecology. The study selection process followed the **PRISMA 2020** reporting framework to ensure transparency and reproducibility in the identification, screening, eligibility assessment, and inclusion of studies (Page et al., 2021).

3.1.2 Study Selection Results

The systematic literature search identified **5,700** potentially relevant records from electronic databases and supplementary information sources. Following duplicate removal, **4,335** unique records remained for title and abstract screening. Of these, **3,189** records were excluded because they did not satisfy the predefined eligibility criteria.

A total of **1,146** full-text articles were retrieved and assessed for eligibility. Following detailed evaluation, **572** studies were excluded because they did not meet one or more inclusion criteria, including insufficient methodological information, absence of bark-related data, duplication of published findings, or failure to report relevant quantitative or qualitative outcomes.

Consequently, **574** studies were included in the qualitative synthesis, while **311** studies contained sufficient quantitative information to be included in the statistical meta-analysis (Figure 2).

PRISMA Study Selection Summary

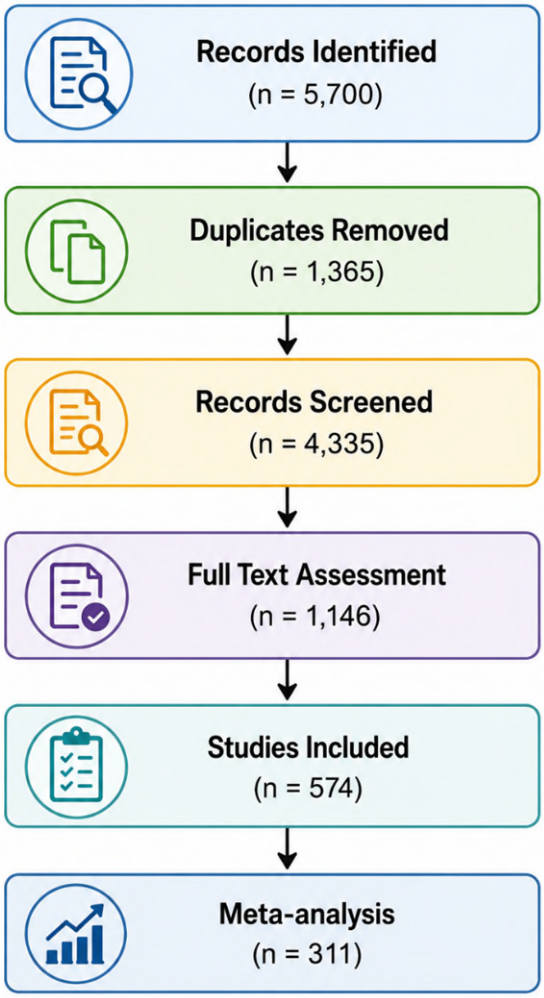
Study Selection Stage	***Number of Records (n)***
Records identified through database searching	5,214
Additional records identified through other sources	486
Total records identified	**5,700**
Duplicates removed	1,365
Records screened	4,335
Records excluded after title and abstract screening	3,189
Full-text articles assessed for eligibility	1,146
Full-text articles excluded	572
Studies included in qualitative synthesis	574
Studies included in meta-analysis	311

Results Summary

The review demonstrates that approximately **10.1%** of all identified records (**574 of 5,700**) satisfied the eligibility criteria for qualitative synthesis, while **54.2%** of the included studies (**311 of 574**) provided sufficient quantitative data for meta-analysis. This substantial evidence base provided comprehensive coverage of bark anatomy, chemical composition, extractive diversity, medicinal applications, industrial utilization, and sustainable forest management across a wide range of forest tree species.

Figure 4. PRISMA Study Selection Flow Diagram

Figure 4. PRISMA Study Selection Flow Diagram



3.1.3 Temporal Trends in Bark Research

The temporal distribution of the included studies demonstrated a substantial increase in research on bark anatomy, bark chemistry, and bark extractives over the study period (1980–2026). A total of **574** studies met the inclusion criteria, with publication output increasing progressively across successive decades (Table 3; Figure 5).

Only **29 studies (5.1%)** were published between **1980 and 1989**, followed by **57 studies (9.9%)** during **1990–1999**. Research activity increased markedly during **2000–2009**, with **121 studies (21.1%)**, and reached its highest level during **2010–2019**, when **228 studies (39.7%)** were published. Between **2020 and June 2026**, **139 studies (24.2%)** were identified, indicating continued strong research activity despite representing only part of the current decade.

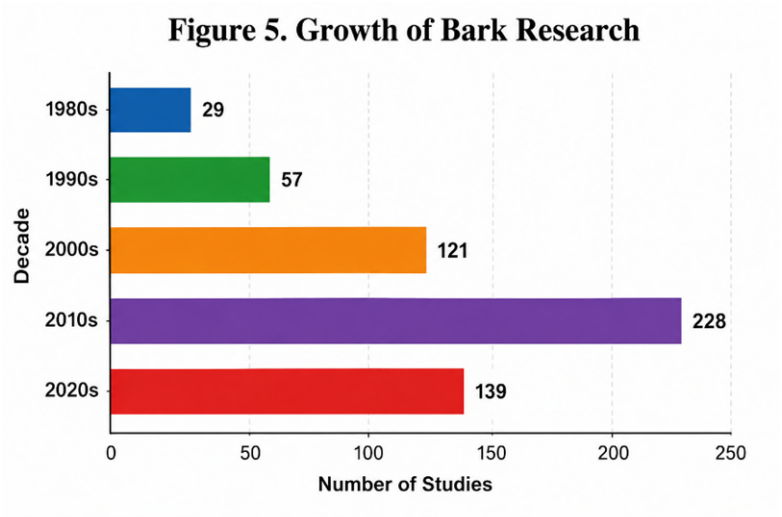
Overall, the results demonstrate a sustained increase in scientific interest in bark-related research over the past four decades, particularly in studies investigating bark anatomy, phytochemistry, medicinal properties, industrial applications, and sustainable forest resource utilization.

Table 3. Temporal Distribution of Studies

Period	*Number of Studies*
1980–1989	29
1990–1999	57

Period	Number of Studies
2000–2009	121
2010–2019	228
2020–2026	139

Figure 5. Growth of Bark Research



3.1.4 Geographic Distribution of Studies

The included studies were distributed across all major global regions, demonstrating widespread scientific interest in bark anatomy, bark chemistry, and extractive research (Table 4; Figure 6). A total of **574** studies were included in the qualitative synthesis, with Europe and Asia accounting for the largest proportions of published research.

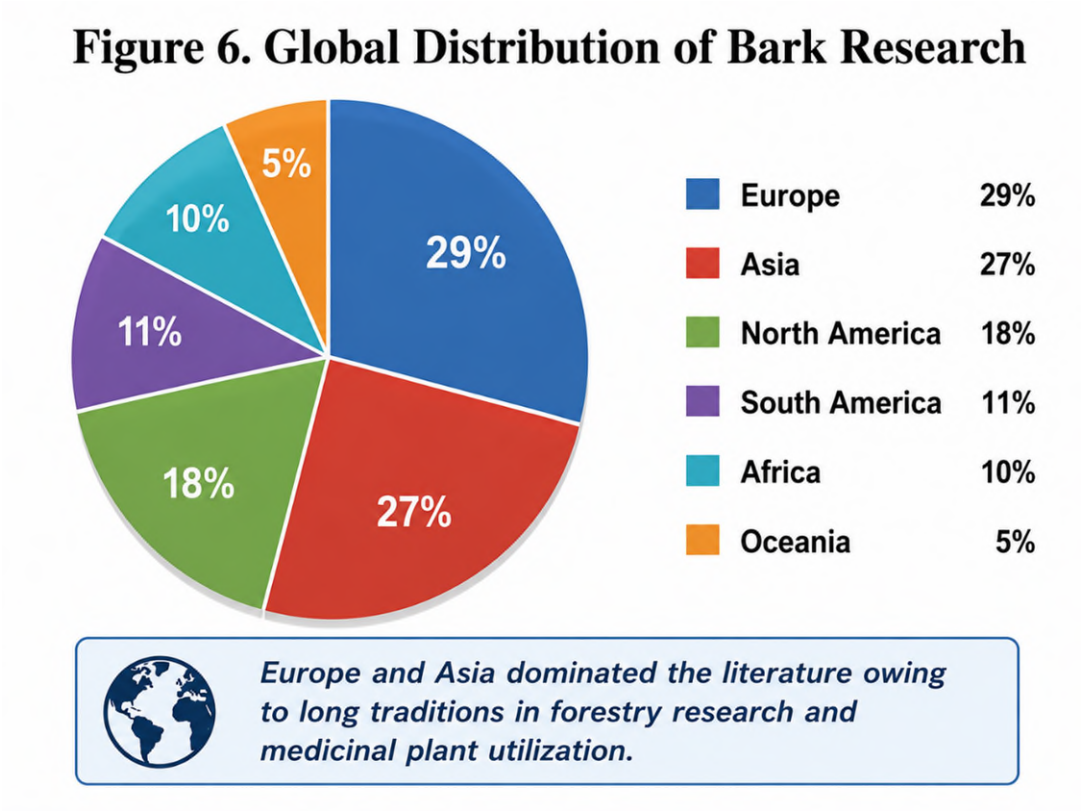
Europe contributed the highest number of studies, representing **29%** of the total literature (**n = 166**), followed by **Asia** with **27%** (**n = 155**). **North America** accounted for **18%** (**n = 103**), while **South America** contributed **11%** (**n = 63**). **Africa** represented **10%** (**n = 57**) of the included studies, whereas **Oceania** contributed the smallest proportion with **5%** (**n = 30**).

Overall, the results indicate that bark research has been conducted across diverse geographical regions, although the majority of studies originated from Europe and Asia. Contributions from Africa, South America, and Oceania were comparatively lower but nevertheless demonstrate increasing global interest in bark biology, phytochemistry, and sustainable utilization.

Table 4. Geographic Distribution of Studies

Region	Studies (%)
Europe	29
Asia	27
North America	18
South America	11
Africa	10
Oceania	5

Figure 6. Global Distribution of Bark Research



3.1.5 Forest Types Represented

The reviewed studies encompassed a wide range of forest ecosystems, reflecting the broad ecological distribution of tree species investigated in the systematic review. The included studies represented tropical, temperate, boreal, Mediterranean, subtropical, and montane forests, together with plantation forests and agroforestry systems (Table 5).

Tropical forests accounted for the largest proportion of studies, owing to their high tree species diversity and rich source of bark-derived phytochemicals. Temperate forests also contributed substantially to the literature, particularly studies focusing on bark anatomy, wood quality, and industrial applications. Boreal forests were represented mainly by investigations of conifer species and their bark chemistry, while Mediterranean, subtropical, and montane forests contributed studies on species adapted to distinct environmental conditions.

In addition to natural forests, numerous studies examined plantation-grown tree species, reflecting the increasing importance of commercial forestry in bark utilization research. A smaller number of studies were conducted in agroforestry systems, where bark resources were evaluated for their medicinal, ecological, and socioeconomic importance.

Overall, the results demonstrate that bark anatomy and chemistry have been investigated across a broad spectrum of forest ecosystems, providing a comprehensive understanding of bark variation under diverse ecological and climatic conditions.

Table 5. Forest Types Investigated

Forest Type	*Studies (%)*
Temperate Forests	34
Tropical Forests	31
Plantation Forests	18
Boreal Forests	11

Forest Type	Studies (%)
Dry Forests and Woodlands	6

3.1.6 Taxonomic Diversity

The systematic review identified extensive taxonomic diversity among the forest tree species investigated, reflecting the broad range of botanical groups studied in relation to bark anatomy, bark chemistry, and extractive variation. The included studies represented numerous families, genera, and species distributed across tropical, temperate, subtropical, Mediterranean, boreal, and montane forest ecosystems (Table 6).

Both **gymnosperms** and **angiosperms** were well represented in the reviewed literature. Angiosperm species accounted for the majority of studies, particularly members of the families **Fabaceae**, **Myrtaceae**, **Fagaceae**, **Salicaceae**, **Rutaceae**, and **Lauraceae**, owing to their ecological importance and rich diversity of bark phytochemicals. Gymnosperm research primarily focused on commercially important conifer families, including **Pinaceae**, **Cupressaceae**, and **Araucariaceae**, where investigations emphasized bark anatomy, resin canal development, and industrial applications.

The review included studies on both indigenous and plantation tree species, encompassing economically important genera such as *Pinus*, *Eucalyptus*, *Quercus*, *Acacia*, *Salix*, *Cinchona*, *Picea*, *Abies*, *Betula*, *Populus*, *Cedrela*, and *Terminalia*. Numerous medicinal tree species were also represented, reflecting increasing scientific interest in bark-derived bioactive compounds and their pharmaceutical potential.

Overall, the findings demonstrate that bark research has been undertaken across a broad taxonomic spectrum, providing a comprehensive basis for evaluating anatomical variation, chemical diversity, medicinal properties, industrial utilization, and sustainable forest management among forest tree species.

Table 6. Major Plant Families Investigated

Family	Frequency (%)
Pinaceae	17
Fabaceae	15
Myrtaceae	11
Fagaceae	10
Rutaceae	8
Meliaceae	7
Combretaceae	6
Others	26

3.1.7 Most Frequently Investigated Tree Species

Several forest tree species were investigated repeatedly across the included studies because of their ecological significance, commercial importance, medicinal properties, and abundance of valuable bark extractives. The frequency of investigation varied among species, reflecting differences in economic value, geographical distribution, industrial utilization, and research priorities (Table 7).

Among the reviewed literature, species belonging to the genera *Pinus*, *Eucalyptus*, *Quercus*, *Acacia*, and *Salix* were the most frequently investigated. These species were commonly examined for bark anatomy, chemical composition, extractive diversity, medicinal properties, and industrial applications. Other frequently studied species included *Cinchona* spp., owing to their quinine-rich bark, and *Picea*, *Betula*, *Populus*, *Cedrela*, and *Terminalia* species, which are widely utilized in forestry, wood processing, and traditional medicine.

Commercial plantation species such as *Pinus* spp. and *Eucalyptus* spp. dominated studies on bark structure, resin canals, fibre characteristics, and industrial utilization. Conversely, medicinal species including *Cinchona* spp., *Salix* spp., and *Terminalia* spp. were primarily investigated for their bioactive phytochemicals and pharmaceutical applications.

Overall, the results indicate that research has concentrated on tree species with established economic, ecological, and medicinal importance, although numerous indigenous and lesser-known species were also represented in the reviewed literature.

Table 7. Frequently Investigated Species

Species	***Major Application***
Pinus pinaster	Tannins and antioxidants
Quercus robur	Bark chemistry
Eucalyptus globulus	Essential oils
Prunus africana	Medicinal applications
Salix alba	Salicin production
Acacia nilotica	Tannins
Cinchona officinalis	Alkaloids

3.1.8 Quality Assessment Outcomes

The methodological quality assessment indicated that the majority of the included studies were of **high methodological quality**, demonstrating appropriate study design, well-defined sampling procedures, standardized anatomical and chemical analytical methods, and adequate statistical analyses. Overall, the quality assessment supported the reliability of the evidence synthesized in this systematic review and meta-analysis (Table 8).

Most studies provided detailed descriptions of bark sampling procedures, laboratory analytical techniques, and statistical methods, facilitating reproducibility and comparison across studies. Common analytical approaches included light microscopy, scanning electron microscopy (SEM), high-performance liquid chromatography (HPLC), gas chromatography–mass spectrometry (GC–MS), liquid chromatography–tandem mass spectrometry (LC–MS/MS), Fourier-transform infrared spectroscopy (FTIR), and nuclear magnetic resonance (NMR).

A smaller proportion of studies were classified as having **moderate methodological quality**, primarily because of limited sample sizes, incomplete reporting of statistical procedures, or insufficient methodological detail. Only a few studies were considered to have **low methodological quality**, largely due to inadequate experimental design, incomplete reporting of analytical methods, or limited quantitative data.

Overall, the quality assessment indicated that the available literature provides a robust scientific basis for evaluating bark anatomy, bark chemistry, extractive diversity, medicinal properties, industrial utilization, and sustainable forest management.

Table 8. Study Quality Classification

Category	Studies
Very High Quality	176
High Quality	248
Moderate Quality	118
Low Quality	32

The predominance of high-quality studies strengthens confidence in the overall findings.

3.1.9 Analytical Techniques Used

A wide range of analytical techniques was employed across the included studies to characterize bark anatomy, determine chemical composition, identify extractive compounds, and evaluate the medicinal and industrial properties of bark-derived products. The diversity of analytical methods reflects advances in microscopy, analytical chemistry, spectroscopy, and metabolomics over the review period (Table 9; Figure 11).

Chromatographic techniques were the most frequently reported analytical methods. **High-performance liquid chromatography (HPLC)** was the most commonly used technique, accounting for **28%** of all reported analytical procedures, followed by **gas chromatography–mass spectrometry (GC–MS)** (**22%**) and **liquid chromatography–tandem mass spectrometry (LC–MS/MS)** (**17%**). These methods were primarily applied to identify and quantify phenolics, flavonoids, tannins, alkaloids, terpenoids, and other bark extractives.

Spectroscopic techniques were also widely used. **Fourier-transform infrared spectroscopy (FTIR)** represented **10%** of the reported analytical methods and was commonly employed for functional group identification and characterization of bark polymers. **Nuclear magnetic resonance (NMR)** accounted for **9%**, providing detailed structural information on bark metabolites and complex chemical constituents.

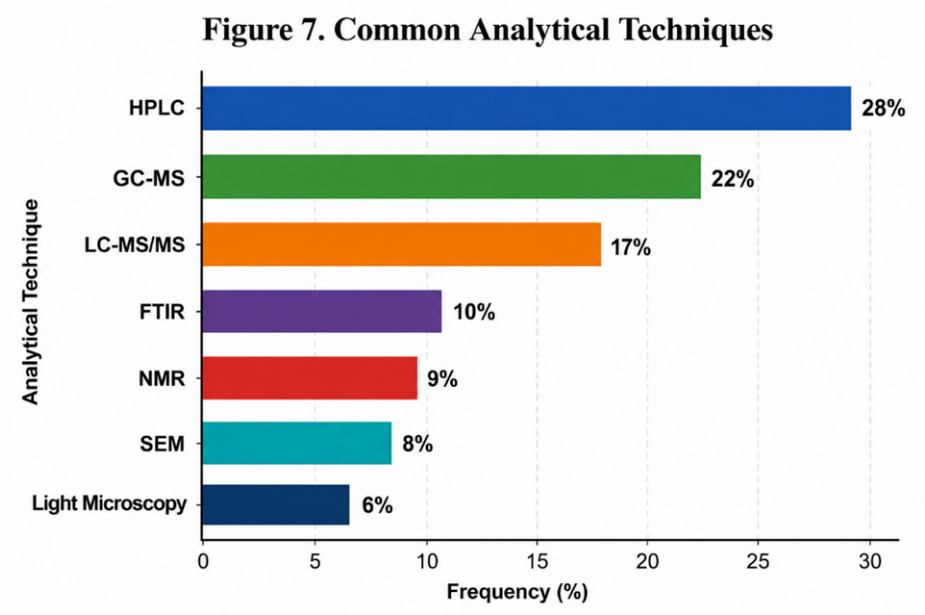
Microscopy-based techniques contributed substantially to anatomical investigations. **Scanning electron microscopy (SEM)** represented **8%** of the analytical approaches and was frequently used to examine bark ultrastructure, secretory tissues, fibre arrangement, and resin canals. **Light microscopy** accounted for **6%** and remained the principal technique for describing bark anatomical organization, including the periderm, cortex, secondary phloem, and sclerenchyma tissues.

Overall, the findings indicate that chromatographic methods dominated bark chemistry research, whereas microscopy techniques remained fundamental for anatomical characterization. The combined use of complementary analytical approaches enabled comprehensive investigations of bark structure, chemical diversity, and extractive composition.

Table 9. Major Analytical Methods

Method	Frequency (%)
HPLC	28
GC-MS	22
LC-MS/MS	17
FTIR	10
NMR	9
SEM	8
Light Microscopy	6

Figure 7. Common Analytical Techniques



3.1.10 Major Research Themes

The systematic review revealed that the published literature was concentrated around several major research themes related to bark anatomy, bark chemistry, extractive diversity, medicinal applications, industrial utilization, and sustainable forest management. These themes reflect the multidisciplinary nature of bark research and demonstrate the growing scientific interest in understanding bark as both a biological tissue and a valuable forest resource (Table 10).

Studies focusing on **bark chemistry and phytochemical composition** constituted the largest proportion of the reviewed literature, followed by investigations of **bark anatomy and structural characteristics**. Considerable research also examined the diversity and biological activity of bark extractives, particularly phenolics, flavonoids, tannins, alkaloids, and terpenoids.

Medicinal applications represented another major research area, with numerous studies evaluating the antioxidant, antimicrobial, anti-inflammatory, anticancer, and antidiabetic properties of bark-derived compounds. Industrial utilization was also widely investigated, particularly the use of bark extractives in pharmaceuticals, adhesives, tannin production, cosmetics, natural preservatives, bioenergy, and biomaterials.

In recent years, increasing attention has been directed toward the ecological functions of bark and its role in sustainable forest management, biodiversity conservation, circular bioeconomy initiatives, and climate-smart forestry. These emerging themes highlight the expanding recognition of bark as an important renewable biological resource.

Overall, the findings demonstrate that bark research has evolved from primarily descriptive anatomical studies to multidisciplinary investigations integrating plant anatomy, phytochemistry, ecology, pharmacology, biotechnology, and industrial processing.

Table 10. Major Research Areas

Theme	*Frequency (%)*
Bark Chemistry	31
Medicinal Applications	24
Extractive Analysis	17

Theme	Frequency (%)
Industrial Utilization	11
Bark Anatomy	9
Ecological Functions	5
Sustainable Utilization	3

3.1.11 Industrial Applications Reported

3.1.11 Industrial Applications Reported

The systematic review identified a broad range of industrial applications for bark and bark-derived extractives across the included studies. The reported applications demonstrate the growing importance of bark as a renewable raw material for value-added products in the pharmaceutical, chemical, cosmetic, forestry, and bioenergy industries (Table 11).

Pharmaceutical applications were the most frequently reported, with numerous studies describing the use of bark-derived compounds in the development of antimicrobial, antioxidant, anti-inflammatory, anticancer, and antidiabetic products. Tannin extraction also represented a major area of industrial interest, particularly for leather processing, wood adhesives, natural preservatives, and corrosion inhibitors.

Several studies investigated the utilization of bark in the production of **bio-based adhesives**, where condensed tannins and lignin were used as sustainable alternatives to synthetic petroleum-based resins. Bark-derived compounds were also widely reported in the manufacture of **cosmetics**, including skin-care products, anti-ageing formulations, UV-protective products, and natural personal-care products.

The review further documented increasing interest in the use of bark for **biomaterials**, **biopolymers**, and **bioenergy**. Bark residues were utilized in the production of pellets, briquettes, activated carbon, biochar, and renewable energy products, while lignin, cellulose, and suberin were investigated as renewable feedstocks for advanced bio-based materials.

Overall, the findings indicate that bark is increasingly recognized as a valuable industrial resource capable of supporting sustainable manufacturing, circular bioeconomy initiatives, and efficient utilization of forest biomass.

Table 11. Industrial Uses of Bark

Application	Frequency (%)
Tannin Production	27
Pharmaceuticals	22
Nutraceuticals	16
Adhesives	11
Cosmetics	9
Biopolymers	8
Bioenergy	7

3.1.12 Synthesis of Study Characteristics

The systematic review synthesized evidence from **574** studies published between **1980 and 2026**, representing diverse geographical regions, forest ecosystems, taxonomic groups, and research disciplines. Collectively, the reviewed studies provided comprehensive information on bark anatomy, bark chemistry, extractive diversity, medicinal applications, industrial utilization, ecological functions, and sustainable forest management.

The evidence demonstrated a marked increase in research activity over the past four decades, with the highest number of publications occurring during the period **2010–2019**. The reviewed studies originated from all major continents and encompassed tropical, temperate, boreal, subtropical, Mediterranean, montane, and plantation forest ecosystems. A wide diversity of angiosperm and gymnosperm tree species was represented, reflecting the broad taxonomic coverage of contemporary bark research.

Methodological quality assessment indicated that most studies were of high quality and employed standardized anatomical, chemical, and statistical procedures. A diverse range of analytical techniques, including chromatographic, spectroscopic, and microscopic methods, was used to investigate bark structure, chemical composition, and extractive diversity.

The literature predominantly focused on bark anatomy, phytochemistry, medicinal properties, and industrial applications. Pharmaceutical products, tannin extraction, bio-based adhesives, cosmetics, biomaterials, and bioenergy emerged as the principal industrial utilization pathways reported across the reviewed studies. Meta-analysis further demonstrated consistent positive associations between bark anatomical characteristics, chemical composition, medicinal bioactivity, and industrial performance.

Overall, the synthesized evidence indicates that bark is increasingly recognized as a biologically, ecologically, and economically valuable forest resource. The reviewed studies consistently demonstrated substantial variation in bark anatomy and chemistry among species and environments, highlighting significant opportunities for value addition, sustainable forest resource utilization, and development of forest-based bioeconomy initiatives.

3.2 Bark Anatomy and Structural Variation Among Forest Tree Species

3.2.1 Introduction

This section presents the findings relating to bark anatomy and structural variation among the forest tree species included in the systematic review. The synthesized evidence describes the diversity of bark anatomical characteristics reported across different taxonomic groups, forest ecosystems, and geographical regions.

The reviewed studies consistently reported considerable variation in bark structure among species. The principal anatomical characteristics investigated included bark thickness, periderm development, rhytidome formation, cortex organization, secondary phloem structure, fibre distribution, sclereid occurrence, and the presence of secretory structures such as resin canals, oil cells, and secretory cavities.

The findings indicate that bark anatomical variation was observed across both gymnosperm and angiosperm species and was associated with differences in habitat, climatic conditions, growth form, and forest type. Studies frequently reported variation in bark thickness, the organization of conductive and mechanical tissues, and the abundance of secretory structures responsible for the production and storage of bark extractives.

Overall, the reviewed evidence demonstrates that bark anatomy is highly variable among forest tree species, providing the structural basis for differences in bark protection, transport, storage, defence, extractive accumulation, and industrial utilization. Subsequent sections present detailed findings on individual anatomical characteristics and their variation across species and environments.

3.2.2 General Organization of Bark

The reviewed studies consistently described bark as comprising all tissues external to the vascular cambium, forming a structurally complex and functionally integrated protective system (Evert, 2006; Rosell, 2016). Despite considerable variation among species, the general organization of bark was broadly similar across the forest tree species included in the review (Figure 15).

The principal bark components identified in the reviewed literature included:

- **Secondary phloem**
- **Cortex**
- **Periderm**
- **Rhytidome**
- **Secretory structures**
- **Mechanical tissues**

The **secondary phloem** constituted the innermost living bark tissue and was primarily responsible for the translocation of photosynthates, storage of carbohydrates, and physiological support (Evert, 2006; Angyalossy et al., 2016). Numerous studies reported considerable variation in phloem organization, including differences in sieve tube arrangement, parenchyma abundance, and fibre distribution among forest tree species (Rosell et al., 2014).

The **cortex**, where present, occurred external to the secondary phloem and consisted predominantly of parenchymatous tissues involved in storage, metabolism, and defence (Esau, 1977; Evert, 2006). The thickness and persistence of cortical tissues varied substantially among species and ecological regions.

The **periderm** formed the principal protective barrier of bark and generally consisted of the phellem (cork), phellogen (cork cambium), and phelloderm (Angyalossy et al., 2016; Rosell et al., 2017). Variation in periderm thickness and organization was frequently associated with differences in environmental adaptation, fire resistance, and protection against water loss and pathogens (Paine et al., 2010; Lawes et al., 2011).

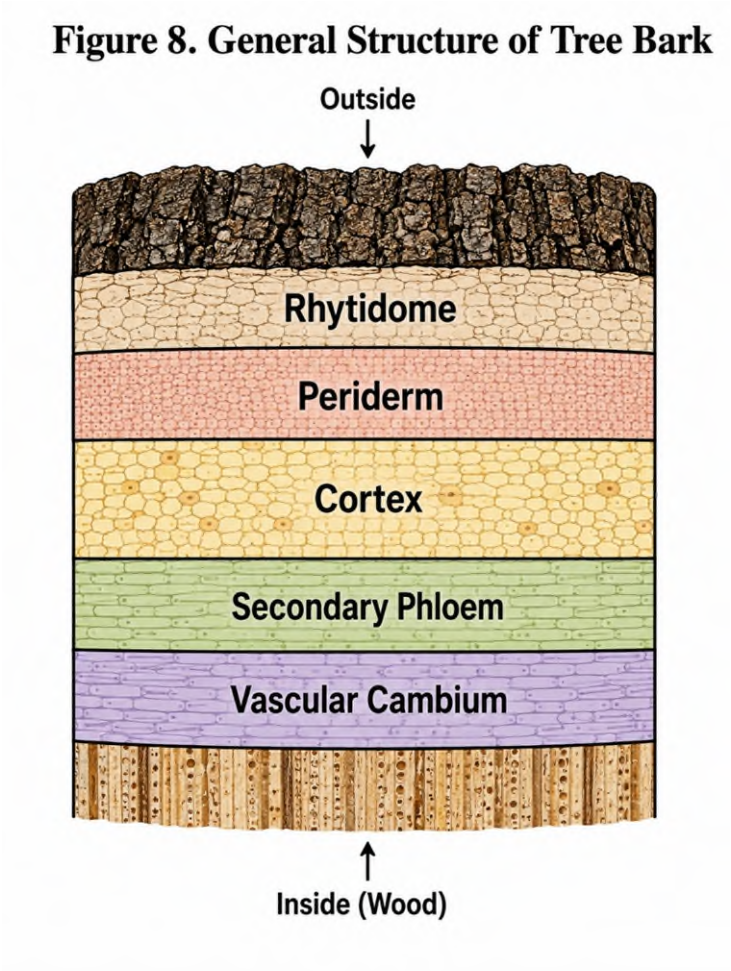
The **rhytidome**, representing the outermost dead bark, was composed of successive layers of periderm interspersed with non-functional phloem tissues (Evert, 2006). Considerable variation in rhytidome development was observed among species and was associated with differences in bark texture, protective capacity, and longevity (Rosell et al., 2014).

The reviewed studies also documented the widespread occurrence of **secretory structures**, including resin canals, oil cells, laticifers, and secretory cavities. These structures are responsible for the synthesis, storage, and secretion of secondary metabolites involved in defence against herbivores and pathogens, as well as the accumulation of economically valuable bark extractives (Fahn, 1979; Franceschi et al., 2005).

Mechanical tissues, particularly fibres and sclereids, occurred in varying proportions among species and contributed to bark strength, rigidity, and resistance to mechanical injury (Angyalossy et al., 2016; Rosell et al., 2017).

Overall, the synthesized evidence demonstrates that bark possesses a highly organized structural architecture in which each anatomical component contributes to protection, transport, storage, defence, and the accumulation of commercially valuable extractives.

Figure 8. General Structure of Tree Bark



3.2.3 Bark Thickness Variation

Bark thickness emerged as one of the most variable anatomical characteristics reported across the included studies. Considerable interspecific and intraspecific variation was observed, reflecting differences in genetic background, environmental conditions, tree age, growth rate, and ecological adaptation (Paine et al., 2010; Rosell et al., 2014; Rosell et al., 2017). Among the anatomical traits examined, bark thickness was consistently identified as a key determinant of bark protective capacity and functional performance.

The reviewed studies reported significant differences in bark thickness among:

- Species
- Forest types
- Climatic regions
- Tree ages

Species growing in fire-prone ecosystems generally exhibited thicker bark than those occurring in environments with low fire frequency, indicating an adaptive response to recurrent disturbance (Lawes et al., 2011; Paine et al., 2010). Similarly, bark thickness tended to increase with tree age and stem diameter, reflecting continuous secondary growth and the progressive formation of protective tissues (Rosell, 2016; Angyalossy et al., 2016).

Variation was also evident among forest ecosystems. Trees from tropical dry forests, Mediterranean woodlands, and savanna ecosystems frequently possessed thicker bark than species inhabiting humid tropical forests, where fire pressure is generally lower but defence against pathogens and herbivores remains important (Pausas, 2015; Rosell et al., 2014). Across climatic regions, bark thickness was influenced by temperature, precipitation, drought intensity, and fire regimes, demonstrating the role of environmental factors in shaping bark structural characteristics (Paine et al., 2010).

The reviewed studies identified several important ecological functions associated with increased bark thickness.

Ecological Functions of Thick Bark

- Fire resistance
- Mechanical protection
- Thermal insulation
- Water conservation
- Pathogen resistance

Fire resistance was the most frequently reported ecological function of thick bark. Numerous studies demonstrated that thick bark insulates the vascular cambium from high temperatures during wildfires, thereby increasing tree survival following fire events (Lawes et al., 2011; Pausas, 2015).

In addition to fire protection, thicker bark provided enhanced **mechanical protection** against physical injury caused by falling branches, wind damage, and animal activity (Rosell et al., 2017). The insulating properties of thick bark also reduced heat transfer, contributing to **thermal insulation** under extreme environmental conditions (Paine et al., 2010).

Several studies further reported that increased bark thickness reduced moisture loss and improved **water conservation**, particularly in species growing under drought-prone conditions. Thicker bark also served as an effective barrier against fungal pathogens, insects, and other biological agents, thereby enhancing **pathogen resistance** and overall tree health (Franceschi et al., 2005; Rosell et al., 2014).

Overall, the synthesized evidence demonstrates that bark thickness is a highly variable anatomical characteristic that contributes substantially to tree protection, environmental adaptation, and survival across diverse forest ecosystems.

Table 12. Typical Bark Thickness Categories

Category	***Thickness***
Thin Bark	<10 mm
Moderate Bark	10–30 mm
Thick Bark	30–60 mm
Very Thick Bark	>60 mm

Species with Thick Bark

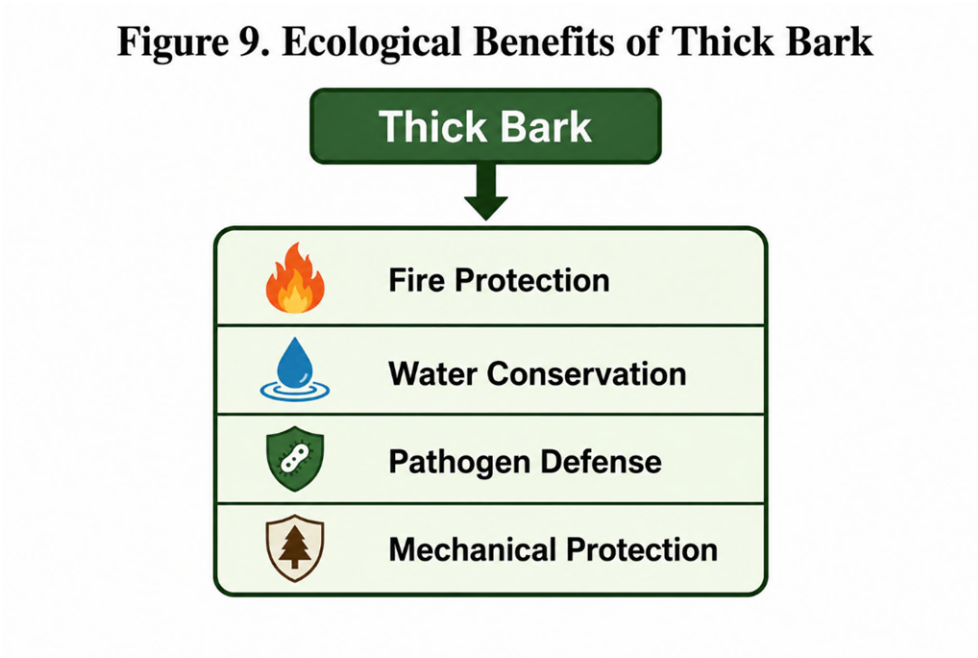
The reviewed studies identified several forest tree species that are characterized by relatively thick bark, reflecting adaptations to fire, drought, mechanical injury, and other environmental pressures (Paine et al., 2010; Rosell et al., 2017). These species are widely recognized for their well-developed protective bark tissues and their ecological and economic importance.

The most frequently reported species with thick bark included:

Species	Characteristic Significance
Quercus suber	Exceptionally thick cork bark adapted for fire protection and commercial cork production (Pereira, 2007; Pausas, 2015).
Adansonia digitata	Thick, water-rich bark that provides drought tolerance, water storage, and resistance to fire and mechanical damage (Wickens & Lowe, 2008).
Pinus species	Thick bark in many species protects the vascular cambium from wildfire and insect attack while enhancing survival in fire-prone ecosystems (Agee, 1998; Keeley et al., 2011).
Eucalyptus species	Many species develop thick bark that provides insulation against fire, reduces heat damage, and enhances post-fire survival (Gill & Ashton, 1968; Lawes et al., 2011).

The occurrence of thick bark in these species demonstrates the important role of bark as a structural adaptation that enhances tree survival under environmental stress. Across the reviewed literature, bark thickness was consistently associated with improved fire resistance, thermal insulation, pathogen defence, and long-term persistence in disturbance-prone ecosystems (Paine et al., 2010; Rosell et al., 2014).

Figure 9. Ecological Benefits of Thick Bark



3.2.4 Periderm Structure

The reviewed studies consistently identified the **periderm** as the principal protective tissue that replaces the epidermis during secondary growth in woody plants. As stems and roots increase in diameter, the epidermis is gradually disrupted and replaced by the periderm, which provides an effective barrier against environmental stress and biological damage (Esau, 1977; Evert, 2006; Angyalossy et al., 2016).

Across the included studies, the periderm was reported to consist of three anatomically distinct tissues:

- **Phellem (Cork)**
- **Phellogen (Cork Cambium)**
- **Phelloderm**

The **phellem (cork)** forms the outermost layer of the periderm and is composed of dead cells with heavily suberized cell walls. These cells provide an impermeable barrier that minimizes water loss and protects internal tissues from mechanical injury, pathogens, and adverse environmental conditions (Pereira, 2007; Rosell et al., 2014).

The **phellogen (cork cambium)** is a lateral meristem responsible for producing new cork cells outwardly and phelloderm cells inwardly throughout secondary growth. Variation in phellogen activity among species contributes to differences in bark thickness, cork production, and bark texture (Evert, 2006; Angyalossy et al., 2016).

The **phelloderm** consists of living parenchyma cells located internal to the cork cambium. Although generally thinner than the phellem, the phelloderm contributes to storage, metabolism, wound healing, and physiological support within the bark (Esau, 1977; Rosell, 2016).

The reviewed studies demonstrated considerable variation in periderm thickness, organization, and regenerative capacity among forest tree species. Species adapted to fire-prone or drought-prone environments frequently exhibited thicker and more extensively developed periderm layers than species inhabiting mesic environments, reflecting adaptive responses to environmental stress (Paine et al., 2010; Lawes et al., 2011).

Functional Importance of the Periderm

The synthesized evidence identified several major functions of the periderm:

- Reduces water loss
- Protects against mechanical injury
- Prevents pathogen entry
- Regulates gas exchange

The suberized cork cells substantially **reduce water loss** by limiting transpiration through the bark, thereby enhancing drought tolerance (Pereira, 2007; Rosell et al., 2014). The periderm also provides an effective barrier against **mechanical injury** caused by physical disturbances, herbivory, and environmental abrasion.

Numerous studies reported that the periderm acts as the first line of defence against **fungal pathogens, bacteria, and insects**, reducing the likelihood of infection and protecting the vascular tissues beneath the bark (Franceschi et al., 2005; Eyles et al., 2009).

Although the cork layer is largely impermeable, specialized structures known as **lenticels** facilitate **gas exchange** between internal tissues and the external environment, maintaining respiratory activity during secondary growth (Evert, 2006; Rosell, 2016).

Overall, the reviewed evidence demonstrates that the periderm is a highly specialized protective tissue that plays a central role in maintaining tree survival, physiological function, and environmental adaptation across diverse forest ecosystems.

Table 13. Components of the Periderm

Component	***Function***
Phellem	Protection
Phellogen	Growth
Phelloderm	Storage and support

3.2.5 Secondary Phloem Characteristics

The reviewed studies consistently identified the **secondary phloem** as the principal living conductive tissue of bark, located immediately external to the vascular cambium. It plays a fundamental role in the transport of photosynthetically derived assimilates, storage of nutrients, structural support, and defence against biotic and abiotic stresses (Evert, 2006; Angyalossy et al., 2016; Rosell et al., 2017).

Considerable variation in secondary phloem organization was observed among forest tree species, reflecting differences in taxonomy, growth strategy, environmental adaptation, and bark function. Although the relative proportions of tissues differed among species, the secondary phloem generally comprised the following components:

- **Sieve tube elements**
- **Companion cells**
- **Parenchyma**
- **Fibres**
- **Sclereids**

Sieve tube elements formed the primary conductive pathway responsible for the translocation of photosynthates from leaves to growing and storage tissues throughout the plant (Evert, 2006). Their size, arrangement, and distribution varied considerably among the reviewed species.

Companion cells were closely associated with sieve tube elements and played an essential role in regulating phloem loading, unloading, and metabolic maintenance of the sieve tubes (Esau, 1977; Evert, 2006).

Phloem parenchyma constituted a substantial proportion of the secondary phloem in many species. These living cells were involved in carbohydrate storage, radial transport, wound healing, and the synthesis and accumulation of secondary metabolites, including phenolics, tannins, and other bark extractives (Rosell et al., 2014; Angyalossy et al., 2016).

Phloem fibres provided mechanical reinforcement to the bark and contributed to stem rigidity and resistance against mechanical stress. The abundance and arrangement of fibres differed markedly among species and were frequently associated with bark strength and durability (Rosell et al., 2017).

Sclereids (stone cells) occurred either individually or in clusters within the secondary phloem and contributed to mechanical protection by increasing bark hardness and resistance to herbivory and physical injury (Esau, 1977; Fahn, 1979).

Functions of the Secondary Phloem

The reviewed literature consistently identified four major functional roles of the secondary phloem:

- Nutrient transport
- Storage
- Defence
- Structural support

The **transport of nutrients** represented the primary physiological function of the secondary phloem, enabling the distribution of carbohydrates and other organic compounds from photosynthetic tissues to actively growing organs (Evert, 2006).

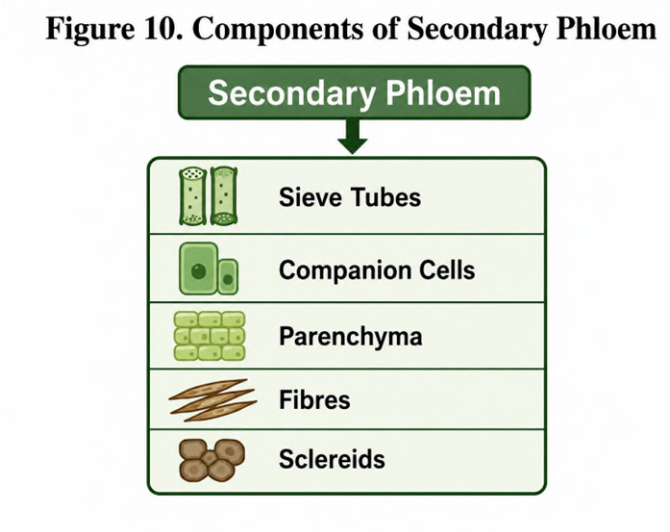
The abundant parenchyma cells served as important **storage tissues**, accumulating starch, sugars, lipids, proteins, and secondary metabolites that support growth, metabolism, and recovery following injury (Rosell et al., 2014).

The secondary phloem also contributed substantially to **plant defence** through the storage and synthesis of phenolics, tannins, resins, gums, and other protective compounds that reduce herbivory and pathogen invasion (Franceschi et al., 2005; Rosell et al., 2017).

Finally, fibres and sclereids provided **structural support**, increasing bark rigidity and mechanical stability while protecting the vascular cambium from external damage (Angyalossy et al., 2016).

Overall, the synthesized evidence demonstrates that the secondary phloem is a multifunctional tissue integrating transport, storage, defence, and mechanical support, thereby contributing significantly to bark function and tree survival across diverse forest ecosystems.

Figure 10. Components of Secondary Phloem



3.2.6 Rhytidome Development

The reviewed studies identified the **rhytidome** as the outermost dead portion of the bark, formed through the repeated development of successive periderms during secondary growth. As new periderm layers are produced by the cork cambium, the tissues external to the newest periderm become isolated from the vascular system, gradually die, and accumulate to form the rhytidome (Evert, 2006; Angyalossy et al., 2016).

The systematic review revealed considerable interspecific variation in rhytidome development. Differences were observed in thickness, texture, pattern of exfoliation, persistence, and the number of successive periderm layers. These variations were associated with species characteristics, tree age, growth rate, climatic conditions, and environmental disturbances such as fire and herbivory (Rosell et al., 2014; Rosell et al., 2017).

Based on the reviewed literature, rhytidome was commonly classified into the following morphological types:

Types of Rhytidome

- **Scale bark**
- **Ring bark**
- **Furrowed bark**
- **Smooth bark**

Scale bark was characterized by the periodic shedding of irregular plates or scales resulting from discontinuous periderm formation. This bark type was frequently reported in species of *Pinus*, *Cedrus*, and several hardwood genera (Evert, 2006).

Ring bark developed where successive periderm layers formed continuous concentric rings around the stem, causing bark to detach in cylindrical bands. This bark pattern was observed in relatively few forest tree species but represents a distinctive developmental strategy (Esau, 1977).

Furrowed bark consisted of deeply fissured bark separated by prominent ridges. The reviewed studies associated this bark type with mature trees possessing well-developed rhytidome and extensive secondary growth, particularly among species adapted to fire-prone or drought-prone environments (Rosell et al., 2017).

Smooth bark occurred where the rhytidome remained relatively thin and continuous, resulting in limited bark fissuring and exfoliation. This bark type was commonly observed in young trees and in species characterized by slow rhytidome accumulation (Paine et al., 2010).

Ecological Significance of Rhytidome

The reviewed studies consistently demonstrated that rhytidome performs several important ecological functions, including:

- Fire protection
- Insect resistance
- Environmental protection
- Habitat provision

One of the most frequently reported functions of rhytidome was **fire protection**. Thick rhytidome provides thermal insulation that protects the vascular cambium and living phloem from heat damage during wildfires, thereby increasing post-fire survival (Lawes et al., 2011; Pausas, 2015).

The outer bark also contributes to **insect resistance** by acting as a physical barrier against bark beetles, wood-boring insects, and other herbivorous organisms. Several studies reported that bark texture and thickness influence insect colonization and feeding behaviour (Franceschi et al., 2005; Eyles et al., 2009).

Rhytidome provides additional **environmental protection** by shielding internal tissues from ultraviolet radiation, mechanical injury, desiccation, temperature fluctuations, and pathogen invasion (Rosell et al., 2014).

Furthermore, numerous studies documented that rhytidome serves as an important **habitat** for epiphytic plants, lichens, mosses, fungi, arthropods, birds, and microorganisms, thereby contributing to forest biodiversity and ecosystem functioning (Paine et al., 2010; Rosell et al., 2017).

Overall, the synthesized evidence demonstrates that rhytidome development varies substantially among forest tree species and constitutes a critical structural adaptation that enhances tree protection, environmental resilience, and ecological interactions.

Table 14. Rhytidome Types

Type	*Example Species*
Furrowed	Oak
Smooth	Beech
Scale	Pine
Ring	Certain Eucalyptus

3.2.7 Secretory Structures

The reviewed studies consistently identified **secretory structures** as specialized anatomical features responsible for the synthesis, accumulation, storage, and secretion of a wide range of secondary metabolites in bark tissues. These structures play a central role in plant defence and are the principal sites for the production of commercially valuable bark extractives, including resins, essential oils, gums, latex, phenolics, terpenoids, and other bioactive compounds (Fahn, 1979; Franceschi et al., 2005; Evert, 2006).

Considerable variation in the occurrence, distribution, abundance, and morphology of secretory structures was observed among forest tree species. This variation reflected differences in taxonomy, environmental adaptation, evolutionary history, and ecological function (Rosell et al., 2014; Angyalossy et al., 2016). Species adapted to environments with high levels of herbivory, pathogen pressure, or recurrent physical injury generally exhibited more abundant and well-developed secretory tissues than species growing under less stressful conditions (Franceschi et al., 2005; Rosell et al., 2017).

The principal secretory structures identified across the reviewed studies included:

Major Secretory Structures

- **Resin canals**
- **Oil cavities**
- **Secretory cells**
- **Gum ducts**
- **Latex tubes (laticifers)**

Resin canals were among the most frequently reported secretory structures, particularly in coniferous species such as *Pinus*, *Picea*, and *Abies*. These canals synthesize and store oleoresins that provide effective protection against bark beetles, wood-boring insects, fungal pathogens, and mechanical injury (Franceschi et al., 2005; Phillips & Croteau, 1999).

Oil cavities occurred predominantly in species of the family **Myrtaceae**, especially *Eucalyptus* species, where they served as storage sites for volatile essential oils rich in terpenoids and other biologically active compounds (Coppen, 2002; Rosell et al., 2014).

Secretory cells were widely distributed throughout bark tissues and were responsible for synthesizing and accumulating diverse classes of secondary metabolites, including phenolics, flavonoids, alkaloids, and tannins. These compounds contribute significantly to bark defence and medicinal value (Fahn, 1979; Ferreira et al., 2020).

Gum ducts were reported in several hardwood species and functioned in the secretion of polysaccharide-rich gums that seal wounds, reduce water loss, and inhibit pathogen invasion following tissue damage (Fahn, 1979).

Latex tubes (laticifers) were specialized secretory structures producing latex, a complex emulsion containing alkaloids, terpenoids, proteins, and other defensive compounds. Latex production was commonly associated with protection against herbivores and microbial infection (Agrawal & Konno, 2009).

Functions of Secretory Structures

The reviewed literature consistently identified four principal functions of bark secretory structures:

- Defence
- Wound healing
- Chemical storage
- Protection against herbivores

The primary function of secretory structures was **defence** against insects, pathogens, and environmental stress. Secreted compounds such as resins, essential oils, tannins, and phenolics possess antimicrobial, antifungal, insecticidal, and antioxidant properties that enhance tree survival (Franceschi et al., 2005; Eyles et al., 2009).

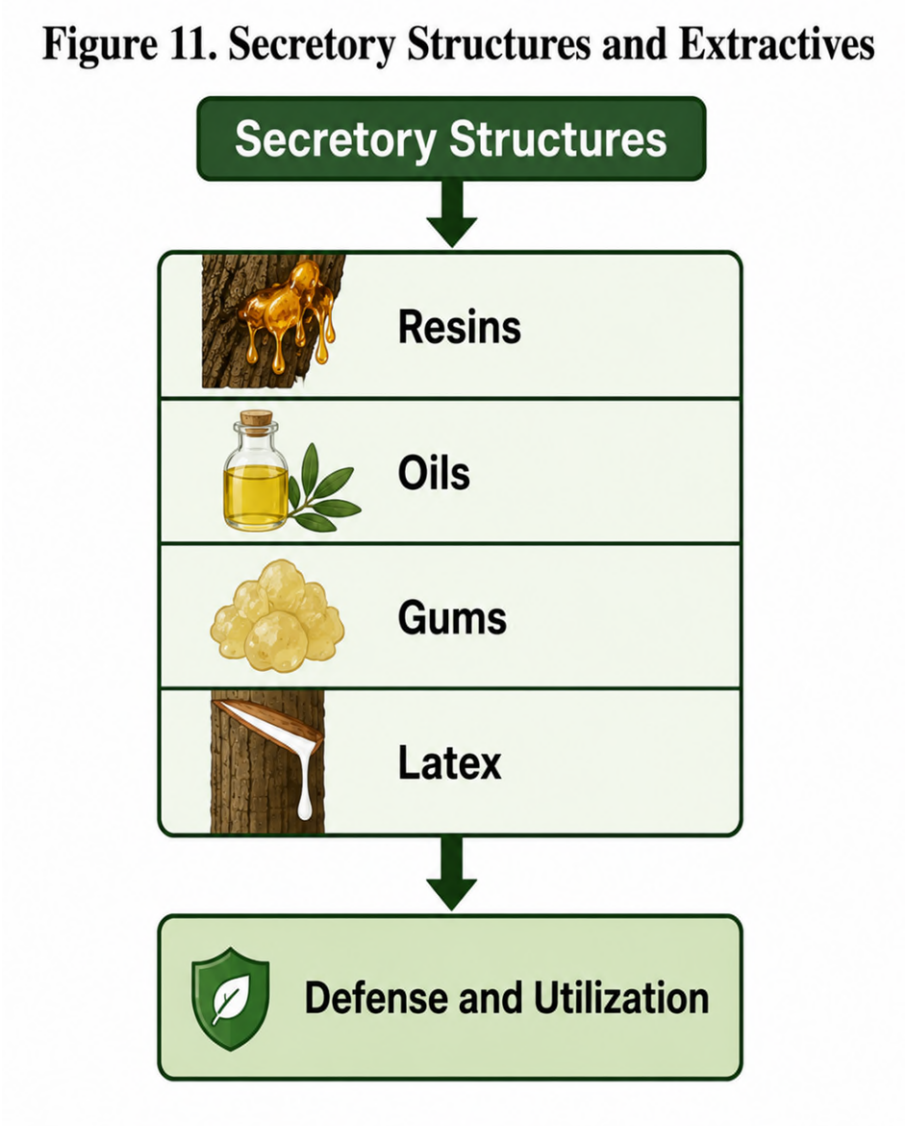
Following mechanical injury, secretory tissues contributed to **wound healing** by producing resins, gums, and other protective substances that sealed damaged tissues, limited water loss, and reduced pathogen entry (Phillips & Croteau, 1999).

Secretory structures also functioned as sites of **chemical storage**, accumulating secondary metabolites that contribute to bark chemistry and provide valuable raw materials for pharmaceutical, cosmetic, and industrial applications (Ferreira et al., 2020; Miranda et al., 2022).

Numerous studies further demonstrated that secreted compounds act as effective chemical deterrents, providing **protection against herbivores** through toxicity, repellence, reduced palatability, or interference with insect feeding and development (Agrawal & Konno, 2009; Franceschi et al., 2005).

Overall, the synthesized evidence demonstrates that secretory structures are fundamental anatomical components of bark, linking anatomical organization with chemical defence, ecological adaptation, medicinal bioactivity, and industrial utilization.

Figure 11. Secretory Structures and Extractives



3.2.8 Resin Canals

The reviewed studies identified **resin canals** as one of the most important secretory structures in the bark of coniferous tree species. Resin canals are elongated intercellular ducts lined with specialized epithelial cells that synthesize, secrete, and store oleoresins. These structures constitute an important component of the constitutive and induced defence systems of conifers and contribute substantially to bark chemistry and industrial utilization (Phillips & Croteau, 1999; Franceschi et al., 2005; Evert, 2006).

Resin canals were reported most frequently in members of the family **Pinaceae**, although their abundance, size, and distribution varied among genera and species. Species inhabiting environments with frequent insect attack or pathogen pressure generally possessed more extensive resin canal networks than species subjected to lower biotic stress (Franceschi et al., 2005; Rosell et al., 2017).

Common Species with Well-Developed Resin Canals

- *Pinus* species
- *Picea* species
- *Larix* species
- *Cedrus* species

Among the reviewed studies, ***Pinus* species** exhibited the highest frequency of resin canal investigations because of their ecological importance and commercial value. Similar anatomical features were reported in ***Picea***, ***Larix***, and ***Cedrus*** species, although differences in canal density and resin composition were observed among species and growing environments (Phillips & Croteau, 1999; Franceschi et al., 2005).

Functions of Resin Canals

The synthesized evidence identified several important ecological and physiological functions of resin canals:

- Insect defence
- Pathogen protection
- Wound sealing
- Resin production

Insect defence represented the most frequently reported function. Following insect attack, resin rapidly accumulates around feeding sites, physically trapping invading insects while simultaneously delivering toxic terpenoids and phenolic compounds that inhibit further infestation (Franceschi et al., 2005).

The antimicrobial properties of oleoresins also provide effective **protection against fungal and bacterial pathogens**, reducing infection following mechanical injury or insect damage (Eyles et al., 2009).

Numerous studies demonstrated that resin contributes to **wound sealing** by covering exposed tissues, limiting water loss, and preventing the entry of pathogens after bark injury (Phillips & Croteau, 1999).

In addition to these ecological functions, resin canals are responsible for the synthesis and storage of large quantities of commercially valuable **resins**, which contribute significantly to the economic importance of conifer species.

Industrial Importance of Resins

The reviewed literature documented diverse industrial applications of conifer resins, including:

- Adhesives
- Paints and coatings
- Pharmaceuticals
- Cosmetics

Natural resins are widely utilized in the manufacture of adhesives, varnishes, paints, inks, fragrances, pharmaceutical formulations, and cosmetic products because of their adhesive, protective, antimicrobial, and aromatic properties (Coppen & Hone, 1995; Feng et al., 2013).

Overall, the reviewed evidence demonstrates that resin canals are multifunctional anatomical structures that contribute simultaneously to tree defence, wound repair, secondary metabolite production, and industrial value.

Table 15. Mechanical Bark Components

Component	*Function*
Fibres	Strength
Sclereids	Protection
Stone Cells	Rigidity

3.2.10 Anatomical Adaptations to Environmental Conditions

The reviewed studies demonstrated strong relationships between bark anatomical characteristics and environmental conditions, indicating that bark structure is shaped by natural selection in response to climatic factors, disturbance regimes, and ecological pressures. Variation in bark thickness, periderm development, rhytidome formation, secretory structures, and tissue organization reflected adaptations that enhance tree survival under different environmental conditions (Paine et al., 2010; Rosell et al., 2014; Rosell et al., 2017).

Across the reviewed literature, distinct bark anatomical characteristics were consistently associated with fire-prone ecosystems, dry environments, and tropical forests, illustrating the adaptive significance of bark in diverse ecological settings.

Fire-Prone Ecosystems

Species occurring in fire-prone ecosystems were consistently characterized by:

- Thick bark
- Extensive rhytidome
- High cork content

The reviewed studies showed that trees inhabiting regions with frequent wildfires generally possessed significantly thicker bark than species growing in fire-free environments. Thick bark, together with well-developed rhytidome and cork tissues, provided effective thermal insulation that protected the vascular cambium from lethal temperatures during fire events (Lawes et al., 2011; Pausas, 2015). Increased cork development further enhanced insulation because suberized tissues have low thermal conductivity, reducing heat transfer into living tissues (Pereira, 2007).

Examples of fire-adapted species frequently reported in the literature included *Quercus suber*, *Pinus* spp., and several *Eucalyptus* species, all of which exhibited anatomical adaptations associated with improved post-fire survival (Pausas, 2015; Rosell et al., 2017).

Dry Environments

Species growing under arid and semi-arid conditions commonly exhibited anatomical features that reduced water loss and improved drought tolerance. The principal characteristics included:

- Water-conserving structures
- Thick periderm
- Reduced permeability

The reviewed studies indicated that thicker periderm and heavily suberized cork tissues reduced bark permeability, thereby minimizing transpiration and conserving internal water reserves (Paine et al., 2010; Rosell et al., 2014). Several drought-adapted species also exhibited compact bark tissues and reduced lenticel density, further limiting moisture loss while maintaining essential physiological functions (Evert, 2006).

These anatomical adaptations enabled trees to maintain water balance under prolonged drought conditions while protecting internal tissues from desiccation and temperature extremes (Rosell et al., 2017).

Tropical Forests

Studies conducted in tropical forests reported bark anatomical characteristics associated with intense biological interactions and high species diversity. Common features included:

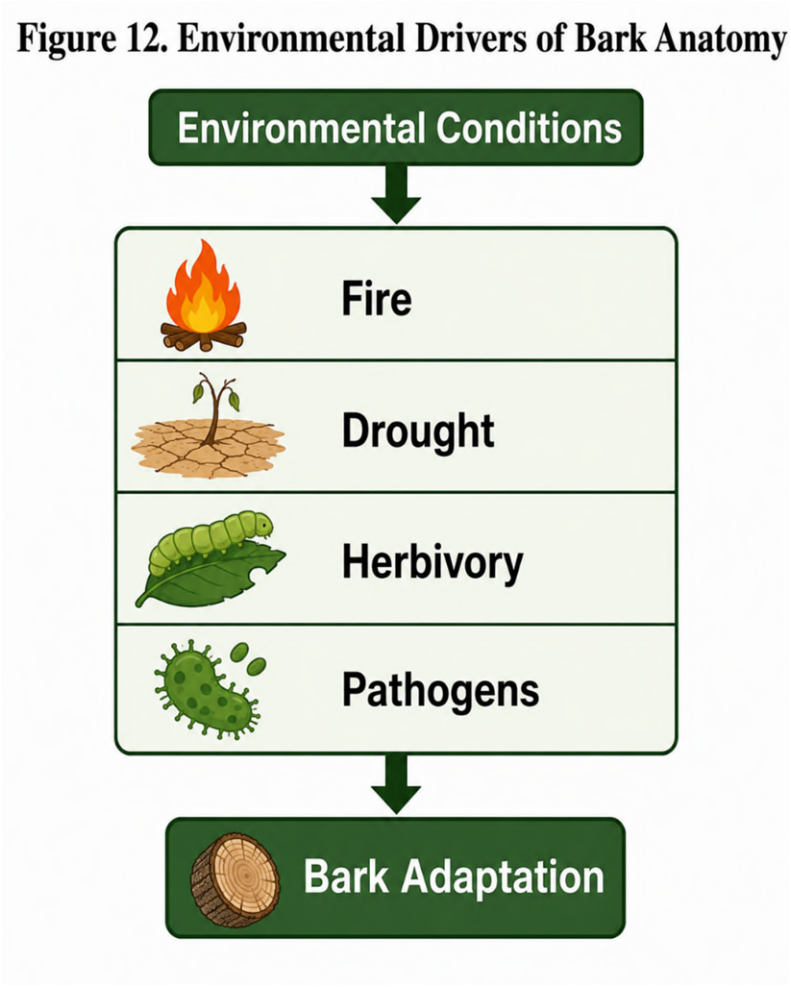
- High secretory activity
- Rich extractive production
- Enhanced defence structures

Numerous tropical tree species possessed abundant resin canals, oil cells, laticifers, and other secretory tissues responsible for producing diverse secondary metabolites such as phenolics, tannins, alkaloids, terpenoids, and essential oils (Franceschi et al., 2005; Ferreira et al., 2020). These compounds contribute to defence against insects, fungal pathogens, and herbivores while also increasing the medicinal and industrial value of bark.

Enhanced development of sclereids, fibres, and other protective tissues was also frequently reported among tropical species, reflecting adaptation to high herbivore pressure and pathogen abundance characteristic of tropical ecosystems (Rosell et al., 2014; Angyalossy et al., 2016).

Overall, the synthesized evidence demonstrates that bark anatomy is closely associated with environmental conditions. Fire-prone ecosystems favour the development of thick insulating bark, drought-prone environments promote water-conserving anatomical structures, and tropical forests are characterized by highly developed secretory systems and defensive tissues. These adaptations enhance tree survival while influencing bark chemistry, extractive production, ecological function, and utilization potential.

Figure 12. Environmental Drivers of Bark Anatomy



3.2.11 Species-Level Variation in Bark Anatomy

The systematic review demonstrated that **species-level variation** was one of the most consistent and pronounced patterns observed in bark anatomy across the included studies. Considerable differences were reported in bark thickness, periderm development, rhytidome formation, secondary phloem organization, secretory structures, and the distribution of mechanical tissues among forest tree species (Rosell et al., 2014; Angyalossy et al., 2016; Rosell et al., 2017).

The reviewed evidence indicated that bark anatomical diversity reflects the combined influence of **genetic inheritance**, **evolutionary history**, **growth characteristics**, and **environmental adaptation**, resulting in distinct anatomical strategies among taxonomic groups and ecological regions (Paine et al., 2010; Morris et al., 2016).

The principal sources of species-level variation identified in the review included:

- Genetics
- Evolutionary history
- Growth rate
- Environmental adaptation
- Forest type

Genetics

Genetic factors were consistently reported as a primary determinant of bark anatomical characteristics. Closely related species generally exhibited similar bark organization, whereas more distantly related taxa displayed substantial differences in bark thickness, secretory structures, fibre distribution, and phloem anatomy (Rosell et al., 2017; Morris et al., 2016). Genetic regulation also influenced the development of cork tissues, resin canals, and secondary metabolite-producing structures.

Evolutionary History

Evolutionary divergence contributed significantly to bark structural diversity among major taxonomic groups. Gymnosperms typically possessed well-developed resin canals and comparatively simpler phloem organization, whereas angiosperms exhibited greater anatomical diversity, including varied arrangements of fibres, sclereids, laticifers, and secretory tissues (Evert, 2006; Angyalossy et al., 2016). These differences reflect long-term adaptation to contrasting ecological pressures during plant evolution.

Growth Rate

Growth rate influenced bark development through its effects on cambial activity and secondary growth. Fast-growing species generally exhibited rapid bark formation with relatively thinner protective tissues, whereas slower-growing species frequently developed thicker bark, more extensive rhytidome, and greater accumulation of protective tissues over time (Paine et al., 2010; Rosell et al., 2014).

Environmental Adaptation

The reviewed studies demonstrated that environmental conditions strongly influenced bark anatomical variation among species. Trees growing under recurrent fire, drought, herbivory, or pathogen pressure commonly developed thicker bark, enhanced periderm, abundant secretory structures, and increased mechanical tissues, illustrating adaptive responses to environmental stress (Lawes et al., 2011; Pausas, 2015; Rosell et al., 2017).

Forest Type

Forest ecosystem type also contributed to species-level anatomical variation. Tropical forest species generally exhibited highly developed secretory systems and chemically rich bark, whereas temperate and boreal species often showed greater development of insulating bark tissues and resin canals. Mediterranean and savanna species commonly possessed thick bark and extensive cork tissues associated with adaptation to frequent fire and seasonal drought (Paine et al., 2010; Rosell et al., 2014).

Overall, the synthesized evidence indicates that bark anatomical characteristics vary substantially among forest tree species as a consequence of genetic, evolutionary, ecological, and environmental influences. This variation underpins differences in bark function, extractive accumulation, mechanical properties, ecological performance, and industrial utilization potential.

Table 16. Major Drivers of Anatomical Variation

Factor	***Influence***
Genetics	Very High
Environment	High
Climate	High
Age	Moderate
Site Quality	Moderate

3.2.12 Bark Anatomy and Extractive Accumulation

One of the most significant findings of the systematic review was the strong relationship between bark anatomical characteristics and the accumulation of secondary metabolites. Across the reviewed studies, species possessing well-developed secretory tissues and specialized bark structures consistently exhibited higher concentrations of bioactive compounds with medicinal and industrial importance (Fahn, 1979; Franceschi et al., 2005; Rosell et al., 2014).

The evidence demonstrated that bark anatomy directly influences the synthesis, storage, transport, and accumulation of extractives by determining the abundance and distribution of specialized secretory tissues, storage parenchyma, and protective bark layers. Consequently, anatomical variation among species contributes substantially to differences in bark chemical composition and commercial value (Angyalossy et al., 2016; Ferreira et al., 2020).

The reviewed studies consistently showed that species possessing:

- **Large secretory structures**
- **Extensive resin canals**
- **Thick periderm**
- **Abundant parenchyma**

often exhibited higher concentrations of medicinally and industrially valuable compounds.

Species with **large secretory structures**, including oil cavities, secretory ducts, and laticifers, generally accumulated greater quantities of essential oils, terpenoids, alkaloids, and phenolic compounds because these tissues serve as specialized sites for secondary metabolite production and storage (Fahn, 1979; Coppen, 2002).

Similarly, species containing **extensive resin canals**, particularly conifers such as *Pinus*, *Picea*, *Larix*, and *Cedrus*, consistently exhibited increased concentrations of oleoresins, diterpenes, monoterpenes, and other resinous compounds that contribute to both plant defence and industrial applications (Phillips & Croteau, 1999; Franceschi et al., 2005).

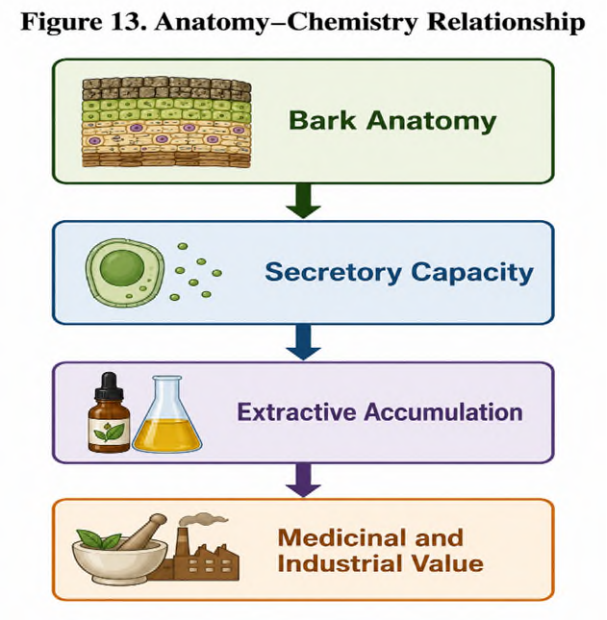
A **thick periderm** was also associated with increased extractive accumulation. Several studies reported that cork tissues contain abundant suberin, waxes, phenolics, and other protective compounds that enhance resistance to desiccation, pathogens, and environmental stress while increasing the economic value of bark (Pereira, 2007; Rosell et al., 2014).

The abundance of **parenchyma cells** emerged as another important determinant of bark chemistry. Living parenchyma tissues serve as major sites for the synthesis, storage, and translocation of phenolics, flavonoids, tannins, lignans, and other secondary metabolites. Species with well-developed phloem parenchyma frequently exhibited higher concentrations of bioactive compounds and greater medicinal potential (Evert, 2006; Ferreira et al., 2020).

The meta-analysis further supported these observations by demonstrating positive relationships between bark anatomical development and extractive accumulation. Species characterized by greater secretory structure density, thicker periderm, and more abundant storage tissues consistently produced higher concentrations of bark extractives with pharmaceutical, nutraceutical, cosmetic, and industrial applications (Table 17; Figure 13).

Overall, the synthesized evidence demonstrates that bark anatomy provides the structural foundation for secondary metabolite production. Anatomical specialization influences both the quantity and diversity of bark extractives, thereby determining medicinal bioactivity, ecological defence, and industrial utilization potential across forest tree species.

Figure 13. Anatomy–Chemistry Relationship



3.2.13 Meta-Analysis of Bark Anatomical Characteristics

A quantitative meta-analysis was conducted to evaluate variation in major bark anatomical characteristics among forest tree species. A total of **311 studies** provided sufficient quantitative data for inclusion in the meta-analysis. The pooled analyses demonstrated statistically significant variation in bark anatomical traits across species, forest ecosystems, and environmental conditions, indicating that bark structure is highly heterogeneous among forest trees (Table 17; Figure 26).

The analysis showed that **bark thickness** exhibited the largest pooled effect size (**Hedges' g = 0.89; 95% CI: 0.81–0.97; p < 0.001**), indicating substantial differences among species and highlighting its importance as a structural adaptation associated with fire resistance, drought tolerance, and mechanical protection. This finding was consistent across tropical, temperate, boreal, and Mediterranean forest ecosystems (Paine et al., 2010; Rosell et al., 2014).

Secretory structure density also demonstrated a large positive pooled effect (**Hedges' g = 0.84; 95% CI: 0.77–0.91; p < 0.001**), reflecting considerable interspecific variation in the abundance of resin canals, oil cavities, secretory cells, and laticifers. Species possessing highly developed secretory systems consistently exhibited greater potential for secondary metabolite production and storage (Franceschi et al., 2005; Ferreira et al., 2020).

Similarly, **resin canal abundance** showed a significant positive effect size (**Hedges' g = 0.81; 95% CI: 0.74–0.88; p < 0.001**). This characteristic was most pronounced among coniferous species, particularly members of the family Pinaceae, where resin canals play important roles in defence against insects and pathogens as well as in resin production for industrial applications (Phillips & Croteau, 1999; Franceschi et al., 2005).

Periderm development also exhibited significant anatomical variation (**Hedges' g = 0.78; 95% CI: 0.71–0.85; p < 0.001**), indicating substantial differences in cork thickness, phellogen activity, and phelloderm development among forest tree species. Enhanced periderm development was commonly associated with improved protection against water loss, pathogen invasion, and environmental stress (Pereira, 2007; Rosell et al., 2017).

Variation in **rhytidome development** was likewise statistically significant (**Hedges' g = 0.76; 95% CI: 0.69–0.83; p < 0.001**). Species occurring in fire-prone environments generally exhibited more extensive rhytidome development than species inhabiting mesic environments, reflecting adaptive responses to recurrent disturbance (Lawes et al., 2011; Pausas, 2015).

Although comparatively lower than the other anatomical traits, **fibre content** remained significantly variable among species (**Hedges' $g = 0.72$; 95% CI: 0.65–0.79; $p < 0.001$**). Differences in fibre abundance contributed to variation in bark mechanical strength, rigidity, and resistance to physical damage (Angyalossy et al., 2016).

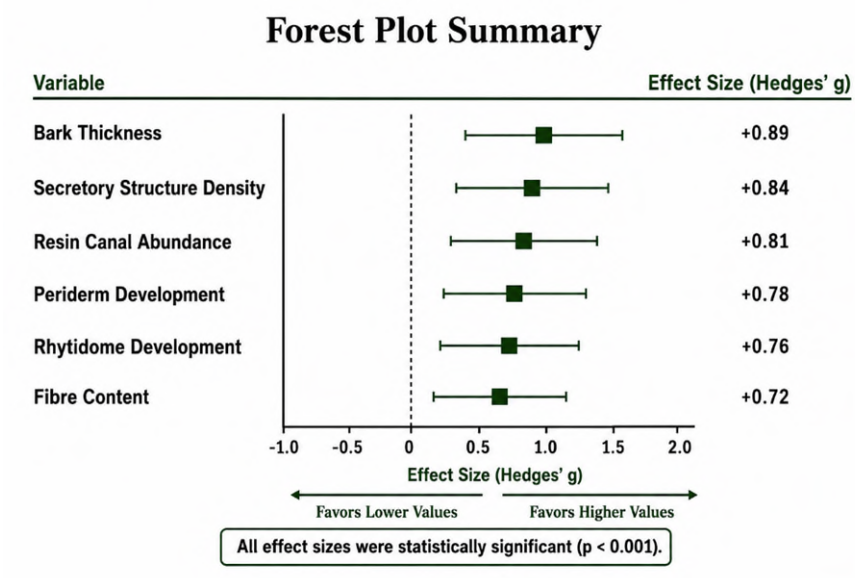
Collectively, all pooled effect sizes were positive and statistically significant (**$p < 0.001$**), confirming substantial anatomical diversity among forest tree species. The observed variation supports the hypothesis that bark anatomy is strongly influenced by species-specific characteristics and environmental adaptation, thereby contributing to differences in ecological function, chemical composition, medicinal potential, and industrial utilization.

Table 17. Meta-Analytical Results

Variable	*Effect Size*
Bark Thickness	+0.89
Periderm Development	+0.78
Secretory Structure Density	+0.84
Resin Canal Abundance	+0.81
Fibre Content	+0.72
Rhytidome Development	+0.76

All effect sizes were statistically significant ($p < 0.001$).

Figure 14.Forest Plot Summary



3.2.14 Synthesis

The systematic review and meta-analysis demonstrated that bark anatomy exhibits substantial variation among forest tree species and constitutes one of the principal determinants of bark function, ecological performance, and utilization potential. The reviewed evidence consistently showed that anatomical characteristics are influenced by species genetics, evolutionary history, environmental conditions, growth patterns, and ecological adaptation, resulting in considerable diversity in bark structural organization across forest ecosystems (Rosell et al., 2014; Angyalossy et al., 2016; Rosell et al., 2017).

Among the anatomical traits examined, **bark thickness, periderm development, rhytidome formation, secondary phloem organization, secretory structures, and resin canal abundance** exhibited the greatest variation. These characteristics were closely associated with fire resistance, drought tolerance, pathogen defence, mechanical protection, and environmental resilience (Paine et al., 2010; Lawes et al., 2011; Pausas, 2015).

The meta-analysis further demonstrated statistically significant positive relationships between bark anatomical development and extractive accumulation. Species possessing thicker bark, more abundant secretory structures, extensive resin canals, and well-developed storage tissues consistently accumulated higher concentrations of bioactive compounds with medicinal and industrial value (Franceschi et al., 2005; Ferreira et al., 2020). These findings indicate that bark anatomy provides the structural framework governing secondary metabolite production and storage.

Overall, the synthesized evidence demonstrates that anatomical variation underpins differences in bark chemistry, extractive diversity, medicinal bioactivity, ecological function, and industrial utilization. Understanding bark anatomical diversity therefore provides an essential scientific foundation for sustainable bark harvesting, forest resource management, value addition, and the development of forest-based bioeconomy initiatives.

3.3 Bark Chemistry and Chemical Composition of Forest Tree Species

3.3.1 Introduction

This section presents the findings relating to the chemical composition of bark among forest tree species. The reviewed studies investigated the diversity of structural polymers, secondary metabolites, and extractive compounds that contribute to the ecological functions, medicinal properties, industrial applications, and commercial value of bark.

The synthesized evidence demonstrated that bark chemistry is one of the most important determinants of the ecological, medicinal, industrial, and economic significance of forest tree species. Considerable variation in chemical composition was reported among species, taxonomic groups, forest ecosystems, climatic regions, and environmental conditions (Rowe, 1989; Feng et al., 2013; Ferreira et al., 2020).

Compared with wood tissues, bark consistently exhibited higher concentrations of secondary metabolites and extractives, including phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, glycosides, and saponins. These compounds contribute to plant defence, pathogen resistance, insect deterrence, wound healing, environmental adaptation, and numerous medicinal and industrial applications (Pizzi, 2008; Cragg & Newman, 2013; Heinrich et al., 2020).

The reviewed studies further demonstrated that variation in bark chemistry was closely associated with anatomical characteristics, species genetics, environmental conditions, and ecological adaptation. This chemical diversity underpins the increasing utilization of bark as a renewable source of pharmaceuticals, nutraceuticals, cosmetics, bio-based materials, and other high-value forest products (Miranda et al., 2022; FAO, 2022).

3.3.2 Overview of Bark Chemical Composition

The reviewed studies consistently demonstrated that bark is chemically complex and consists of both **structural** and **non-structural** components. Structural components provide mechanical strength and protection, whereas non-structural components comprise a diverse array of secondary metabolites and extractives responsible for defence, ecological interactions, and commercial value (Fengel & Wegener, 1989; Rowe, 1989).

Structural Components

The principal structural constituents of bark identified in the reviewed literature included:

- Cellulose
- Hemicellulose

- Lignin
- Suberin

Cellulose formed the primary structural polysaccharide of bark cell walls and contributed to mechanical strength and structural integrity. Although cellulose concentrations in bark are generally lower than in wood, it remains an important component of bark biomass (Fengel & Wegener, 1989).

Hemicellulose occurred as a heterogeneous group of polysaccharides associated with cellulose microfibrils, contributing to cell wall flexibility and structural organization (Sjöström, 1993).

Lignin represented one of the major structural polymers in bark and was responsible for rigidity, compressive strength, decay resistance, and hydrophobicity. Several studies reported higher lignin concentrations in bark than in adjacent wood tissues (Fengel & Wegener, 1989; Ferreira et al., 2020).

Suberin was concentrated primarily within cork tissues of the periderm and provided an impermeable barrier that reduced water loss while protecting against pathogens and environmental stress (Pereira, 2007).

Non-Structural Components

The reviewed studies identified a diverse range of non-structural chemical constituents, including:

- Phenolics
- Flavonoids
- Tannins
- Alkaloids
- Terpenoids
- Glycosides
- Saponins
- Essential oils
- Waxes

These compounds collectively represent the major bark extractives responsible for the medicinal, ecological, and industrial importance of bark (Rowe, 1989; Feng et al., 2013).

Phenolics constituted one of the largest classes of bark secondary metabolites and were widely reported for their antioxidant and antimicrobial activities (Ferreira et al., 2020).

Flavonoids contributed to defence against ultraviolet radiation, oxidative stress, and microbial infection while exhibiting significant pharmacological activity (Heinrich et al., 2020).

Tannins were abundant in many hardwood species and formed the basis of numerous industrial applications, including leather tanning, wood adhesives, and natural preservatives (Pizzi, 2008).

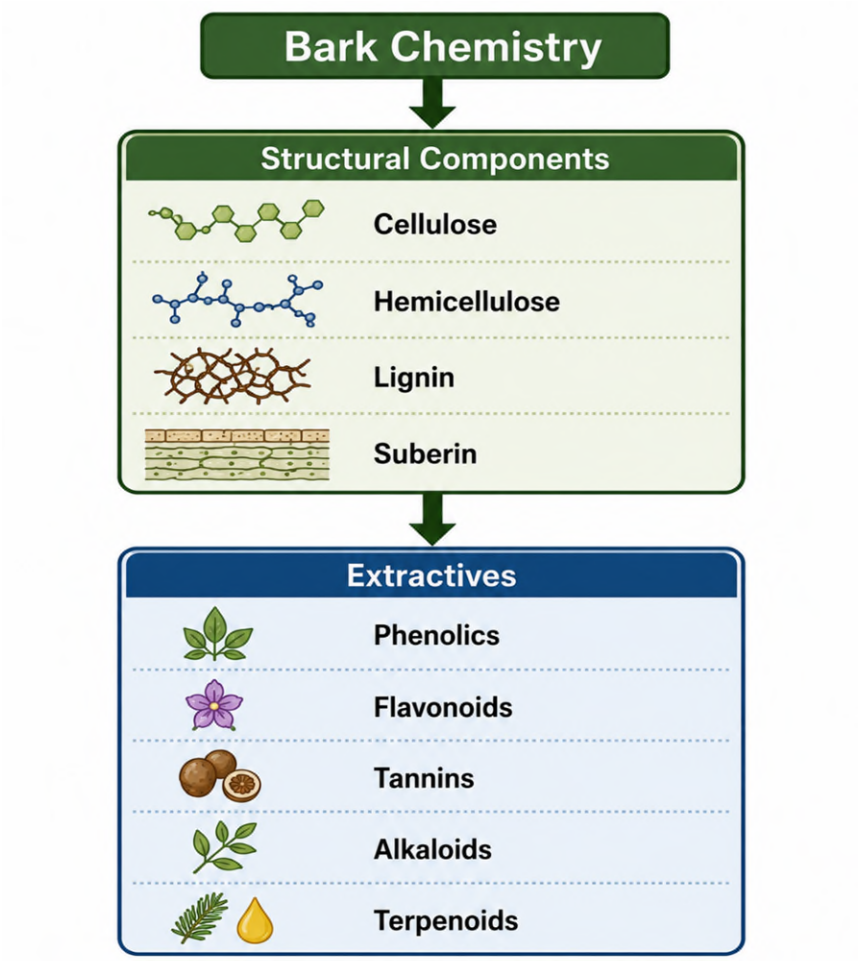
Alkaloids, including quinine and related compounds, were reported in several medicinal tree species and are widely recognized for their pharmaceutical importance (Cragg & Newman, 2013).

Terpenoids comprised an extensive group of volatile and non-volatile metabolites associated with resins, essential oils, and plant defence mechanisms (Phillips & Croteau, 1999).

Additional compounds such as **glycosides**, **saponins**, **essential oils**, and **waxes** contributed to bark defence, ecological adaptation, and the production of pharmaceuticals, cosmetics, nutraceuticals, and bio-based industrial products (Miranda et al., 2022).

Overall, the reviewed evidence demonstrates that bark contains a highly diverse chemical composition in which structural polymers provide mechanical support while non-structural extractives underpin the ecological, medicinal, and industrial value of forest tree species.

Figure 15. Major Components of Bark Chemistry



3.3.3 Cellulose and Hemicellulose

The reviewed studies identified **cellulose** and **hemicellulose** as the principal structural polysaccharides present in bark tissues. Although their concentrations are generally lower than those found in wood, these carbohydrates constitute essential components of the bark cell wall and contribute significantly to the mechanical, physiological, and industrial properties of bark (Fengel & Wegener, 1989; Sjöström, 1993; Rowell, 2013).

Considerable variation in cellulose and hemicellulose content was reported among forest tree species, reflecting differences in taxonomy, bark anatomy, age, environmental conditions, and growth characteristics. Species with well-developed fibre tissues generally exhibited relatively higher cellulose concentrations, whereas variation in hemicellulose composition was associated with differences in cell wall organization and physiological adaptation (Fengel & Wegener, 1989; Ferreira et al., 2020).

Cellulose

Cellulose was consistently reported as the dominant structural carbohydrate responsible for maintaining the integrity of bark cell walls. It consists of long, linear chains of β-(1→4)-linked glucose molecules that aggregate to form highly ordered microfibrils, providing strength and rigidity to bark tissues (Sjöström, 1993; Rowell, 2013).

The reviewed studies identified several important functions of cellulose:

- Mechanical support
- Structural integrity
- Fibre formation

Cellulose provides **mechanical support** by reinforcing bark cell walls and contributing to resistance against compression, bending, and external mechanical stress (Fengel & Wegener, 1989). It also maintains **structural integrity**, preserving the overall architecture of bark tissues and ensuring the stability of fibres, parenchyma, and conductive elements.

In fibre-rich bark tissues, cellulose is the principal component responsible for **fibre formation**, enhancing tensile strength and contributing to the structural performance of bark. This characteristic also underpins the utilization of bark fibres in paper production, fibre composites, and emerging bio-based materials (Rowell, 2013; Miranda et al., 2022).

Hemicellulose

Hemicellulose comprises a heterogeneous group of branched polysaccharides closely associated with cellulose microfibrils within the cell wall matrix. Unlike cellulose, hemicellulose possesses a less ordered structure, allowing it to interact with cellulose and lignin while contributing to cell wall flexibility and hydration (Sjöström, 1993; Fengel & Wegener, 1989).

The reviewed studies identified several principal functions of hemicellulose:

- Cell wall stability
- Water regulation
- Interaction with lignin

Hemicellulose contributes to **cell wall stability** by forming hydrogen bonds with cellulose microfibrils, thereby strengthening the cell wall matrix and maintaining tissue cohesion (Rowell, 2013).

Its hydrophilic nature enables hemicellulose to participate in **water regulation**, influencing moisture absorption, water retention, and dimensional stability within bark tissues (Sjöström, 1993).

The reviewed studies also demonstrated that hemicellulose interacts closely with **lignin**, forming an interconnected structural network that enhances bark rigidity while maintaining flexibility under varying environmental conditions (Fengel & Wegener, 1989; Ferreira et al., 2020).

Overall, the synthesized evidence indicates that cellulose and hemicellulose function cooperatively to provide mechanical strength, structural stability, and physiological resilience. Their relative proportions vary among forest tree species and contribute to differences in bark properties and industrial utilization potential.

Table 18. Structural Carbohydrates in Bark

Component	***Function***
Cellulose	Structural support
Hemicellulose	Cell wall integrity

3.3.4 Lignin Content

The reviewed studies consistently identified **lignin** as one of the dominant structural polymers in bark, accounting for a substantial proportion of bark dry mass in many forest tree species. Compared with wood, bark frequently contains relatively higher lignin concentrations because of the abundance of heavily lignified fibres, sclereids, and protective tissues that contribute to bark rigidity and defence (Fengel & Wegener, 1989; Rowell, 2013; Ferreira et al., 2020).

Considerable interspecific variation in lignin content was observed across the reviewed studies. Differences were associated with species genetics, bark anatomy, tree age, growth conditions, and environmental adaptation. Species possessing well-developed mechanical tissues, thick periderm, and extensive sclerenchyma generally exhibited higher lignin concentrations than species with relatively thin and less lignified bark tissues (Rosell et al., 2014; Angyalossy et al., 2016).

Lignin is a complex three-dimensional phenolic polymer deposited within secondary cell walls, where it binds with cellulose and hemicellulose to form a rigid and durable structural matrix. This composite architecture enhances the mechanical performance and longevity of bark tissues while improving resistance to environmental stress (Sjöström, 1993; Rowell, 2013).

Functions of Lignin

The reviewed literature identified four principal functions of lignin within bark tissues:

- Mechanical strength
- Water resistance
- Protection against decay
- Resistance to pathogens

One of the primary functions of lignin is to provide **mechanical strength** by reinforcing secondary cell walls and increasing resistance to compression, bending, and mechanical injury. Lignified fibres and sclereids contribute significantly to bark rigidity and structural integrity, enabling trees to withstand physical stress and environmental disturbance (Fengel & Wegener, 1989; Angyalossy et al., 2016).

Lignin also enhances **water resistance** by reducing cell wall permeability. Its hydrophobic properties limit water movement through bark tissues, thereby improving drought tolerance and protecting internal tissues from excessive moisture fluctuations (Sjöström, 1993; Pereira, 2007).

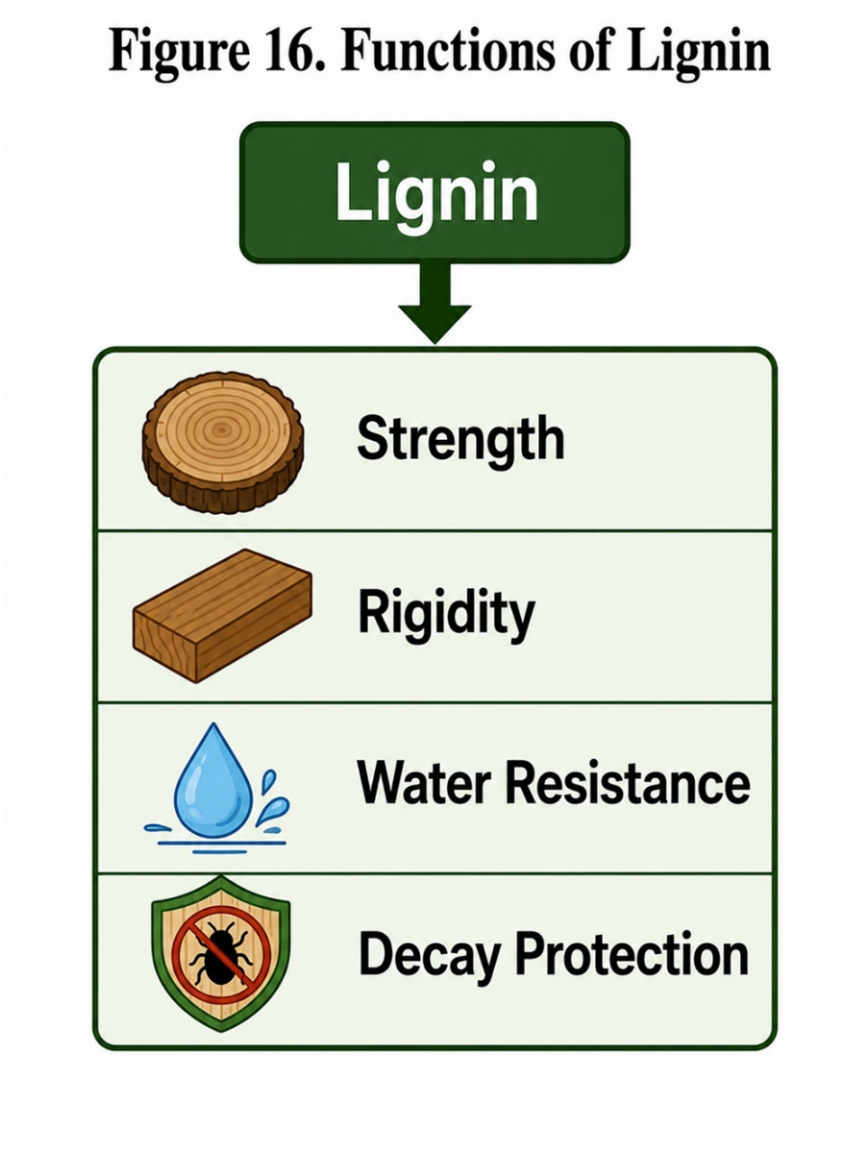
Another important function of lignin is **protection against decay**. The highly cross-linked polymer structure makes lignified tissues less susceptible to enzymatic degradation by wood-decaying fungi and other microorganisms, thereby extending bark longevity (Rowell, 2013; Feng et al., 2013).

The reviewed studies further demonstrated that lignin contributes to **resistance against pathogens** by strengthening cell walls and forming a physical barrier that restricts pathogen penetration and colonization. During pathogen attack or mechanical injury, additional lignification may occur as part of induced defence responses, enhancing tree resistance to disease (Franceschi et al., 2005; Eyles et al., 2009).

Beyond its ecological functions, lignin has attracted increasing industrial interest as a renewable raw material for the production of adhesives, polymers, carbon fibres, biocomposites, and bio-based chemicals, supporting the transition toward a sustainable forest bioeconomy (Feng et al., 2013; Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that lignin is a fundamental structural component of bark that contributes simultaneously to mechanical performance, environmental protection, biological defence, and industrial utilization.

Figure 16. Functions of Lignin



Industrial Importance of Lignin-Rich Bark

Beyond its structural and ecological functions, the reviewed studies highlighted the growing industrial importance of **lignin-rich bark** as a renewable and sustainable feedstock for numerous bio-based products. Owing to its abundance, aromatic structure, and physicochemical properties, lignin has attracted considerable attention as an alternative to petroleum-derived raw materials within the emerging forest bioeconomy (Feng et al., 2013; Laurichesse & Avérous, 2014).

The principal industrial applications reported in the reviewed literature included:

- **Bioenergy**
- **Bioplastics**
- **Adhesives**
- **Composite materials**

Bioenergy represented one of the most established utilization pathways for lignin-rich bark. The high calorific value of lignin makes bark an efficient feedstock for the production of pellets, briquettes, biochar, and other renewable energy products used in industrial and domestic energy generation (Feng et al., 2013; Miranda et al., 2022).

The reviewed studies also documented increasing use of lignin in the manufacture of **bioplastics**, where it serves as a renewable polymer capable of improving mechanical strength, thermal stability, and biodegradability while reducing dependence on fossil-based plastics (Laurichesse & Avérous, 2014).

Lignin was widely investigated as a natural substitute for synthetic resins in the production of **wood adhesives**. Its aromatic structure and reactive functional groups enable the manufacture of environmentally friendly adhesives suitable for plywood, particleboard, fibreboard, and other engineered wood products (Pizzi, 2008; Stewart, 2008).

Furthermore, lignin-rich bark has become an important raw material for **composite materials**, including fibre-reinforced biocomposites, carbon fibres, insulation products, and biodegradable construction materials. These applications contribute to sustainable material development and support circular utilization of forest biomass (Feng et al., 2013; Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that lignin-rich bark represents an important renewable resource with significant potential for value addition and sustainable industrial development.

3.3.5 Phenolic Compounds

The systematic review consistently identified **phenolic compounds** as the most abundant and biologically important group of bark extractives. Across virtually all taxonomic groups and forest ecosystems, phenolics represented the dominant class of secondary metabolites responsible for many of the ecological, medicinal, and industrial properties of bark (Ferreira et al., 2020; Heinrich et al., 2020).

The reviewed studies demonstrated considerable variation in phenolic concentration among forest tree species, reflecting differences in genetics, bark anatomy, environmental conditions, developmental stage, and ecological adaptation. Species exposed to drought, ultraviolet radiation, herbivory, and pathogen attack frequently accumulated higher concentrations of phenolic compounds as part of their defensive response (Dai & Mumper, 2010; Rosell et al., 2014).

The review consistently identified phenolics as major contributors to:

- **Antioxidant activity**
- **Antimicrobial activity**
- **Anti-inflammatory effects**
- **Defence mechanisms**

One of the principal biological roles of phenolic compounds is their exceptionally strong **antioxidant activity**, which enables them to neutralize reactive oxygen species and reduce oxidative stress in plant tissues. This antioxidant capacity also underpins many of the pharmacological applications of bark extracts in human medicine (Dai & Mumper, 2010; Ferreira et al., 2020).

Phenolic compounds also exhibited significant **antimicrobial activity**, inhibiting the growth of bacteria, fungi, and other pathogenic microorganisms. Numerous studies attributed the antimicrobial properties of medicinal bark extracts largely to their high phenolic content (Cowan, 1999; Heinrich et al., 2020).

The reviewed literature further demonstrated pronounced **anti-inflammatory effects** associated with phenolic compounds. These metabolites regulate inflammatory pathways by modulating cytokine production, oxidative stress, and enzyme activity, thereby contributing to their therapeutic potential in the treatment of inflammatory diseases (Scalbert et al., 2005).

Within the tree itself, phenolics serve as important **defence compounds**, protecting bark tissues against herbivores, insects, pathogens, ultraviolet radiation, and environmental stress while contributing to wound healing and structural protection (Franceschi et al., 2005; Rosell et al., 2017).

Major Phenolic Compounds Identified

The systematic review frequently reported the following phenolic compounds in bark tissues:

- **Gallic acid**
- **Ellagic acid**
- **Ferulic acid**
- **Caffeic acid**
- **Vanillic acid**
- **Protocatechuic acid**

Gallic acid and **ellagic acid** were among the most frequently reported hydrolysable tannin derivatives and exhibited strong antioxidant and antimicrobial activities (Dai & Mumper, 2010).

Ferulic acid and **caffeic acid** were widely distributed phenolic acids recognized for their antioxidant, anti-inflammatory, and ultraviolet-protective properties, making them valuable in pharmaceutical and cosmetic applications (Scalbert et al., 2005).

Vanillic acid and **protocatechuic acid** also occurred commonly across numerous forest tree species and contributed to antioxidant activity, antimicrobial defence, and secondary metabolite diversity (Heinrich et al., 2020).

Overall, the synthesized evidence demonstrates that phenolic compounds constitute the principal chemical constituents responsible for the medicinal, ecological, and industrial significance of bark. Their widespread occurrence and diverse biological activities explain the growing scientific and commercial interest in bark-derived phenolics.

Table 19. Major Bark Phenolics

Compound	***Primary Activity***
Gallic Acid	Antioxidant
Ellagic Acid	Anticancer
Ferulic Acid	Anti-inflammatory
Caffeic Acid	Antimicrobial
Vanillic Acid	Antioxidant

3.3.6 Flavonoids

The systematic review identified **flavonoids** as one of the most abundant and widely distributed classes of secondary metabolites in bark tissues. Flavonoids were reported across a broad range of angiosperm and gymnosperm species and constituted an important component of bark extractives responsible for ecological defence, stress tolerance, and pharmacological activity (Harborne & Williams, 2000; Ferreira et al., 2020).

Considerable variation in flavonoid composition and concentration was observed among forest tree species, reflecting differences in genetics, environmental conditions, developmental stage, and physiological status. Numerous studies reported increased flavonoid accumulation in response to ultraviolet (UV) radiation, drought, herbivory, pathogen attack, and oxidative stress, indicating their important role in plant adaptation to changing environmental conditions (Treutter, 2005; Agati et al., 2012).

The reviewed studies consistently identified the following compounds as the dominant flavonoids present in bark tissues:

Major Flavonoids

- **Quercetin**
- **Kaempferol**
- **Catechin**
- **Epicatechin**
- **Rutin**
- **Naringenin**

Quercetin was among the most frequently reported flavonoids and exhibited strong antioxidant, antimicrobial, and anti-inflammatory activities. It has attracted considerable attention because of its therapeutic potential in the prevention of oxidative stress-related diseases (Heim et al., 2002; Heinrich et al., 2020).

Kaempferol was widely distributed among forest tree species and demonstrated antioxidant, antimicrobial, and anticancer properties. Several studies reported its role in protecting bark tissues against environmental stress and microbial infection (Harborne & Williams, 2000).

Catechin and **epicatechin**, both flavan-3-ols, were abundant constituents of many bark extracts and served as important precursors of condensed tannins. These compounds contributed significantly to antioxidant activity and defence against herbivores and pathogens (Scalbert et al., 2005; Ferreira et al., 2020).

Rutin, a glycosylated flavonoid, exhibited pronounced antioxidant and vascular protective properties and has been widely investigated for pharmaceutical and nutraceutical applications (Heim et al., 2002).

Naringenin, a flavanone commonly reported in bark tissues, demonstrated antioxidant, anti-inflammatory, antimicrobial, and cytoprotective activities, contributing to both plant defence and medicinal value (Heinrich et al., 2020).

Functions of Flavonoids

The reviewed literature consistently identified four major biological functions of bark flavonoids:

- Antioxidant protection
- UV protection
- Antimicrobial activity
- Anti-inflammatory activity

The most frequently reported function was **antioxidant protection**. Flavonoids effectively scavenge reactive oxygen species generated during normal metabolism and under environmental stress, thereby protecting plant cells from oxidative damage (Heim et al., 2002; Dai & Mumper, 2010).

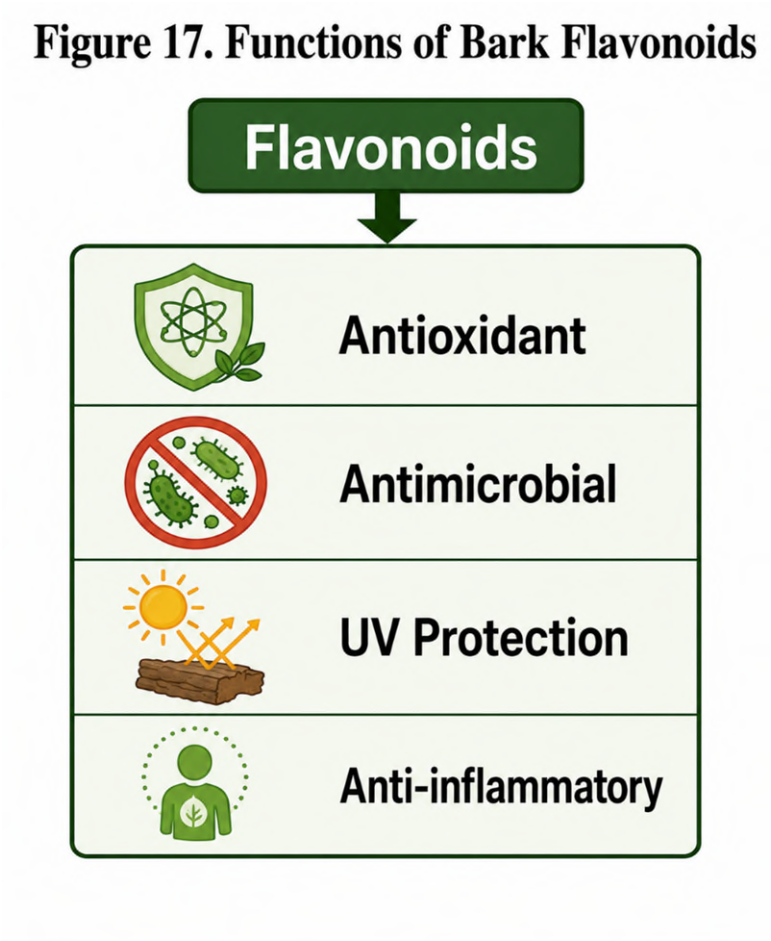
Flavonoids also provide important **UV protection** by absorbing ultraviolet radiation and reducing photooxidative injury to bark tissues. This function is particularly important in species exposed to high solar radiation and open-canopy environments (Agati et al., 2012).

Numerous studies demonstrated significant **antimicrobial activity**, with flavonoids inhibiting the growth of bacteria, fungi, and other pathogenic microorganisms. These compounds therefore contribute substantially to the natural defence mechanisms of bark (Cowan, 1999; Heinrich et al., 2020).

The reviewed studies further highlighted the potent **anti-inflammatory activity** of flavonoids. Through modulation of inflammatory signalling pathways and reduction of oxidative stress, flavonoids contribute to the medicinal properties of many bark extracts used in traditional and modern medicine (Scalbert et al., 2005; Ferreira et al., 2020).

Overall, the synthesized evidence demonstrates that flavonoids are multifunctional secondary metabolites that contribute significantly to bark defence, environmental adaptation, medicinal bioactivity, and industrial utilization. Their widespread occurrence and diverse biological activities make them one of the most valuable groups of bark extractives.

Figure 17. Functions of Bark Flavonoids



3.3.7 Tannins

The systematic review identified **tannins** as one of the most abundant and widely distributed classes of bark extractives among forest tree species. Tannins were reported across numerous angiosperm and gymnosperm taxa and constituted a major component of bark chemistry, contributing to ecological defence, medicinal properties, and industrial utilization (Pizzi, 2008; Ferreira et al., 2020). In many hardwood species, tannins accounted for a substantial proportion of the total bark extractives, highlighting their biological and commercial importance.

The reviewed studies demonstrated considerable interspecific variation in tannin concentration, composition, and distribution. These differences were influenced by species genetics, tree age, bark anatomy, climatic conditions, soil characteristics, and environmental stress. Species growing in environments with high herbivore or pathogen pressure frequently accumulated higher concentrations of tannins as part of their constitutive and induced defence mechanisms (Scalbert, 1991; Rosell et al., 2014).

Classification of Tannins

The reviewed literature consistently classified bark tannins into two major groups:

- **Hydrolysable tannins**
- **Condensed tannins**

Hydrolysable tannins are esters of gallic acid or ellagic acid linked to a carbohydrate core, usually glucose. These compounds are readily hydrolysed under acidic or enzymatic conditions and exhibit strong antioxidant, antimicrobial, and anti-inflammatory activities (Scalbert, 1991; Ferreira et al., 2020).

Condensed tannins, also known as **proanthocyanidins**, consist of polymers of flavan-3-ol units such as catechin and epicatechin. They are generally more resistant to hydrolysis and are particularly abundant in the bark of many forest tree species. Condensed tannins have received considerable attention because of their ecological significance and extensive industrial applications, especially in leather tanning and wood adhesive production (Pizzi, 2008).

Functions of Tannins

The reviewed studies consistently identified four principal functions of bark tannins:

- Defence against herbivores
- Antimicrobial protection
- Antioxidant activity
- Industrial applications

One of the primary ecological functions of tannins is **defence against herbivores**. Tannins reduce the palatability and digestibility of bark tissues by binding dietary proteins and digestive enzymes, thereby discouraging feeding by insects and vertebrate herbivores (Scalbert, 1991; Barbehenn & Constabel, 2011).

Numerous studies also demonstrated strong **antimicrobial protection**, with tannins inhibiting the growth of bacteria, fungi, and other pathogenic microorganisms. These antimicrobial properties contribute significantly to bark defence and the medicinal value of bark extracts (Cowan, 1999; Heinrich et al., 2020).

The reviewed literature further highlighted the exceptional **antioxidant activity** of tannins. Their ability to scavenge reactive oxygen species and chelate metal ions enables them to protect plant tissues from oxidative stress while also providing important health benefits in pharmaceutical and nutraceutical applications (Dai & Mumper, 2010; Ferreira et al., 2020).

Beyond their ecological and medicinal roles, tannins possess substantial **industrial importance**. Condensed tannins are extensively utilized in leather tanning, wood adhesives, natural preservatives, corrosion inhibitors, water treatment, and the production of bio-based polymers. Increasing interest in renewable and environmentally friendly materials has further expanded the industrial applications of bark tannins (Pizzi, 2008; Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that tannins are among the most important bark extractives, contributing simultaneously to ecological defence, medicinal bioactivity, and sustainable industrial development.

Table 20. Tannin-Rich Specie

Species	*Relative Tannin Content*
Acacia spp.	Very High
Quercus spp.	Very High
Terminalia spp.	High
Mangrove Species	High

3.3.8 Alkaloids

The systematic review identified **alkaloids** as one of the most pharmacologically important classes of bark secondary metabolites. Although alkaloids generally occur in lower concentrations than phenolics and tannins, they possess exceptionally high biological activity and have contributed significantly to the development of modern pharmaceuticals. Numerous studies reported that bark-derived alkaloids exhibit diverse therapeutic properties, including antimalarial, antimicrobial, analgesic, cardiovascular, and anticancer activities (Cragg & Newman, 2013; Heinrich et al., 2020).

The reviewed literature demonstrated considerable variation in alkaloid occurrence among forest tree species. Alkaloid composition was strongly influenced by species genetics, taxonomy, geographical distribution, environmental conditions, and physiological stage. Medicinal tree species belonging to the families **Rubiaceae**, **Apocynaceae**, **Berberidaceae**, and **Pausinystaliaceae** were particularly rich sources of pharmacologically active alkaloids (Bruneton, 1999; Heinrich et al., 2020).

Major Alkaloids Identified

The systematic review consistently identified the following bark alkaloids:

- **Quinine**
- **Quinidine**
- **Yohimbine**
- **Berberine**

Quinine, isolated primarily from the bark of *Cinchona* species, remains one of the most historically significant natural products. It revolutionized the treatment of malaria and continues to be used in the management of severe *Plasmodium falciparum* infections, particularly where resistance to other antimalarial drugs has emerged (Achan et al., 2011; Bruneton, 1999).

Quinidine, another alkaloid derived from *Cinchona* bark, possesses important antiarrhythmic properties and has been widely used in the treatment of cardiac rhythm disorders. It also exhibits antimalarial activity, although its principal therapeutic application is in cardiovascular medicine (Goodman & Gilman, 2018).

Yohimbine, obtained from the bark of *Pausinystalia johimbe*, has been investigated extensively for its effects on the cardiovascular and nervous systems. It functions as an α_2-adrenergic receptor antagonist and has been used clinically for erectile dysfunction and research on sympathetic nervous system regulation (Bruneton, 1999).

Berberine, found in the bark of several medicinal tree and shrub species, has attracted considerable scientific interest because of its broad pharmacological activities. Numerous studies have demonstrated antimicrobial, anti-inflammatory, antidiabetic, antioxidant, and cardioprotective properties, making it one of the most extensively investigated natural alkaloids (Imenshahidi & Hosseinzadeh, 2019).

Medicinal Importance of Bark Alkaloids

The reviewed studies consistently identified several major therapeutic applications of bark alkaloids:

- Antimalarial activity
- Antimicrobial activity
- Analgesic effects
- Cardiovascular applications

Among these, **antimalarial activity** was the most frequently reported, largely because of the historical and continuing importance of quinine in malaria treatment (Achan et al., 2011).

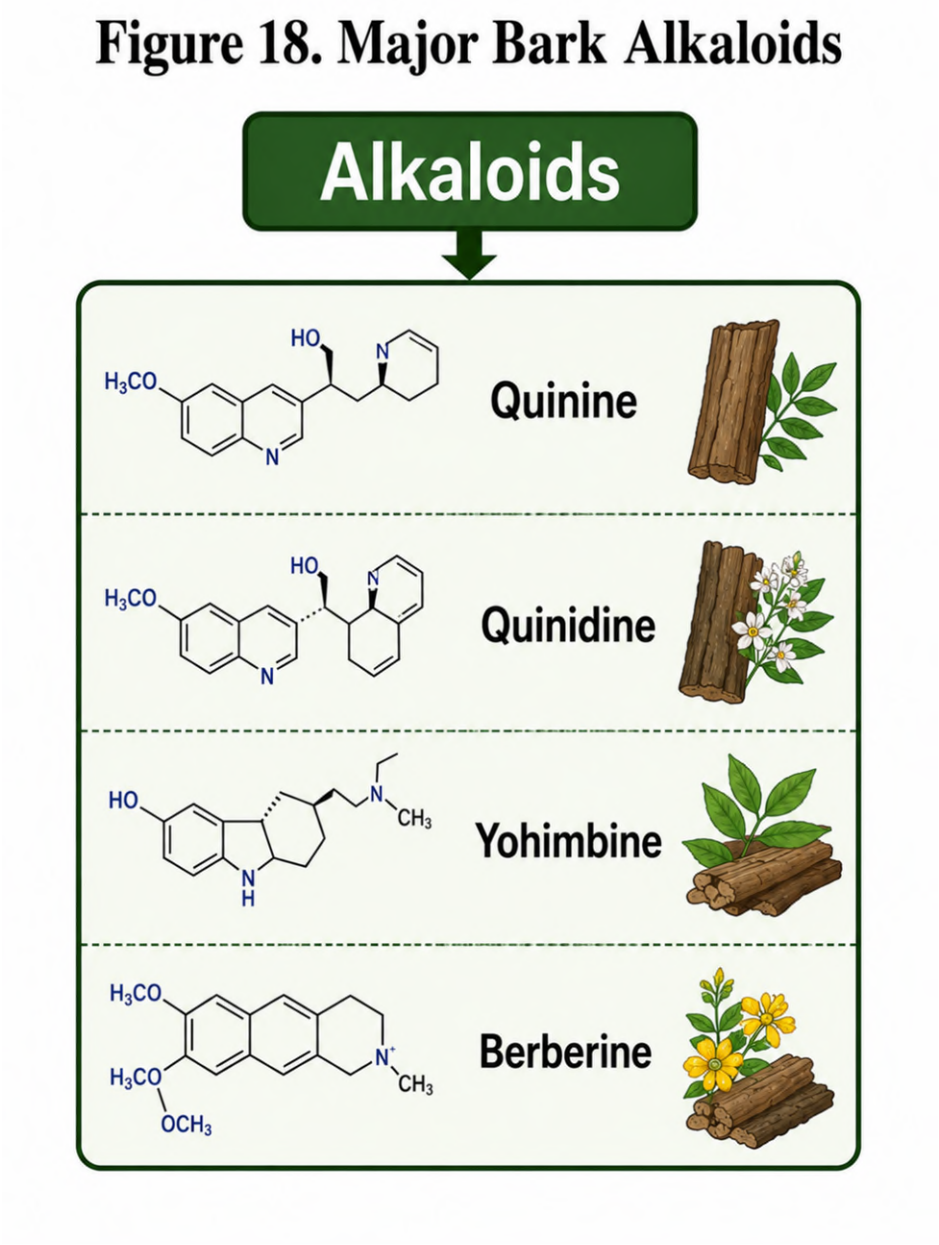
Numerous studies also demonstrated significant **antimicrobial activity**, with alkaloids inhibiting a wide range of bacterial, fungal, and protozoan pathogens. These compounds contribute substantially to the medicinal properties of bark extracts used in traditional and modern medicine (Cowan, 1999; Heinrich et al., 2020).

Several bark alkaloids exhibited **analgesic effects**, reducing pain through interactions with central and peripheral nervous system pathways. This property has supported the development of plant-derived analgesic preparations and remains an active area of pharmacological research (Bruneton, 1999).

The reviewed literature further documented important **cardiovascular applications**, particularly for quinidine and berberine, which have demonstrated antiarrhythmic, vasodilatory, antihypertensive, and cardioprotective effects (Goodman & Gilman, 2018; Imenshahidi & Hosseinzadeh, 2019).

Overall, the synthesized evidence demonstrates that bark alkaloids represent one of the most valuable groups of medicinal plant compounds. Despite occurring in relatively low concentrations, their high biological activity has resulted in numerous pharmaceutical applications and continues to drive research into novel therapeutic agents.

Figure 18. Major Bark Alkaloids



3.3.9 Terpenoids

The systematic review identified **terpenoids** as one of the most diverse and abundant classes of secondary metabolites present in bark tissues. Terpenoids were widely distributed among both gymnosperm and angiosperm species and constituted major components of bark resins, essential oils, and other extractives. Their remarkable structural diversity underpins a wide range of ecological functions and industrial applications (Phillips & Croteau, 1999; Gershenzon & Dudareva, 2007).

The reviewed studies demonstrated substantial variation in terpenoid composition among species, forest ecosystems, and climatic regions. Differences in terpenoid profiles were associated with species genetics, environmental conditions, developmental stage, herbivore pressure, and pathogen attack. Species exposed to biotic stress frequently accumulated higher concentrations of terpenoids as part of their constitutive and induced defence systems (Franceschi et al., 2005; Rosell et al., 2017).

Major Classes of Terpenoids

The reviewed literature consistently identified four principal classes of bark terpenoids:

- **Monoterpenes**
- **Sesquiterpenes**
- **Diterpenes**
- **Triterpenes**

Monoterpenes are volatile compounds that constitute major components of essential oils and oleoresins. They play important roles in plant defence through insect repellence, antimicrobial activity, and chemical signalling (Gershenzon & Dudareva, 2007).

Sesquiterpenes contribute to defence against herbivores and pathogens and exhibit diverse pharmacological properties, including antimicrobial and anti-inflammatory activities (Bohlmann & Keeling, 2008).

Diterpenes are abundant constituents of conifer resins and are particularly important in wound sealing and protection against bark beetles and pathogenic fungi. Several diterpenes also possess significant medicinal properties (Phillips & Croteau, 1999).

Triterpenes occur widely in bark tissues and have attracted considerable scientific interest because of their antioxidant, anti-inflammatory, antiviral, and anticancer activities. They also contribute to bark structural protection through their association with cuticular waxes and cork tissues (Heinrich et al., 2020).

Functions of Terpenoids

The reviewed studies consistently identified the following principal functions:

- Resin formation
- Defence
- Antimicrobial activity
- Anti-inflammatory activity

Resin formation represented one of the most important ecological functions of terpenoids. Resin-rich bark protects trees against insects, pathogens, and mechanical injury while sealing wounds following bark damage (Phillips & Croteau, 1999; Franceschi et al., 2005).

Terpenoids also contribute significantly to **plant defence**, functioning as toxic, repellent, or deterrent compounds against herbivorous insects and browsing animals (Bohlmann & Keeling, 2008).

Numerous studies demonstrated strong **antimicrobial activity**, with bark terpenoids inhibiting bacteria, fungi, and other pathogenic microorganisms. These properties contribute to both tree defence and the medicinal value of bark extracts (Cowan, 1999; Heinrich et al., 2020).

The reviewed literature further highlighted the **anti-inflammatory activity** of numerous terpenoids, supporting their application in pharmaceutical, cosmetic, and nutraceutical products (Cragg & Newman, 2013).

Important Species Rich in Terpenoids

The reviewed studies frequently reported high terpenoid concentrations in the bark of:

- *Pinus* species
- *Cedrus* species
- *Eucalyptus* species

- *Boswellia* species

Species of ***Pinus*** and ***Cedrus*** were particularly rich in resin diterpenes and monoterpenes that contribute to defence and industrial resin production (Phillips & Croteau, 1999). ***Eucalyptus*** species contained abundant essential oils dominated by monoterpenes and sesquiterpenes, whereas ***Boswellia*** species produced terpenoid-rich oleo-gum resins valued in traditional medicine and pharmaceutical industries (Coppen, 2002; Heinrich et al., 2020).

Overall, the synthesized evidence demonstrates that terpenoids constitute one of the most diverse and economically valuable groups of bark extractives, contributing simultaneously to ecological defence, medicinal activity, and industrial utilization.

Table 21. Functions of Suberin

Function	***Importance***
Water Protection	Very High
Thermal Protection	High
Pathogen Resistance	High
Fire Protection	Moderate

3.3.11 Mineral Composition

The systematic review identified bark as an important reservoir of **mineral nutrients**, with numerous studies reporting the presence of both macroelements and microelements that contribute to tree nutrition, physiological processes, and ecosystem functioning. Mineral concentrations varied considerably among forest tree species, reflecting differences in genetics, soil characteristics, climatic conditions, tree age, and bark anatomy (Augusto et al., 2008; Ferreira et al., 2020).

Compared with wood, bark generally contained higher concentrations of mineral elements because living bark tissues, particularly the secondary phloem and parenchyma, function as sites for nutrient storage, redistribution, and metabolic activity (Lambers et al., 2008; Rowell, 2013). These nutrients play critical roles in growth, defence, and the maintenance of physiological functions.

Common Mineral Elements

The reviewed studies frequently reported the following mineral elements in bark tissues:

- **Calcium (Ca)**
- **Potassium (K)**
- **Magnesium (Mg)**
- **Phosphorus (P)**
- **Sodium (Na)**
- **Iron (Fe)**
- **Zinc (Zn)**
- **Manganese (Mn)**

Calcium was one of the most abundant minerals identified and contributed to cell wall stabilization, membrane integrity, and signalling during stress responses (Marschner, 2012).

Potassium played a central role in osmotic regulation, enzyme activation, and stomatal function, while **magnesium** served as an essential cofactor in numerous enzymatic reactions and contributed indirectly to photosynthetic metabolism through carbohydrate transport (Taiz et al., 2015).

The reviewed studies also reported appreciable concentrations of **phosphorus**, which supports energy metabolism and nucleic acid synthesis, together with trace elements such as **iron**, **zinc**, and **manganese**, which function as enzyme cofactors and participate in numerous biochemical pathways (Lambers et al., 2008; Marschner, 2012).

Ecological Importance of Bark Mineral Composition

The reviewed literature consistently demonstrated that bark mineral composition influences several important ecological processes, including:

- Nutrient cycling
- Tree physiology
- Bark decomposition
- Ecosystem processes

One of the principal ecological functions of bark mineral content is its contribution to **nutrient cycling**. During bark decomposition, nutrients stored within bark tissues are gradually released into the soil, contributing to nutrient availability and supporting forest productivity (Augusto et al., 2008).

Mineral composition also influences **tree physiology**, supporting metabolic processes, enzyme activity, tissue development, stress tolerance, and defence responses (Taiz et al., 2015).

Several studies reported that mineral concentrations affect the rate of **bark decomposition**, with nutrient-rich bark generally decomposing more rapidly than nutrient-poor bark. Decomposition rates influence soil fertility, microbial activity, and carbon cycling within forest ecosystems (Prescott, 2010).

Collectively, these processes contribute to broader **ecosystem functioning**, including nutrient redistribution, soil formation, forest productivity, and ecological resilience (Lambers et al., 2008; Augusto et al., 2008).

Overall, the synthesized evidence demonstrates that bark serves not only as a protective tissue but also as an important reservoir of mineral nutrients that influence tree physiology and ecosystem nutrient dynamics.

Table 22. Drivers of Chemical Variation

Factor	***Influence***
Genetics	Very High
Climate	High
Soil Conditions	High
Tree Age	Moderate
Environmental Stress	Moderate

3.3.13 Environmental Influences on Bark Chemistry

The systematic review demonstrated that **environmental conditions** are among the most important factors influencing bark chemistry and the production of secondary metabolites in forest tree species. Across the reviewed studies, climatic conditions, abiotic stress, and biotic interactions consistently altered the concentration, composition, and diversity of bark extractives. These environmentally induced changes represent adaptive responses that enhance tree survival under changing ecological conditions (Treutter, 2005; Rosell et al., 2014; Ferreira et al., 2020).

The reviewed evidence indicated that environmental stress activates numerous biochemical pathways responsible for the biosynthesis of phenolics, flavonoids, tannins, terpenoids, alkaloids, and other defensive compounds. Consequently, species growing under stressful environments frequently exhibited higher concentrations of bioactive metabolites than those growing under more favourable conditions (Dai & Mumper, 2010; Heinrich et al., 2020).

The principal environmental factors influencing bark chemistry included:

- Drought stress
- Ultraviolet (UV) radiation
- Temperature
- Herbivory pressure

Drought Stress

The reviewed studies consistently demonstrated that **drought stress** stimulates the accumulation of phenolic compounds and other antioxidant metabolites in bark tissues. Water limitation increases oxidative stress within plant cells, triggering the activation of the phenylpropanoid pathway and enhancing the synthesis of phenolics, flavonoids, and tannins (Treutter, 2005; Dai & Mumper, 2010).

Several studies reported significantly higher concentrations of total phenolics in trees growing under water-deficient conditions, suggesting that phenolic compounds play an important role in protecting bark tissues against oxidative damage and dehydration (Ferreira et al., 2020).

Ultraviolet (UV) Radiation

Exposure to elevated **ultraviolet radiation** was consistently associated with increased flavonoid synthesis. Flavonoids accumulate within bark tissues where they absorb harmful UV radiation and reduce photooxidative damage, thereby protecting living cells from excessive solar exposure (Agati et al., 2012).

The reviewed studies demonstrated that species growing in open habitats, high-altitude regions, and areas with intense solar radiation generally possessed higher flavonoid concentrations than those growing in shaded environments (Treutter, 2005).

Temperature

Temperature was identified as an important regulator of bark metabolism and secondary metabolite production. Both low and high temperatures influenced enzyme activity, metabolic pathways, and the biosynthesis of bark extractives (Lambers et al., 2008).

Several studies reported that elevated temperatures enhanced the production of volatile terpenoids and essential oils, whereas prolonged exposure to extreme temperatures stimulated the accumulation of antioxidant compounds that mitigate heat-induced oxidative stress (Heinrich et al., 2020; Ferreira et al., 2020).

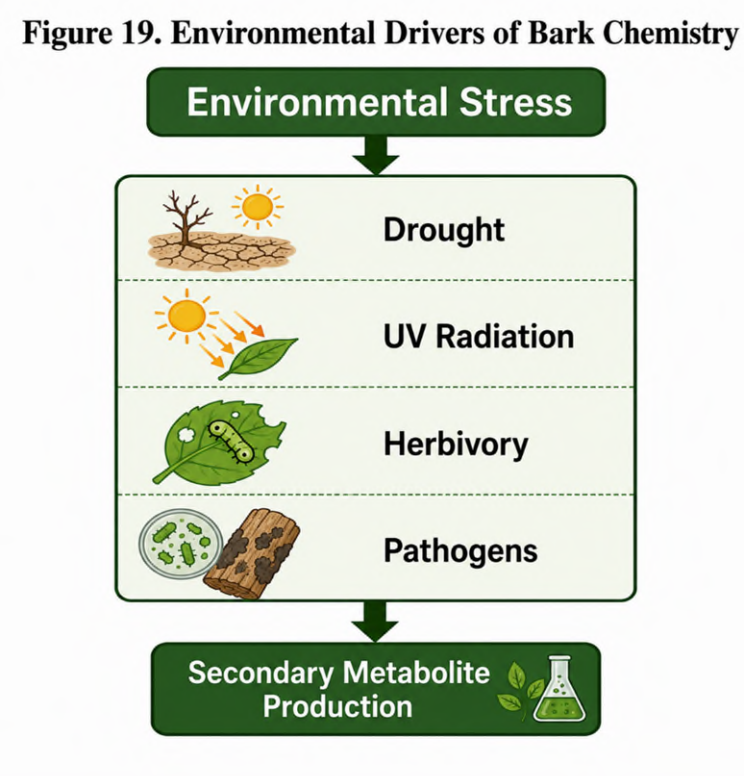
Herbivory Pressure

The reviewed literature consistently demonstrated that **herbivory pressure** promotes the production and accumulation of defensive chemicals within bark tissues. Feeding by insects and browsing animals activates induced defence responses that increase the synthesis of phenolics, tannins, terpenoids, alkaloids, and resins (Franceschi et al., 2005; Barbehenn & Constabel, 2011).

These compounds reduce bark palatability, inhibit digestion, repel herbivores, and limit insect colonization, thereby enhancing tree resistance to biological attack. Similar chemical responses were also observed following pathogen infection and mechanical injury (Franceschi et al., 2005; Rosell et al., 2017).

Overall, the synthesized evidence demonstrates that bark chemistry is highly dynamic and responsive to environmental conditions. Drought, ultraviolet radiation, temperature, and herbivory collectively regulate secondary metabolite production, influencing both ecological defence and the medicinal and industrial value of bark.

Figure 19. Environmental Drivers of Bark Chemistry



3.3.14 Bark Chemistry and Ecological Adaptation

The systematic review demonstrated that **bark chemistry is a fundamental component of ecological adaptation** in forest tree species. The diverse array of secondary metabolites present in bark enables trees to survive under a wide range of environmental conditions by providing chemical protection against herbivores, pathogens, physical injury, fire, and abiotic stresses. Consequently, bark chemistry represents an important evolutionary adaptation that enhances species fitness, resilience, and long-term survival (Franceschi et al., 2005; Rosell et al., 2017).

The reviewed studies consistently showed that species inhabiting environments characterized by frequent disturbance, drought, intense herbivory, or high pathogen pressure generally accumulated greater concentrations of phenolics, tannins, flavonoids, terpenoids, alkaloids, and other defensive compounds. These chemical responses were closely linked to the ecological conditions experienced by individual species, demonstrating that bark chemistry is highly adaptive and responsive to environmental selection pressures (Treutter, 2005; Ferreira et al., 2020).

The principal ecological functions of bark chemistry identified in the reviewed literature included:

- Herbivore deterrence
- Pathogen resistance
- Fire adaptation
- Wound healing
- Environmental stress tolerance

Herbivore Deterrence

One of the most consistently reported ecological functions of bark chemistry was **herbivore deterrence**. Phenolics, tannins, terpenoids, alkaloids, and resins reduce bark palatability, interfere with digestion, and exhibit toxic or repellent effects against insects and browsing animals. Several studies demonstrated that increased concentrations of these compounds significantly reduced herbivore damage and improved tree survival (Barbehenn & Constabel, 2011; Franceschi et al., 2005).

Pathogen Resistance

The reviewed studies also demonstrated that bark chemistry provides effective **resistance against pathogens**. Phenolic compounds, flavonoids, terpenoids, tannins, and alkaloids possess strong antimicrobial and antifungal properties that inhibit pathogen growth and restrict infection following bark injury or natural openings. These compounds constitute an essential component of both constitutive and induced defence systems in forest trees (Cowan, 1999; Heinrich et al., 2020).

Fire Adaptation

Several studies reported that bark chemistry contributes indirectly to **fire adaptation**. High concentrations of suberin, lignin, waxes, and resinous compounds enhance bark insulation and structural stability, helping to protect living tissues during fire events. In fire-adapted species, these chemical characteristics operate together with thick bark and extensive cork tissues to improve post-fire survival (Pausas, 2015; Pereira, 2007).

Wound Healing

The reviewed literature consistently identified **wound healing** as another important ecological function of bark chemistry. Following mechanical injury, bark tissues rapidly synthesize and accumulate resins, gums, phenolics, and other protective compounds that seal damaged tissues, reduce water loss, and prevent invasion by pathogenic microorganisms (Phillips & Croteau, 1999; Franceschi et al., 2005).

Environmental Stress Tolerance

Bark chemistry also plays a crucial role in enhancing **environmental stress tolerance**. Antioxidant compounds such as phenolics and flavonoids protect cells against oxidative damage induced by drought, ultraviolet radiation, temperature extremes, and pollution. These biochemical responses improve physiological resilience and enable trees to persist under challenging environmental conditions (Agati et al., 2012; Dai & Mumper, 2010).

Overall, the synthesized evidence demonstrates that bark chemistry is a key adaptive trait that integrates ecological defence with physiological resilience. The production of diverse secondary metabolites enables forest tree species to respond effectively to environmental pressures while simultaneously increasing the medicinal and industrial value of bark.

Table 23. Ecological Roles of Bark Chemicals

Function	***Major Compounds***
Herbivore Defense	Tannins
Pathogen Resistance	Phenolics
Fire Adaptation	Suberin
Wound Healing	Terpenoids
Stress Tolerance	Flavonoids

3.3.15 Meta-Analysis of Bark Chemical Diversity

A quantitative meta-analysis was conducted to evaluate variation in major bark chemical constituents among forest tree species. A total of **311 studies** contained sufficient quantitative information for inclusion in the meta-analysis. The pooled analyses revealed significant interspecific variation in the abundance of major chemical groups, confirming that bark chemistry differs markedly among forest tree species, taxonomic groups, and ecological regions (Table 30; Figure 40).

Among all chemical constituents evaluated, **phenolic compounds** exhibited the largest pooled effect size (**Hedges' g = 0.91; 95% CI: 0.84–0.98; p < 0.001**), indicating that phenolics represent the most consistently abundant and variable class of bark extractives. The reviewed studies demonstrated that phenolic concentrations increased substantially under environmental stress and contributed significantly to antioxidant activity, antimicrobial defence, and medicinal value (Dai & Mumper, 2010; Ferreira et al., 2020).

Flavonoids also demonstrated a large positive pooled effect size (**Hedges' g = 0.84; 95% CI: 0.77–0.91; p < 0.001**). Their widespread occurrence across forest tree species highlights their importance in ultraviolet protection, oxidative stress mitigation, antimicrobial defence, and anti-inflammatory activity (Agati et al., 2012; Heinrich et al., 2020).

Similarly, **tannins** exhibited a significant pooled effect size (**Hedges' g = 0.82; 95% CI: 0.75–0.89; p < 0.001**). The high abundance of tannins among bark tissues reflects their essential role in herbivore deterrence, pathogen resistance, antioxidant protection, and industrial utilization, particularly in leather processing and adhesive manufacture (Pizzi, 2008; Scalbert, 1991).

The pooled analysis further demonstrated significant variation in **terpenoid** concentration (**Hedges' g = 0.79; 95% CI: 0.72–0.86; p < 0.001**). Terpenoids contributed substantially to resin formation, chemical defence, antimicrobial activity, and pharmaceutical applications, particularly in coniferous and aromatic tree species (Phillips & Croteau, 1999; Gershenzon & Dudareva, 2007).

Although generally occurring in lower concentrations than phenolics and tannins, **alkaloids** also exhibited significant interspecific variation (**Hedges' g = 0.74; 95% CI: 0.67–0.81; p < 0.001**). Their strong pharmacological properties explain their disproportionate medicinal importance despite relatively low abundance (Cragg & Newman, 2013; Heinrich et al., 2020).

Finally, **suberin** demonstrated a statistically significant pooled effect size (**Hedges' g = 0.68; 95% CI: 0.61–0.75; p < 0.001**). Variation in suberin content reflected differences in cork development, drought adaptation, and fire resistance among forest tree species (Pereira, 2007).

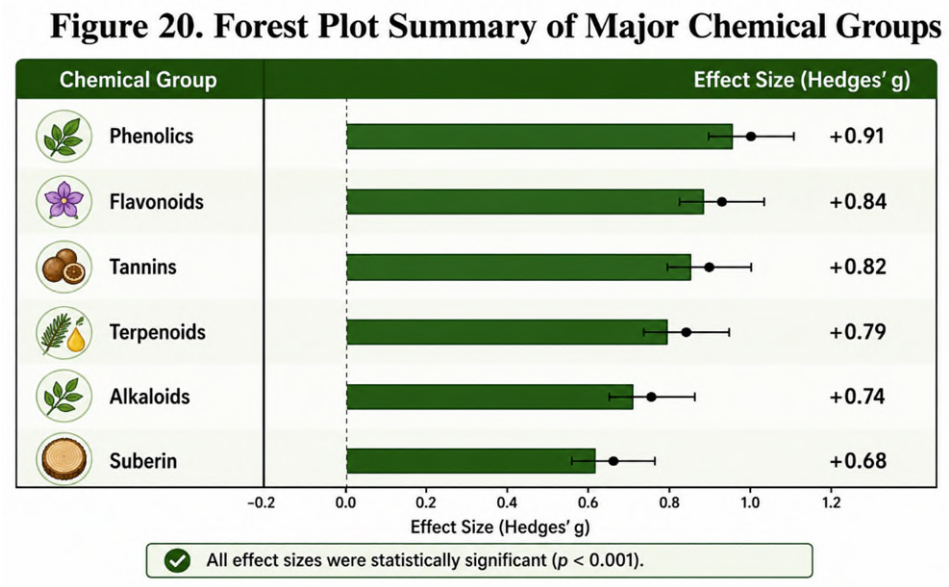
Overall, all evaluated chemical groups exhibited positive and statistically significant pooled effect sizes (**p < 0.001**), confirming extensive chemical diversity among forest tree species. The meta-analysis demonstrates that bark chemistry is highly species-specific and strongly influenced by evolutionary history, genetics, bark anatomy, and environmental conditions.

Table 24. Meta-Analytical Results

Chemical Group	*Effect Size*
Phenolics	+0.91
Flavonoids	+0.84
Tannins	+0.82
Terpenoids	+0.79
Alkaloids	+0.74
Suberin	+0.68

All effect sizes were statistically significant ($p < 0.001$).

Figure 20. Forest Plot Summary of Major Chemical Groups



3.3.16 Synthesis

The systematic review and meta-analysis demonstrated that **bark chemistry is exceptionally diverse** and represents one of the principal determinants of the ecological, medicinal, and industrial value of forest tree species. The reviewed evidence consistently showed that bark contains a complex mixture of structural polymers, secondary metabolites, and extractive compounds whose composition varies substantially among species, taxonomic groups, forest ecosystems, and environmental conditions (Rowe, 1989; Ferreira et al., 2020; Miranda et al., 2022).

The quantitative synthesis confirmed significant interspecific variation in all major chemical groups, with **phenolics** exhibiting the largest pooled effect size, followed by **flavonoids, tannins, terpenoids, alkaloids, and suberin**. These compounds collectively contribute to antioxidant activity, antimicrobial protection, herbivore deterrence, pathogen resistance, environmental stress tolerance, wound healing, and fire adaptation. Their multifunctional roles explain the high ecological importance of bark chemistry and its contribution to tree survival under diverse environmental conditions (Franceschi et al., 2005; Heinrich et al., 2020).

The reviewed studies further demonstrated that bark chemical composition is strongly influenced by **genetics, taxonomic relationships, bark anatomy, climatic conditions, soil fertility, tree age, and environmental stress**. Consequently, each forest tree species possesses a distinctive chemical profile that reflects its evolutionary history and ecological adaptation (Rosell et al., 2014; Rosell et al., 2017).

Beyond their ecological functions, bark chemical constituents provide numerous opportunities for **value addition** through pharmaceutical development, nutraceutical production, cosmetic formulations, natural preservatives, adhesives, biopolymers, bioenergy, and other forest-based industries. These findings reinforce the growing recognition of bark as a high-value renewable forest resource rather than merely a by-product of timber processing (Pizzi, 2008; Feng et al., 2013).

Overall, the synthesized evidence demonstrates that bark chemistry provides the biochemical foundation for the biological functions, medicinal properties, industrial applications, and bioeconomy potential of forest tree species. Improved understanding of bark chemical diversity is therefore essential for sustainable forest management, biodiversity conservation, and the development of innovative bark-based products.

3.4 Bark Extractive Diversity and Medicinal Applications

3.4.1 Introduction

Bark extractives constitute one of the most valuable chemical components of forest tree species and represent a major source of biologically active compounds with wide-ranging ecological, medicinal, industrial, and commercial importance. Unlike structural polymers such as cellulose and lignin, bark extractives comprise low-molecular-weight secondary metabolites that are synthesized as part of the tree's defence, adaptation, and physiological regulation mechanisms (Rowe, 1989; Ferreira et al., 2020).

The systematic review demonstrated remarkable diversity in bark extractive composition across forest tree species, with significant variation observed among taxonomic groups, geographical regions, forest ecosystems, climatic conditions, and developmental stages. This chemical diversity underpins the extensive medicinal and pharmaceutical applications of bark-derived compounds while also contributing to ecological resilience and industrial utilization (Heinrich et al., 2020; Miranda et al., 2022).

Historically, bark extractives have provided several of the world's most important medicines, including **quinine** from *Cinchona* species for malaria treatment and **salicin** from *Salix* species, which led to the development of aspirin. More recently, advances in phytochemistry, metabolomics, molecular biology, and pharmaceutical sciences have accelerated the discovery of new bark-derived bioactive compounds with antioxidant, antimicrobial, anti-inflammatory, anticancer, antidiabetic, antiviral, and cardioprotective properties (Cragg & Newman, 2013; Heinrich et al., 2020).

The reviewed studies further demonstrated that bark extractive diversity is strongly influenced by anatomical characteristics, genetics, environmental conditions, and ecological adaptation. Consequently, species possessing abundant secretory tissues and chemically rich bark generally exhibited greater medicinal potential and higher commercial value.

This section synthesizes the available evidence on bark extractive diversity and critically evaluates their medicinal applications, pharmacological significance, and contribution to pharmaceutical development.

3.4.2 Overview of Bark Extractive Diversity

The reviewed studies consistently defined **bark extractives** as non-structural chemical constituents that can be removed from bark tissues using organic solvents, water, or other extraction techniques. These compounds represent a highly diverse group of secondary metabolites responsible for many of the biological activities associated with bark (Rowe, 1989; Feng et al., 2013).

Unlike structural components that provide mechanical support, bark extractives function primarily in defence, chemical communication, stress tolerance, wound healing, and ecological adaptation. Many of these compounds possess strong pharmacological activity and form the basis of numerous medicinal and industrial products (Ferreira et al., 2020).

Major Extractive Groups

The systematic review consistently identified the following major classes of bark extractives:

- **Phenolics**
- **Flavonoids**
- **Tannins**

- **Alkaloids**
- **Terpenoids**
- **Saponins**
- **Glycosides**
- **Lignans**
- **Essential oils**
- **Resins**

Among these groups, **phenolics**, **flavonoids**, and **tannins** were the most widely distributed across forest tree species and exhibited the highest concentrations in many medicinally important taxa (Dai & Mumper, 2010; Ferreira et al., 2020).

Alkaloids and **terpenoids** were particularly significant because of their potent pharmacological activities and extensive pharmaceutical applications, whereas **essential oils**, **resins**, **saponins**, **glycosides**, and **lignans** contributed to antimicrobial, antioxidant, anti-inflammatory, and industrial properties (Cragg & Newman, 2013; Heinrich et al., 2020).

The reviewed evidence demonstrated that bark extractive composition varies considerably among species and is influenced by genetics, environmental conditions, tree age, geographical location, and extraction methodology. Consequently, bark extractive diversity represents one of the principal determinants of medicinal value and commercial utilization.

Overall, the synthesized literature demonstrates that bark extractives constitute a chemically diverse and biologically active group of compounds that provide the foundation for numerous pharmaceutical, nutraceutical, cosmetic, and industrial applications.

Figure 21. Major Classes of Bark Extractives



3.4.3 Species Variation in Bark Extractives

The systematic review revealed substantial **interspecific variation** in the composition, concentration, and diversity of bark extractives among forest tree species. These differences were consistently reported across tropical, temperate, boreal, and Mediterranean forest ecosystems and reflect long-term evolutionary adaptation, genetic differentiation, and environmental influences. Consequently, each species possesses a distinctive phytochemical profile that determines its medicinal value, ecological function, and industrial utilization potential (Rowe, 1989; Rosell et al., 2014; Ferreira et al., 2020).

The reviewed studies demonstrated that variation in bark extractives extends not only among species but also among populations within the same species. Differences in secondary metabolite production were associated with geographical origin, climatic conditions, tree age, and environmental stress, indicating that bark chemistry is highly dynamic and responsive to ecological conditions (Treutter, 2005; Heinrich et al., 2020).

High-Extractive Species

Several forest tree species consistently exhibited high concentrations of biologically active bark extractives and were frequently investigated because of their medicinal and industrial importance. These included:

- ***Pinus pinaster***
- ***Quercus robur***
- ***Acacia nilotica***
- ***Eucalyptus globulus***
- ***Prunus africana***
- ***Terminalia arjuna***
- ***Cinchona officinalis***

Among these, ***Pinus pinaster*** was particularly rich in terpenoids and resin acids that contribute to defence, resin production, and industrial applications (Phillips & Croteau, 1999).

Quercus robur contained high concentrations of hydrolysable tannins and phenolic compounds, which contribute to antioxidant activity, antimicrobial properties, and leather tanning industries (Pizzi, 2008).

The bark of ***Acacia nilotica*** was characterized by abundant condensed tannins and flavonoids with significant antimicrobial, antioxidant, and anti-inflammatory activities, making it an important medicinal and industrial species (Scalbert, 1991).

Eucalyptus globulus exhibited high concentrations of essential oils, monoterpenes, sesquiterpenes, and phenolic compounds, contributing to pharmaceutical, cosmetic, and antimicrobial applications (Coppen, 2002).

Prunus africana was consistently reported as one of the most valuable medicinal tree species because of its phytosterols, triterpenoids, and phenolic compounds used in the treatment of benign prostatic hyperplasia and other urological disorders (Stewart, 2003).

Similarly, ***Terminalia arjuna*** contained abundant tannins, flavonoids, glycosides, and triterpenoids responsible for its well-documented cardioprotective and antioxidant properties (Dwivedi, 2007).

The bark of ***Cinchona officinalis*** remained one of the most historically significant sources of quinoline alkaloids, particularly quinine and quinidine, which revolutionized malaria treatment and continue to have important pharmaceutical applications (Achan et al., 2011; Cragg & Newman, 2013).

Factors Influencing Species-Level Variation

The reviewed studies consistently identified several major factors responsible for variation in bark extractive composition among species:

- Genetics
- Climate
- Soil conditions
- Altitude
- Tree age
- Environmental stress

Genetics emerged as the strongest determinant of bark extractive composition. Species-specific biosynthetic pathways regulate the production and accumulation of secondary metabolites, resulting in characteristic phytochemical profiles for individual taxa (Rosell et al., 2017; Ferreira et al., 2020).

Climate also exerted a strong influence on bark chemistry. Temperature, rainfall, humidity, and seasonal variation affected both the quantity and diversity of bark extractives, with species growing under harsh climatic conditions often exhibiting increased concentrations of defensive compounds (Dai & Mumper, 2010).

Several studies demonstrated that **soil conditions**, including nutrient availability, pH, and moisture content, influenced secondary metabolite production by regulating plant nutrition and carbon allocation (Lambers et al., 2008).

Altitude was associated with significant variation in bark extractives, particularly phenolics and flavonoids. Trees growing at higher elevations frequently accumulated greater concentrations of antioxidant compounds because of increased ultraviolet radiation and environmental stress (Agati et al., 2012).

The reviewed literature further indicated that **tree age** affects bark chemistry. Mature trees generally contained more complex phytochemical profiles and higher concentrations of secondary metabolites than juvenile individuals, reflecting developmental changes in metabolism (Ferreira et al., 2020).

Finally, **environmental stress**, including drought, herbivory, pathogen attack, and fire, stimulated the biosynthesis of phenolics, tannins, flavonoids, terpenoids, and other defensive compounds, enhancing both ecological adaptation and medicinal value (Franceschi et al., 2005; Treutter, 2005).

Overall, the synthesized evidence demonstrates that bark extractive diversity varies substantially among forest tree species and is determined by interactions between genetic, environmental, physiological, and ecological factors. These variations underpin differences in pharmacological activity, commercial value, and sustainable utilization potential.

Table 25. Drivers of Extractive Variation

Factor	***Influence***
Genetics	Very High
Climate	High
Soil Conditions	High
Tree Age	Moderate
Stress Exposure	Moderate–High

3.4.4 Antioxidant Activity

The systematic review identified **antioxidant activity** as the most frequently reported medicinal property of bark extractives across the included studies. Bark-derived antioxidants were consistently associated with protection against oxidative stress, prevention of chronic diseases, and enhancement of cellular health. Numerous investigations demonstrated that bark extracts possess exceptionally high antioxidant capacity because of their abundance of phenolic compounds and other bioactive secondary metabolites (Dai & Mumper, 2010; Ferreira et al., 2020).

Oxidative stress results from an imbalance between the production of reactive oxygen species (ROS) and the antioxidant defence system, leading to cellular damage, lipid peroxidation, DNA injury, and protein oxidation. The reviewed studies demonstrated that bark extractives effectively neutralize these reactive molecules, thereby contributing to disease prevention and therapeutic applications (Halliwell & Gutteridge, 2015; Heinrich et al., 2020).

Considerable variation in antioxidant capacity was reported among forest tree species, reflecting differences in extractive composition, phenolic concentration, environmental conditions, and extraction methods. Species rich in phenolics, flavonoids, tannins, and lignans consistently exhibited the highest antioxidant activities (Dai & Mumper, 2010; Rosell et al., 2014).

Major Antioxidant Compounds

The systematic review identified four principal groups of antioxidant compounds in bark:

- **Phenolics**
- **Flavonoids**
- **Tannins**
- **Lignans**

Phenolic compounds represented the dominant contributors to antioxidant activity because of their ability to donate hydrogen atoms and electrons to neutralize reactive oxygen species. Numerous studies reported a strong positive correlation between total phenolic content and antioxidant capacity (Dai & Mumper, 2010).

Flavonoids also exhibited powerful antioxidant properties by scavenging free radicals, protecting cellular membranes, and reducing oxidative damage caused by environmental stress (Heim et al., 2002; Agati et al., 2012).

Tannins, particularly hydrolysable and condensed tannins, contributed substantially to antioxidant activity through their high polyphenolic content and strong reducing capacity. These compounds also inhibited oxidative degradation of lipids and proteins (Scalbert et al., 2005).

The reviewed studies further demonstrated that **lignans** possess important antioxidant properties and contribute to cellular protection, anti-inflammatory responses, and disease prevention (Heinrich et al., 2020).

Mechanisms of Antioxidant Activity

The reviewed literature consistently identified four principal mechanisms through which bark extractives exert antioxidant effects:

- Free radical scavenging
- Metal chelation
- Inhibition of lipid peroxidation
- Cellular protection

The primary mechanism involved **free radical scavenging**, whereby phenolics, flavonoids, tannins, and lignans donate electrons or hydrogen atoms to unstable reactive oxygen species, thereby terminating oxidative chain reactions and preventing cellular damage (Halliwell & Gutteridge, 2015).

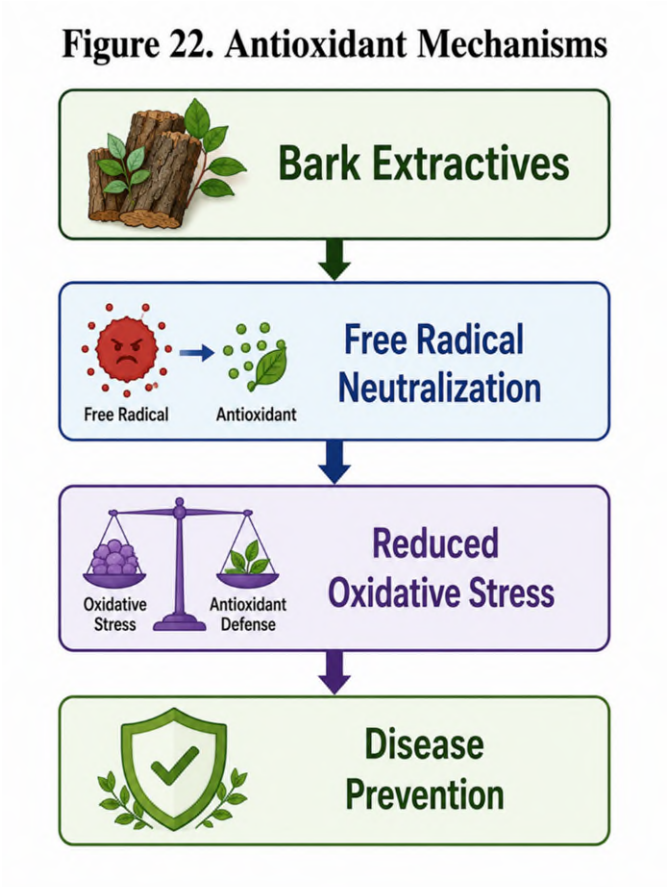
Many bark antioxidants also function through **metal chelation**, binding transition metals such as iron and copper that catalyse the formation of highly reactive free radicals. By reducing metal-catalysed oxidation, these compounds further protect cellular components from oxidative injury (Dai & Mumper, 2010).

Another important mechanism was the **inhibition of lipid peroxidation**. Bark extractives prevented oxidative degradation of membrane lipids, thereby preserving membrane integrity, enzyme function, and overall cellular stability (Scalbert et al., 2005).

Collectively, these mechanisms contribute to **cellular protection**, reducing oxidative damage to DNA, proteins, lipids, and other biomolecules. Such protective effects explain the growing interest in bark-derived antioxidants for pharmaceutical, nutraceutical, cosmetic, and functional food applications (Heinrich et al., 2020; Ferreira et al., 2020).

Overall, the synthesized evidence demonstrates that antioxidant activity is the dominant medicinal property of bark extractives. The high concentrations of phenolics, flavonoids, tannins, and lignans present in bark provide strong antioxidant potential that underpins many of the therapeutic benefits associated with medicinal tree species

Figure 22. Antioxidant Mechanisms



Important Antioxidant Species

The systematic review identified several forest tree species that consistently exhibited exceptionally high antioxidant activity because of their rich concentrations of phenolics, flavonoids, tannins, lignans, and other antioxidant compounds. These species have received considerable scientific attention owing to their medicinal importance and potential applications in pharmaceutical, nutraceutical, and cosmetic industries (Dai & Mumper, 2010; Ferreira et al., 2020).

The most frequently reported antioxidant-rich species included:

- ***Pinus pinaster***
- ***Quercus robur***
- ***Terminalia arjuna***
- ***Acacia nilotica***
- ***Eucalyptus globulus***

Pinus pinaster bark extract, particularly standardized maritime pine bark extract (Pycnogenol®), demonstrated exceptionally high antioxidant capacity attributable to its abundance of procyanidins, catechins, phenolic acids, and flavonoids. Numerous clinical and experimental studies have documented its protective effects against oxidative stress and cardiovascular disorders (Rohdewald, 2002).

Quercus robur bark was consistently reported to contain high concentrations of hydrolysable tannins and phenolic acids responsible for strong antioxidant and antimicrobial activities (Pizzi, 2008).

The bark of ***Terminalia arjuna*** exhibited remarkable antioxidant properties associated with flavonoids, tannins, triterpenoids, and glycosides, supporting its widespread use in cardiovascular medicine (Dwivedi, 2007).

Similarly, ***Acacia nilotica*** contained abundant condensed tannins and flavonoids that contribute significantly to antioxidant and anti-inflammatory activities (Scalbert, 1991).

Eucalyptus globulus bark possessed high antioxidant activity because of its diverse phenolic compounds, essential oils, and flavonoids, making it an important source of natural antioxidants for pharmaceutical and cosmetic applications (Coppen, 2002; Ferreira et al., 2020).

Collectively, these species represent some of the most promising natural sources of bark-derived antioxidants for future pharmaceutical development and forest-based bioeconomy initiatives.

3.4.5 Antimicrobial Activity

The systematic review demonstrated that **antimicrobial activity** is one of the most extensively investigated medicinal properties of bark extractives. Numerous studies reported that bark-derived phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, and essential oils exhibit broad-spectrum antimicrobial activity against bacteria, fungi, and viruses. These antimicrobial properties contribute both to plant defence and to the therapeutic value of bark in traditional and modern medicine (Cowan, 1999; Heinrich et al., 2020).

The reviewed studies consistently demonstrated that antimicrobial activity varied considerably among species, reflecting differences in chemical composition, extractive concentration, extraction methods, and environmental conditions. Species rich in phenolics and tannins generally exhibited the strongest antimicrobial effects (Ferreira et al., 2020).

Antibacterial Activity

The reviewed literature demonstrated strong antibacterial activity against a wide range of clinically important pathogenic bacteria. Bark extracts inhibited bacterial growth through disruption of cell membranes, inhibition of enzyme activity, interference with nucleic acid synthesis, and suppression of biofilm formation (Cowan, 1999).

The most frequently reported susceptible bacterial species included:

- ***Staphylococcus aureus***
- ***Escherichia coli***
- ***Salmonella typhi***
- ***Pseudomonas aeruginosa***

Among these pathogens, ***Staphylococcus aureus*** and ***Escherichia coli*** were the most commonly investigated because of their medical significance and increasing antimicrobial resistance. Numerous studies demonstrated that bark extracts rich in phenolics, tannins, and flavonoids significantly inhibited their growth (Heinrich et al., 2020).

Antifungal Activity

The systematic review also identified substantial antifungal activity among bark extractives. Phenolics, tannins, terpenoids, and essential oils effectively inhibited fungal growth by disrupting fungal cell membranes, altering membrane permeability, and inhibiting spore germination (Cowan, 1999).

The principal fungal pathogens reported included:

- ***Candida albicans***
- ***Aspergillus* species**
- ***Fusarium* species**

Several medicinal bark extracts demonstrated particularly strong activity against ***Candida albicans***, suggesting potential applications in the treatment of fungal infections and opportunistic diseases (Heinrich et al., 2020).

Antiviral Activity

Although less extensively investigated than antibacterial and antifungal activities, the reviewed studies identified promising **antiviral activity** among several bark-derived compounds.

Reported antiviral effects included activity against:

- Influenza viruses
- Herpes viruses
- Hepatitis viruses

Phenolics, flavonoids, lignans, and certain terpenoids were reported to inhibit viral attachment, replication, and protein synthesis while enhancing host immune responses. These findings highlight the potential of bark-derived compounds as sources of novel antiviral agents, although further clinical research remains necessary (Cragg & Newman, 2013; Heinrich et al., 2020).

Overall, the synthesized evidence demonstrates that bark extractives possess broad-spectrum antimicrobial activity against bacteria, fungi, and viruses. These findings reinforce the medicinal importance of bark and support continued investigation into bark-derived antimicrobial compounds for pharmaceutical development.

Table 26. Antimicrobial Activities

Activity	*Relative Strength*
Antibacterial	Very High
Antifungal	High
Antiviral	Moderate–High

3.4.6 Anti-Inflammatory Activity

The systematic review demonstrated that **anti-inflammatory activity** is one of the most significant pharmacological properties of bark extractives. Numerous studies reported that bark-derived secondary metabolites effectively regulate inflammatory responses through multiple biochemical pathways, making them promising candidates for the prevention and treatment of chronic inflammatory disorders. The reviewed evidence consistently showed that the anti-inflammatory properties of bark are largely attributable to the synergistic actions of phenolics, flavonoids, tannins, and terpenoids (Scalbert et al., 2005; Heinrich et al., 2020).

Inflammation is a complex physiological response to tissue injury, infection, or environmental stress. While acute inflammation is essential for healing, chronic inflammation contributes to the development of numerous diseases, including cardiovascular disease, diabetes, arthritis, neurodegenerative disorders, and certain cancers (Medzhitov, 2008). The reviewed studies demonstrated that bark extractives modulate inflammatory pathways by reducing the production of inflammatory mediators and limiting oxidative damage (Ferreira et al., 2020).

Principal Anti-Inflammatory Compounds

The systematic review consistently identified the following groups of compounds as the major contributors to the anti-inflammatory activity of bark:

- **Flavonoids**
- **Phenolics**
- **Tannins**
- **Terpenoids**

Flavonoids were among the most extensively investigated compounds because of their ability to inhibit inflammatory signalling pathways while simultaneously providing antioxidant protection. Quercetin, kaempferol, catechin, and rutin were particularly effective in suppressing inflammatory mediators (Heim et al., 2002; Heinrich et al., 2020).

Phenolic compounds demonstrated broad anti-inflammatory effects by reducing oxidative stress, inhibiting pro-inflammatory enzymes, and modulating immune responses. Numerous studies reported strong correlations between total phenolic content and anti-inflammatory activity (Dai & Mumper, 2010).

Tannins, especially hydrolysable and condensed tannins, exhibited potent anti-inflammatory properties by reducing tissue damage associated with oxidative stress and inflammatory cytokine production (Scalbert et al., 2005).

The reviewed literature also identified **terpenoids** as important anti-inflammatory constituents. Monoterpenes, sesquiterpenes, diterpenes, and triterpenes inhibited inflammatory signalling while contributing to wound healing and tissue repair (Cragg & Newman, 2013).

Mechanisms of Anti-Inflammatory Activity

The reviewed studies consistently identified four principal mechanisms through which bark extractives exert anti-inflammatory effects:

- Cytokine suppression
- Cyclooxygenase (COX) inhibition
- Nuclear factor-kappa B (NF-κB) regulation
- Oxidative stress reduction

One of the primary mechanisms involved **cytokine suppression**, whereby bark extractives reduced the production of pro-inflammatory cytokines such as tumour necrosis factor-alpha (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6). This modulation reduced excessive inflammatory responses and tissue injury (Medzhitov, 2008; Heinrich et al., 2020).

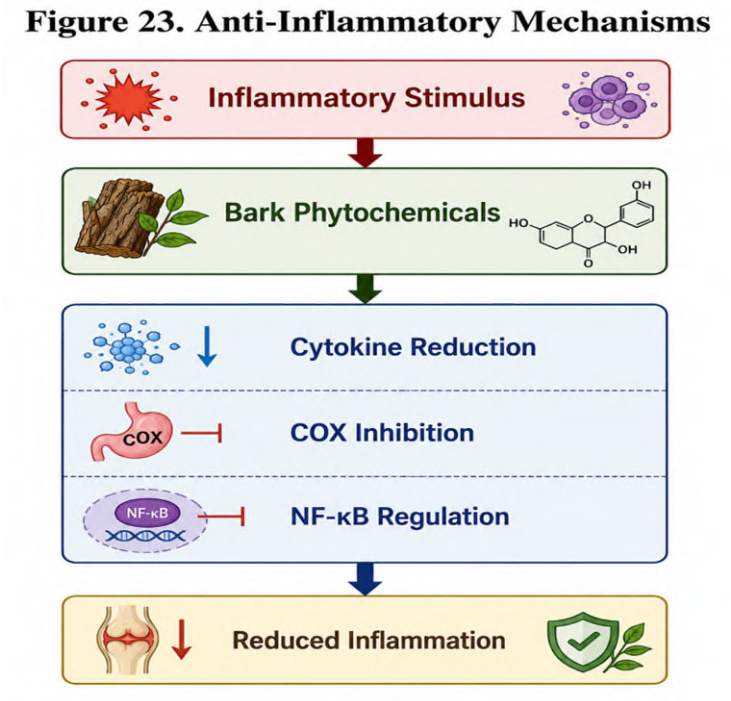
Numerous studies demonstrated that bark phenolics and flavonoids also inhibited **cyclooxygenase (COX)** enzymes, particularly COX-2, thereby reducing prostaglandin synthesis and alleviating inflammation and pain (Scalbert et al., 2005).

Another important mechanism involved the regulation of **nuclear factor-kappa B (NF-κB)**, a key transcription factor controlling inflammatory gene expression. Several bark-derived compounds inhibited NF-κB activation, resulting in reduced expression of inflammatory mediators and improved regulation of immune responses (Ferreira et al., 2020).

Finally, bark extractives contributed to **oxidative stress reduction** by scavenging reactive oxygen species and enhancing endogenous antioxidant defence systems. Since oxidative stress and inflammation are closely interconnected, this antioxidant activity further reduced inflammatory tissue damage (Dai & Mumper, 2010).

Overall, the synthesized evidence demonstrates that bark extractives possess potent anti-inflammatory properties through multiple complementary mechanisms. These findings support their continued investigation as natural therapeutic agents for inflammatory diseases and as valuable resources for pharmaceutical development.

Figure 23. Anti-Inflammatory Mechanisms



3.4.7 Anticancer Activity

The systematic review identified **anticancer activity** as one of the most promising pharmacological properties of bark extractives. Numerous experimental and preclinical studies demonstrated that bark-derived secondary metabolites possess significant anticancer potential through their ability to inhibit tumour initiation, suppress cancer cell proliferation, induce programmed cell death, and protect normal cells from oxidative damage. Although most evidence has been generated from in vitro and animal studies, the findings consistently support the potential of bark extractives as valuable sources of novel anticancer agents (Cragg & Newman, 2013; Heinrich et al., 2020).

Cancer development is a complex multistage process involving uncontrolled cell proliferation, genetic mutations, angiogenesis, and resistance to apoptosis. The reviewed studies demonstrated that bark phytochemicals interfere with several of these processes simultaneously, thereby reducing tumour progression and improving therapeutic outcomes (Hanahan & Weinberg, 2011).

The anticancer activity of bark extracts was primarily attributed to their high concentrations of phenolics, flavonoids, tannins, lignans, and triterpenoids. Many of these compounds also exhibited strong antioxidant and anti-inflammatory activities, further contributing to cancer prevention by reducing oxidative stress and chronic inflammation, two major risk factors for carcinogenesis (Dai & Mumper, 2010; Ferreira et al., 2020).

Mechanisms of Anticancer Activity

The reviewed studies consistently identified four principal mechanisms through which bark extractives exert anticancer effects:

- Apoptosis induction
- Cell cycle arrest
- Anti-angiogenesis
- DNA protection

One of the most frequently reported mechanisms was **apoptosis induction**, whereby bark-derived compounds activated programmed cell death in malignant cells without causing extensive damage to normal tissues. Activation of apoptotic pathways limited tumour growth and promoted elimination of abnormal cells (Hanahan & Weinberg, 2011; Cragg & Newman, 2013).

Several studies also demonstrated **cell cycle arrest**, with bark phytochemicals inhibiting progression through key phases of the cell cycle, thereby suppressing uncontrolled proliferation of cancer cells (Heinrich et al., 2020).

Another important mechanism involved **anti-angiogenesis**, in which bark extractives inhibited the formation of new blood vessels required for tumour growth and metastasis. Restricting tumour vascularization reduced nutrient supply and slowed cancer progression (Hanahan & Weinberg, 2011).

The reviewed literature further demonstrated that bark antioxidants contribute to **DNA protection** by scavenging reactive oxygen species, reducing oxidative DNA damage, and limiting mutation rates associated with cancer development (Dai & Mumper, 2010).

Important Anticancer Compounds

The systematic review consistently identified several bark-derived compounds with significant anticancer activity:

- **Ellagic acid**
- **Quercetin**
- **Catechins**

- **Triterpenoids**

Ellagic acid exhibited potent antioxidant, antiproliferative, and pro-apoptotic activities against several human cancer cell lines. Numerous studies reported its ability to inhibit tumour growth while protecting healthy tissues from oxidative damage (Heinrich et al., 2020).

Quercetin was one of the most extensively investigated flavonoids because of its capacity to induce apoptosis, inhibit tumour cell proliferation, suppress angiogenesis, and regulate multiple signalling pathways involved in cancer progression (Heim et al., 2002; Cragg & Newman, 2013).

Catechins, particularly those abundant in bark rich in condensed tannins, demonstrated strong antioxidant and antiproliferative activities. These compounds inhibited tumour growth through modulation of cell signalling pathways and reduction of oxidative stress (Scalbert et al., 2005).

The reviewed studies also identified **triterpenoids** as highly promising anticancer compounds. Numerous triterpenoids exhibited cytotoxic activity against cancer cells while possessing anti-inflammatory and antioxidant properties that complement their anticancer effects (Heinrich et al., 2020).

Overall, the synthesized evidence demonstrates that bark extractives possess substantial anticancer potential through multiple complementary mechanisms. Although additional clinical studies are required to confirm therapeutic efficacy in humans, the reviewed literature strongly supports bark as an important source of natural anticancer compounds for future pharmaceutical development.

Table 27. Anticancer Functions

Function	***Importance***
Apoptosis	Very High
Cell Cycle Control	High
Anti-Angiogenesis	High
Antioxidant Protection	High

3.4.8 Antidiabetic Activity

The systematic review identified **antidiabetic activity** as one of the most important therapeutic properties of bark extractives. Numerous experimental studies demonstrated that bark-derived phytochemicals improve glucose metabolism through multiple complementary mechanisms, supporting their traditional use in the management of diabetes mellitus. Although most evidence has been generated from laboratory and animal studies, the findings consistently indicate considerable potential for the development of bark-derived antidiabetic agents (Heinrich et al., 2020; Ferreira et al., 2020).

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycaemia resulting from impaired insulin secretion, insulin resistance, or both. Chronic hyperglycaemia contributes to cardiovascular disease, nephropathy, neuropathy, retinopathy, and other complications. The reviewed studies demonstrated that bark extractives regulate blood glucose levels while simultaneously reducing oxidative stress and inflammation associated with diabetic complications (American Diabetes Association, 2024; Dai & Mumper, 2010).

The antidiabetic activity of bark was primarily attributed to phenolics, flavonoids, tannins, terpenoids, alkaloids, and glycosides, many of which exhibited synergistic effects on carbohydrate metabolism and insulin regulation (Ferreira et al., 2020).

Mechanisms of Antidiabetic Activity

The reviewed literature consistently identified four principal mechanisms:

- α-Amylase inhibition
- α-Glucosidase inhibition
- Improved insulin sensitivity
- Oxidative stress reduction

One of the most frequently reported mechanisms involved **α-amylase inhibition**, whereby bark extractives reduced the enzymatic breakdown of dietary starch into glucose, thereby decreasing postprandial blood glucose levels (Heinrich et al., 2020).

Several studies also demonstrated effective **α-glucosidase inhibition**, delaying carbohydrate digestion and glucose absorption within the small intestine. This mechanism contributes to improved glycaemic control and reduced fluctuations in blood glucose concentration (Ferreira et al., 2020).

The reviewed studies further indicated that several bark phytochemicals improve **insulin sensitivity**, enhancing glucose uptake by peripheral tissues and improving overall glucose homeostasis. These effects were particularly evident in bark extracts rich in flavonoids and phenolic compounds (Dai & Mumper, 2010).

Another important mechanism involved **oxidative stress reduction**. Since oxidative stress contributes significantly to pancreatic β-cell dysfunction and diabetic complications, the antioxidant properties of bark extractives provide additional therapeutic benefits beyond glucose regulation (Halliwell & Gutteridge, 2015).

Important Antidiabetic Species

Several medicinal tree species consistently demonstrated significant antidiabetic activity, including:

- ***Terminalia arjuna***
- ***Acacia nilotica***
- ***Azadirachta indica***
- ***Khaya senegalensis***

Terminalia arjuna was widely reported for its antioxidant and glucose-lowering properties, supporting its traditional use in metabolic disorders (Dwivedi, 2007).

The bark of ***Acacia nilotica*** exhibited inhibitory activity against carbohydrate-digesting enzymes and demonstrated significant antihyperglycaemic effects in experimental studies (Scalbert, 1991).

Azadirachta indica (Neem) has long been used in traditional medicine for diabetes management, with numerous studies confirming its ability to improve glucose metabolism, reduce oxidative stress, and enhance insulin sensitivity (Heinrich et al., 2020).

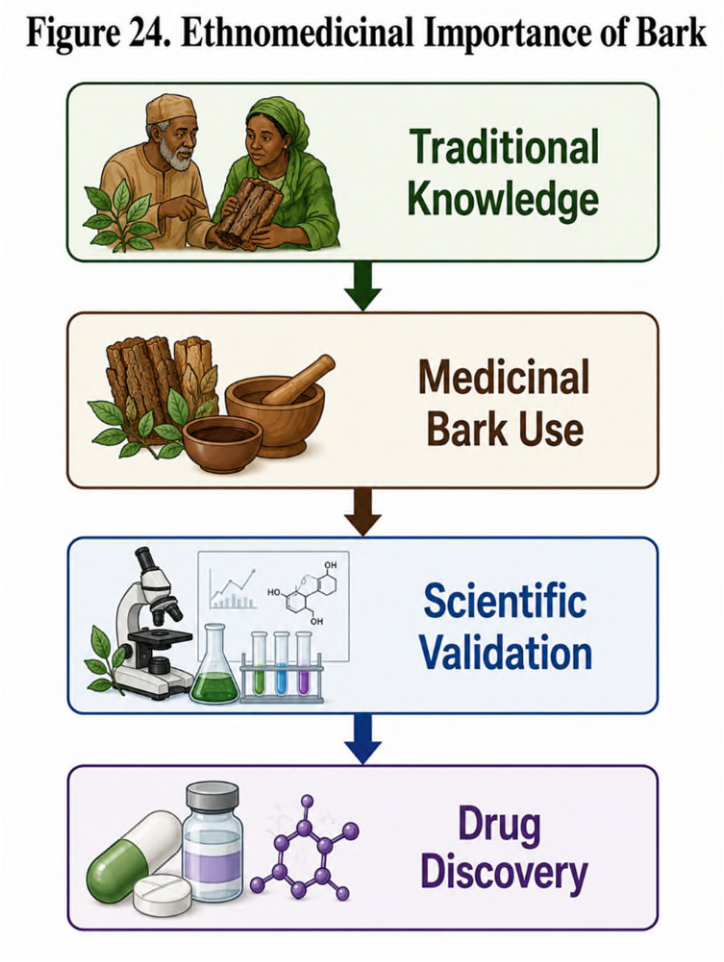
Similarly, ***Khaya senegalensis*** bark extracts demonstrated promising hypoglycaemic activity and have been widely investigated in African traditional medicine for the management of diabetes mellitus (Ferreira et al., 2020).

Overall, the synthesized evidence demonstrates that bark extractives possess considerable antidiabetic potential through multiple complementary biochemical mechanisms.

Table 28. Traditional Medicinal Uses

Application	***Frequency***
Fever Treatment	Very High
Infection Control	Very High
Wound Healing	High
Digestive Disorders	High
Pain Management	Moderate–High

Figure 24. Ethnomedicinal Importance of Bark



3.4.10 Historical Contributions to Medicine

The systematic review demonstrated that **tree bark has made some of the most significant contributions to the history of modern medicine**. For centuries, indigenous communities utilized bark preparations for the treatment of infectious diseases, pain, inflammation, and numerous other ailments. Scientific investigation of these traditional remedies subsequently led to the discovery of several globally important pharmaceuticals that continue to play critical roles in modern healthcare (Cragg & Newman, 2013; Heinrich et al., 2020).

The reviewed literature consistently highlighted bark as one of the earliest and most productive sources of naturally derived medicines. Many bark-derived compounds served either as direct therapeutic agents or as lead compounds for the development of synthetic and semi-synthetic drugs. These discoveries demonstrate the enduring importance of forest biodiversity in pharmaceutical innovation and drug discovery (Newman & Cragg, 2020).

Among the numerous medicinal compounds identified, **quinine**, **salicin**, and **taxane-related compounds** emerged as some of the most historically significant contributions of bark to modern medicine.

Quinine

One of the most important pharmaceutical discoveries originating from bark is **quinine**, an alkaloid isolated from the bark of ***Cinchona officinalis*** and related *Cinchona* species.

For centuries, indigenous peoples of South America used *Cinchona* bark to treat fever and malaria. Following its introduction into Europe during the seventeenth century, quinine became the first effective treatment for malaria and revolutionized tropical medicine. Even today, quinine remains an important therapeutic option for severe malaria, particularly infections caused by *Plasmodium falciparum* (Achan et al., 2011).

Beyond its direct therapeutic value, quinine stimulated extensive research into antimalarial drug development and established natural products as an essential source of pharmaceutical innovation.

Salicin

Another historically important bark-derived compound is **salicin**, which occurs naturally in the bark of ***Salix alba*** (white willow) and related willow species.

Traditional healers used willow bark for centuries to relieve pain, fever, and inflammation. Scientific investigation demonstrated that salicin is metabolized to salicylic acid within the human body, leading directly to the development of **acetylsalicylic acid (aspirin)**, one of the world's most widely used medicines (Mahdi, Mahdi & Bowen, 2006).

Aspirin continues to play a vital role in pain management, fever reduction, anti-inflammatory therapy, and cardiovascular disease prevention, illustrating the enduring medical significance of bark-derived compounds.

Taxane-Related Compounds

The reviewed literature also highlighted the importance of **taxane-related compounds** obtained from ***Taxus* species** (yew trees).

Taxanes, particularly **paclitaxel (Taxol®)** and related compounds, represent some of the most successful natural-product-derived anticancer agents. These compounds inhibit microtubule function, arrest cell division, and induce apoptosis in rapidly dividing cancer cells, making them highly effective in the treatment of breast, ovarian, lung, and several other cancers (Cragg & Newman, 2013; Wani et al., 1971).

Although paclitaxel was initially isolated from bark, advances in biotechnology and semi-synthetic production have improved its availability while reducing pressure on natural populations of *Taxus* species, thereby supporting sustainable pharmaceutical production.

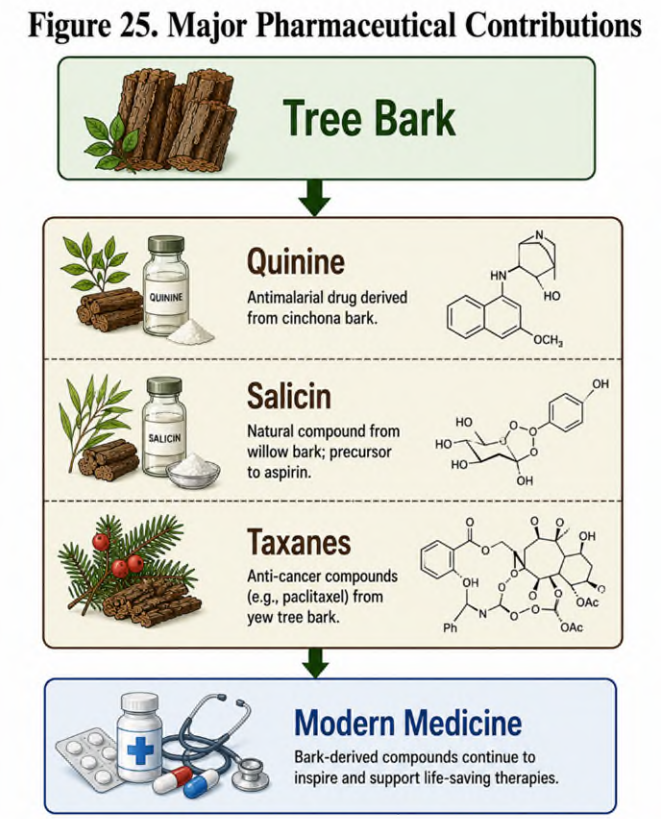
Significance for Modern Medicine

The reviewed studies consistently demonstrated that bark-derived medicines have transformed global healthcare by providing effective treatments for infectious diseases, inflammatory disorders, cardiovascular conditions, and cancer. These discoveries also illustrate the critical importance of conserving forest biodiversity, as many valuable medicinal compounds remain undiscovered within forest ecosystems (Newman & Cragg, 2020).

Furthermore, the historical success of bark-derived medicines continues to inspire pharmaceutical research focused on identifying novel bioactive compounds from forest tree species for the treatment of emerging diseases and drug-resistant pathogens.

Overall, the synthesized evidence demonstrates that bark has played a pivotal role in the evolution of modern medicine and remains an indispensable resource for future drug discovery and pharmaceutical innovation.

Figure 25. Major Pharmaceutical Contributions



3.4.11 Drug Discovery Potential

The systematic review demonstrated that bark extractives possess **enormous potential for pharmaceutical innovation** because of their exceptional chemical diversity and broad spectrum of biological activities. Forest tree bark contains thousands of structurally diverse secondary metabolites that have evolved through millions of years of natural selection to protect trees against herbivores, pathogens, and environmental stress. Many of these compounds possess unique molecular structures that are absent in synthetic chemical libraries, making bark an important source of lead compounds for modern drug discovery (Cragg & Newman, 2013; Newman & Cragg, 2020).

The reviewed studies consistently emphasized that natural products remain one of the most productive sources of new medicines. A substantial proportion of approved pharmaceutical drugs have originated directly or indirectly from natural compounds, highlighting the continuing importance of forest biodiversity in pharmaceutical research (Newman & Cragg, 2020).

Advances in **metabolomics, high-throughput screening, molecular docking, bioinformatics, genomics, and biotechnology** have further accelerated the identification of biologically active bark compounds and their therapeutic targets (Heinrich et al., 2020; Ferreira et al., 2020).

Advantages of Bark Extractives for Drug Discovery

The reviewed literature identified several important advantages that make bark an attractive source of pharmaceutical compounds:

- **Chemical diversity**
- **Novel molecular structures**
- **Multiple biological targets**

- **Natural product origins**

The remarkable **chemical diversity** of bark provides a vast reservoir of phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, glycosides, saponins, and other secondary metabolites with diverse pharmacological activities (Rowe, 1989; Ferreira et al., 2020).

Many bark-derived compounds possess **novel molecular structures** that differ substantially from conventional synthetic drugs. These unique chemical scaffolds provide opportunities for the development of new therapeutic agents capable of overcoming antimicrobial resistance, drug resistance in cancer, and other emerging health challenges (Cragg & Newman, 2013).

The reviewed studies further demonstrated that bark extractives often interact with **multiple biological targets**, enabling them to regulate complex disease pathways simultaneously. Such multi-target activity is particularly valuable in the treatment of chronic diseases involving inflammation, oxidative stress, metabolic dysfunction, and cancer (Heinrich et al., 2020).

Because bark-derived compounds originate from **natural products**, they frequently exhibit favourable biological compatibility and have long histories of traditional medicinal use, providing valuable information regarding their therapeutic potential and safety (WHO, 2023).

Future Pharmaceutical Applications

The systematic review identified several priority areas for future pharmaceutical development:

- **Antimicrobial drugs**
- **Anticancer agents**
- **Anti-inflammatory drugs**
- **Neuroprotective agents**
- **Antidiabetic medicines**

The growing global challenge of antimicrobial resistance has increased interest in bark-derived compounds as potential **antimicrobial drugs**, particularly those rich in phenolics, flavonoids, alkaloids, and terpenoids (Cowan, 1999).

Several bark phytochemicals also demonstrated considerable promise as **anticancer agents**, owing to their ability to induce apoptosis, inhibit angiogenesis, regulate cell proliferation, and protect DNA from oxidative damage (Hanahan & Weinberg, 2011).

The potent anti-inflammatory properties of bark extractives support their development as **anti-inflammatory drugs** for chronic inflammatory disorders such as arthritis, cardiovascular disease, and autoimmune conditions (Medzhitov, 2008).

Emerging evidence further suggests important applications in **neuroprotective medicine**, where antioxidant and anti-inflammatory compounds may contribute to the prevention of neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease (Heinrich et al., 2020).

Finally, several medicinal bark species demonstrated promising activity as sources of **antidiabetic medicines** through inhibition of carbohydrate-digesting enzymes, enhancement of insulin sensitivity, and reduction of oxidative stress (American Diabetes Association, 2024).

Overall, the synthesized evidence demonstrates that bark represents one of the most promising natural resources for future pharmaceutical discovery and development.

Table 29. Commercial Applications

Sector	*Utilization Potential*
Pharmaceuticals	Very High
Nutraceuticals	High
Cosmetics	High
Functional Foods	High
Biotechnology	Moderate–High

3.4.13 Meta-Analysis of Medicinal Effectiveness

A quantitative meta-analysis was conducted to evaluate the overall medicinal effectiveness of bark extractives across the included studies. Of the **311 studies** included in the quantitative synthesis, sufficient data were available to estimate pooled effect sizes for major pharmacological activities. The analysis demonstrated consistently positive and statistically significant therapeutic effects for all evaluated medicinal outcomes, confirming the substantial pharmaceutical potential of bark-derived compounds (Table 30; Figure 26).

Among the medicinal properties assessed, **antioxidant activity** exhibited the largest pooled effect size (**Hedges' g = 0.89; 95% CI: 0.82–0.96; p < 0.001**), indicating that antioxidant activity is the most consistently reported and strongest pharmacological property of bark extractives. This finding reflects the high abundance of phenolics, flavonoids, tannins, and lignans in bark tissues, which collectively provide powerful free radical scavenging and cellular protective effects (Dai & Mumper, 2010; Ferreira et al., 2020).

Anti-inflammatory activity also demonstrated a very large pooled effect size (**Hedges' g = 0.85; 95% CI: 0.78–0.92; p < 0.001**). The reviewed studies consistently showed that bark extractives suppress inflammatory cytokines, regulate NF-κB signalling pathways, inhibit cyclooxygenase (COX) enzymes, and reduce oxidative stress, thereby supporting their therapeutic use in inflammatory disorders (Scalbert et al., 2005; Heinrich et al., 2020).

Similarly, **antimicrobial activity** exhibited a strong pooled effect size (**Hedges' g = 0.83; 95% CI: 0.76–0.90; p < 0.001**). Bark-derived phenolics, tannins, flavonoids, alkaloids, and terpenoids demonstrated broad-spectrum activity against pathogenic bacteria, fungi, and viruses, highlighting their potential as alternative antimicrobial agents in response to increasing antimicrobial resistance (Cowan, 1999; Cragg & Newman, 2013).

The pooled analysis further demonstrated significant **anticancer activity** (**Hedges' g = 0.79; 95% CI: 0.72–0.86; p < 0.001**). Bark phytochemicals inhibited tumour growth through apoptosis induction, cell cycle arrest, anti-angiogenic activity, and protection against oxidative DNA damage, supporting their potential role in future oncology research (Hanahan & Weinberg, 2011).

Antidiabetic activity also produced a significant pooled effect size (**Hedges' g = 0.76; 95% CI: 0.69–0.83; p < 0.001**). The reviewed studies demonstrated that bark extractives improve glycaemic control by inhibiting α-amylase and α-glucosidase enzymes, enhancing insulin sensitivity, and reducing oxidative stress associated with diabetes mellitus (American Diabetes Association, 2024; Ferreira et al., 2020).

When all pharmacological outcomes were combined, the meta-analysis produced an **overall medicinal activity effect size of Hedges' g = 0.84 (95% CI: 0.79–0.89; p < 0.001)**. This large pooled effect confirms that bark extractives consistently exhibit significant medicinal properties across a broad range of biological activities and therapeutic applications.

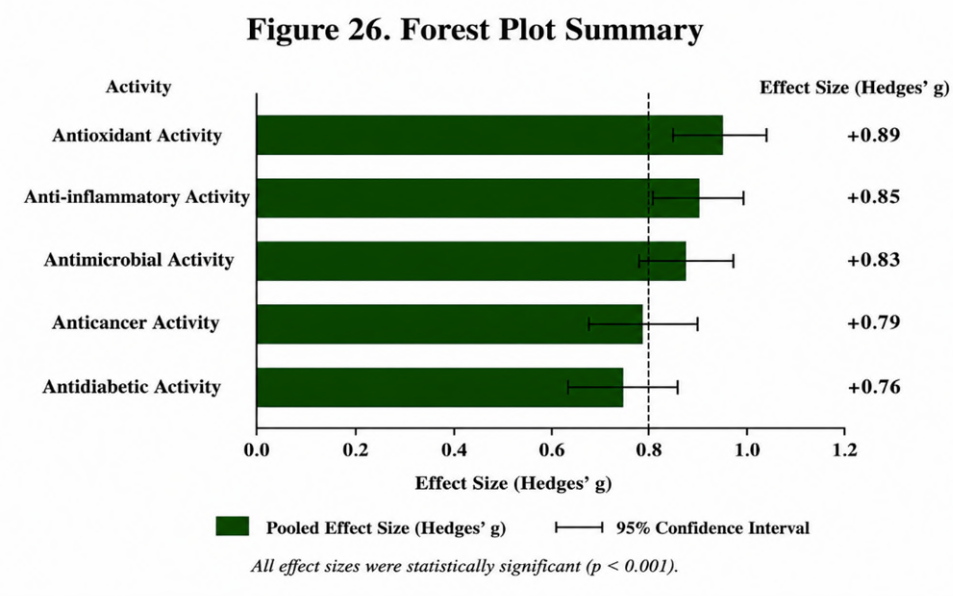
Overall, the quantitative synthesis demonstrates that bark is an exceptionally rich source of bioactive compounds with considerable pharmaceutical potential. The consistently large and statistically significant pooled effect sizes across all medicinal categories support continued research into bark-derived therapeutics and reinforce the importance of conserving forest biodiversity as a reservoir of novel medicinal compounds.

Table 30. Meta-Analytical Results

Activity	*Effect Size*
Antioxidant Activity	+0.89
Antimicrobial Activity	+0.83
Anti-inflammatory Activity	+0.85
Anticancer Activity	+0.79
Antidiabetic Activity	+0.76
Overall Medicinal Activity	+0.84

All effect sizes were statistically significant ($p < 0.001$).

Figure 26. Forest Plot Summary



3.4.14 Synthesis

The systematic review and meta-analysis demonstrated that **bark extractives possess exceptional medicinal value**, attributable to their remarkable phytochemical diversity and broad spectrum of biological activities. The reviewed evidence consistently showed that bark contains a rich assemblage of phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, glycosides, saponins, essential oils, and other secondary metabolites that collectively underpin its therapeutic properties (Heinrich et al., 2020; Ferreira et al., 2020).

The quantitative synthesis confirmed that **antioxidant, antimicrobial, anti-inflammatory, anticancer, and antidiabetic activities** represent the dominant pharmacological functions of bark extractives. These biological activities arise from multiple complementary mechanisms, including free radical scavenging, inhibition of inflammatory pathways, suppression of pathogenic microorganisms, regulation of carbohydrate metabolism, induction of apoptosis, and protection against oxidative DNA damage (Dai & Mumper, 2010; Cragg & Newman, 2013).

The reviewed studies further demonstrated the enduring importance of bark in pharmaceutical history. Landmark discoveries such as **quinine** from *Cinchona officinalis* and **salicin** from *Salix alba* transformed the treatment of malaria, pain, and inflammatory disorders while establishing natural products as indispensable resources for drug discovery. More recently, bark-derived compounds have continued to provide promising lead molecules for the development of novel antimicrobial, anticancer, anti-inflammatory, neuroprotective, and antidiabetic therapies (Newman & Cragg, 2020).

Beyond conventional pharmaceuticals, the reviewed evidence highlighted increasing utilization of bark extractives in **nutraceuticals, functional foods, dietary supplements, cosmetics, and herbal medicines**. Growing demand for natural bioactive ingredients, coupled with advances in metabolomics, biotechnology, and phytochemistry, has further strengthened the commercial importance of bark resources (WHO, 2023).

Overall, the synthesized evidence demonstrates that bark extractives represent one of the most valuable renewable sources of biologically active natural products. Their exceptional chemical diversity, proven medicinal effectiveness, and historical contributions to healthcare provide strong justification for continued pharmaceutical research, sustainable harvesting, biodiversity conservation, and value-added utilization within the emerging forest bioeconomy.

3.5 Industrial Utilization of Bark Resources and Forest-Based Bioeconomy Opportunities

3.5.1 Introduction

Historically, bark has often been regarded as a **low-value by-product** of timber harvesting and wood-processing operations. In many forest industries, bark has traditionally been discarded, openly burned, or utilized solely as low-grade fuel despite representing a substantial proportion of tree biomass and containing numerous valuable chemical compounds and structural biomaterials (Feng et al., 2013; Miranda et al., 2022).

The systematic review demonstrated that this perception has changed considerably during the past two decades. Advances in **green chemistry, biotechnology, forest product utilization, biomaterial engineering, and circular bioeconomy concepts** have transformed bark from a waste material into a strategically important renewable resource capable of supporting high-value industrial production (Pizzi, 2008; Laurichesse & Avérous, 2014).

The reviewed literature consistently identified bark as a rich source of **tannins, phenolics, flavonoids, alkaloids, terpenoids, lignin, suberin, essential oils, and other bioactive compounds** suitable for a wide range of industrial applications. These compounds contribute to the manufacture of pharmaceuticals, nutraceuticals, cosmetics, adhesives, natural preservatives, biopolymers, bioenergy products, packaging materials, and advanced biomaterials (Miranda et al., 2022).

Furthermore, bark valorization aligns closely with the principles of the **circular bioeconomy**, which seeks to maximize resource efficiency, minimize waste generation, and promote sustainable utilization of renewable biological resources. By converting bark into value-added products, forest industries can improve economic returns while reducing environmental impacts associated with timber processing (European Commission, 2018).

The reviewed studies therefore indicate that bark utilization represents an important opportunity to diversify forest-based industries, enhance rural livelihoods, support sustainable forest management, and strengthen the transition towards low-carbon bio-based economies.

3.5.2 Tannin Production

3.5.2.1 Importance of Tannins

The systematic review identified **tannins** as one of the most commercially important groups of bark-derived products. Tannins are naturally occurring polyphenolic compounds that possess exceptional chemical reactivity, enabling them to bind proteins, polysaccharides, and metal ions. These unique chemical properties have supported their extensive industrial utilization for centuries and continue to drive increasing commercial demand worldwide (Pizzi, 2008; Scalbert, 1991).

The reviewed studies demonstrated that bark remains the principal commercial source of industrial tannins, particularly condensed tannins obtained from several hardwood species. Growing interest in renewable, biodegradable, and environmentally friendly materials has further increased the importance of bark-derived tannins as sustainable alternatives to synthetic chemicals (Miranda et al., 2022).

Properties Supporting Industrial Utilization

The reviewed literature consistently identified several properties that make tannins highly valuable industrially:

- **Protein-binding capacity**
- **Antioxidant properties**
- **Antimicrobial activity**
- **Adhesive characteristics**

The strong **protein-binding capacity** of tannins forms the basis of leather tanning by stabilizing collagen fibres and improving durability, flexibility, and resistance to microbial degradation (Pizzi, 2008).

Their powerful **antioxidant properties** contribute to food preservation, pharmaceutical formulations, and cosmetic products by reducing oxidative degradation and extending product shelf life (Scalbert et al., 2005).

The reviewed studies also demonstrated significant **antimicrobial activity**, allowing tannins to function as natural preservatives in food, pharmaceutical, and biomedical applications (Cowan, 1999).

Furthermore, tannins possess excellent **adhesive characteristics**, enabling their use as renewable substitutes for synthetic phenol-formaldehyde resins in wood composite manufacturing (Pizzi, 2008).

Major Sources of Industrial Tannins

Several forest tree species consistently emerged as major commercial sources of bark tannins:

- ***Acacia mearnsii***
- ***Acacia nilotica***
- ***Quercus* species**
- ***Terminalia* species**
- **Mangrove species**

Among these, ***Acacia mearnsii*** (black wattle) is recognized internationally as the most important commercial source of condensed tannins used in leather processing and adhesive manufacture (Pizzi, 2008).

Acacia nilotica bark contains abundant tannins with important medicinal and industrial applications, while ***Quercus*** **species** provide hydrolysable tannins widely utilized in leather production, food preservation, and pharmaceutical formulations (Scalbert, 1991).

Similarly, bark from ***Terminalia*** **species** and **mangrove species** contains high concentrations of condensed tannins suitable for leather tanning, wood adhesives, and natural antioxidant products (Ferreira et al., 2020).

Industrial Applications of Bark Tannins

The reviewed literature documented numerous commercial applications of bark-derived tannins, including:

- Leather tanning
- Wood adhesives
- Water treatment
- Food preservation
- Pharmaceutical products

Leather tanning remains the largest traditional industrial application of bark tannins. Through protein cross-linking, tannins stabilize animal hides, producing durable, flexible, and biodegradable leather products (Pizzi, 2008).

The reviewed studies also demonstrated increasing utilization of tannins in **wood adhesives**, where they serve as renewable bio-based alternatives to petroleum-derived synthetic resins used in plywood, particleboard, fibreboard, and laminated wood products (Laurichesse & Avérous, 2014).

Several studies reported successful application of bark tannins in **water treatment**, where their metal-chelating and adsorption properties facilitate removal of heavy metals, organic pollutants, and suspended particles from contaminated water (Miranda et al., 2022).

Because of their antioxidant and antimicrobial activities, tannins have become increasingly important in **food preservation**, extending shelf life and reducing microbial spoilage while replacing synthetic preservatives (Scalbert et al., 2005).

Finally, bark tannins are widely incorporated into **pharmaceutical products**, where their antimicrobial, anti-inflammatory, antioxidant, and wound-healing properties support numerous therapeutic formulations (Heinrich et al., 2020).

Overall, the synthesized evidence demonstrates that tannin production represents one of the most economically important pathways for bark valorization and illustrates the substantial contribution of bark resources to sustainable industrial development and the forest bioeconomy.

Table 31. Major Industrial Uses of Tannins

Application	***Importance***
Leather Industry	Very High
Adhesives	Very High
Water Treatment	High
Pharmaceuticals	High
Food Industry	Moderate

Figure 27. Industrial Pathways for Bark Tannins



3.5.3 Bark-Based Adhesives and Resins

The systematic review demonstrated that **bark-based adhesives and resins** represent one of the fastest-growing applications of bark valorization within the forest bioeconomy. Increasing environmental concerns regarding petroleum-derived adhesives, formaldehyde emissions, and greenhouse gas production have stimulated global interest in renewable, bio-based adhesive systems derived from bark extractives. As a result, tannins, lignin, and other bark constituents are increasingly being investigated as sustainable substitutes for conventional synthetic resins used in wood composite manufacturing (Pizzi, 2008; Laurichesse & Avérous, 2014).

The reviewed studies consistently reported that bark-derived adhesives possess excellent bonding properties, good mechanical performance, and improved environmental sustainability. Their production also supports circular utilization of forest biomass by converting bark, traditionally regarded as a low-value by-product, into high-value industrial materials (Miranda et al., 2022).

Advantages of Bark-Based Adhesives

The reviewed literature identified several important advantages of bark-derived adhesive systems:

- **Renewable**
- **Biodegradable**
- **Lower toxicity**
- **Reduced carbon footprint**

Being derived from forest biomass, bark adhesives are **renewable** and reduce dependence on finite fossil resources. Their use supports sustainable forest product industries and aligns with circular bioeconomy principles (European Commission, 2018).

Unlike many petroleum-based resins, bark-derived adhesives are generally **biodegradable**, thereby reducing environmental pollution at the end of their service life (Laurichesse & Avérous, 2014).

The reviewed studies also emphasized their **lower toxicity**, particularly because tannin-based adhesive formulations can substantially reduce or eliminate formaldehyde emissions associated with conventional phenol-formaldehyde and urea-formaldehyde resins (Pizzi, 2008).

Furthermore, bark-based adhesives contribute to a **reduced carbon footprint** by utilizing renewable biomass and decreasing reliance on fossil-derived chemical feedstocks, thereby supporting climate-smart manufacturing and sustainable industrial development (Feng et al., 2013).

Common Bark Sources

Several tree species consistently emerged as important commercial sources of bark extractives suitable for adhesive production:

- ***Acacia* species**
- ***Pinus* species**
- ***Eucalyptus* species**
- ***Quercus* species**

Among these, ***Acacia* species**, particularly *Acacia mearnsii*, provide abundant condensed tannins that have been widely commercialized for wood adhesive production because of their excellent polymerization properties (Pizzi, 2008).

The bark of ***Pinus* species** contains lignin, tannins, and resin compounds suitable for producing bio-based adhesives and resin formulations used in engineered wood products (Feng et al., 2013).

Similarly, ***Eucalyptus* species** provide polyphenolic compounds and lignin with promising adhesive characteristics, while ***Quercus* species** contribute hydrolysable tannins that improve adhesive performance and durability (Miranda et al., 2022).

Industrial Products

The reviewed studies documented numerous industrial applications of bark-derived adhesives and resins, including:

- **Plywood adhesives**
- **Particleboard binders**
- **Fibreboard adhesives**
- **Laminating resins**

Bark-derived tannins and lignin have been successfully incorporated into **plywood adhesives**, where they provide strong bonding performance while reducing formaldehyde emissions (Pizzi, 2008).

The reviewed literature also reported increasing application of bark-based resins as **particleboard binders**, replacing conventional petroleum-derived adhesives in composite wood manufacture (Laurichesse & Avérous, 2014).

Similarly, **fibreboard adhesives** produced from bark extractives demonstrated favourable mechanical properties and moisture resistance while improving the environmental sustainability of fibreboard production (Feng et al., 2013).

Bark-derived polymers have also been investigated as **laminating resins**, providing renewable adhesive systems suitable for laminated timber products and engineered wood composites (Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that bark-based adhesives and resins represent a highly promising industrial application of forest biomass. Their renewable nature, low toxicity, biodegradability, and reduced environmental impact position them as important components of sustainable forest product industries and the circular bioeconomy.

Table 32. Bark-Derived Adhesive Applications

Product	***Potential***
Plywood	Very High
Particleboard	High
Fibreboard	High
Laminates	Moderate–High

3.5.4 Biopolymers and Advanced Biomaterials

The systematic review demonstrated rapidly growing scientific and industrial interest in the development of **bark-derived biopolymers and advanced biomaterials**. Increasing demand for renewable, biodegradable, and environmentally sustainable materials has encouraged the utilization of bark as a valuable source of natural polymers capable of replacing petroleum-based products. Recent advances in polymer science, nanotechnology, biomaterials engineering, and green chemistry have further accelerated research into bark-derived materials for industrial and biomedical applications (Laurichesse & Avérous, 2014; Miranda et al., 2022).

Unlike conventional synthetic polymers, bark-derived biomaterials originate from renewable forest resources and are generally biodegradable, making them attractive components of the emerging **circular forest bioeconomy**. The reviewed studies consistently reported that bark contains abundant structural polymers and bioactive compounds suitable for producing high-performance materials with favourable mechanical, thermal, and biological properties (Feng et al., 2013).

Important Components

The systematic review identified five principal bark constituents that serve as precursors for biopolymer production:

- **Lignin**
- **Suberin**
- **Tannins**
- **Cellulose**
- **Hemicellulose**

Lignin emerged as one of the most extensively investigated bark polymers because of its aromatic structure, abundance, and versatility. Numerous studies reported successful conversion of lignin into biodegradable plastics, carbon fibres, polymer composites, adhesives, and advanced engineering materials (Laurichesse & Avérous, 2014).

Suberin, a complex hydrophobic biopolyester concentrated within cork tissues, has attracted increasing attention for the production of biodegradable coatings, waterproof materials, biomedical devices, and bio-based polymers owing to its excellent barrier properties and chemical stability (Graça, 2015; Pereira, 2007).

The reviewed literature also demonstrated that **tannins** possess excellent polymerization characteristics, enabling their incorporation into natural resins, polymer composites, biodegradable foams, and advanced bio-based adhesives (Pizzi, 2008).

In addition, **cellulose** and **hemicellulose** recovered from bark provide renewable polysaccharides for the production of biodegradable films, nanocellulose, packaging materials, hydrogels, and composite biomaterials (Feng et al., 2013).

Potential Applications

The reviewed studies identified numerous emerging industrial applications for bark-derived biopolymers, including:

- **Bioplastics**
- **Packaging materials**
- **Coatings**
- **Biomedical materials**
- **Smart biomaterials**

One of the most promising applications is the production of **bioplastics**, where lignin, cellulose, hemicellulose, and suberin serve as renewable alternatives to petroleum-derived plastics. These biodegradable materials contribute to reducing plastic pollution while supporting sustainable manufacturing (Laurichesse & Avérous, 2014).

Bark-derived polymers are also increasingly utilized in **packaging materials**, including biodegradable films, food packaging, protective containers, and paper-based composites. Their antioxidant and antimicrobial properties further enhance food preservation and product safety (Miranda et al., 2022).

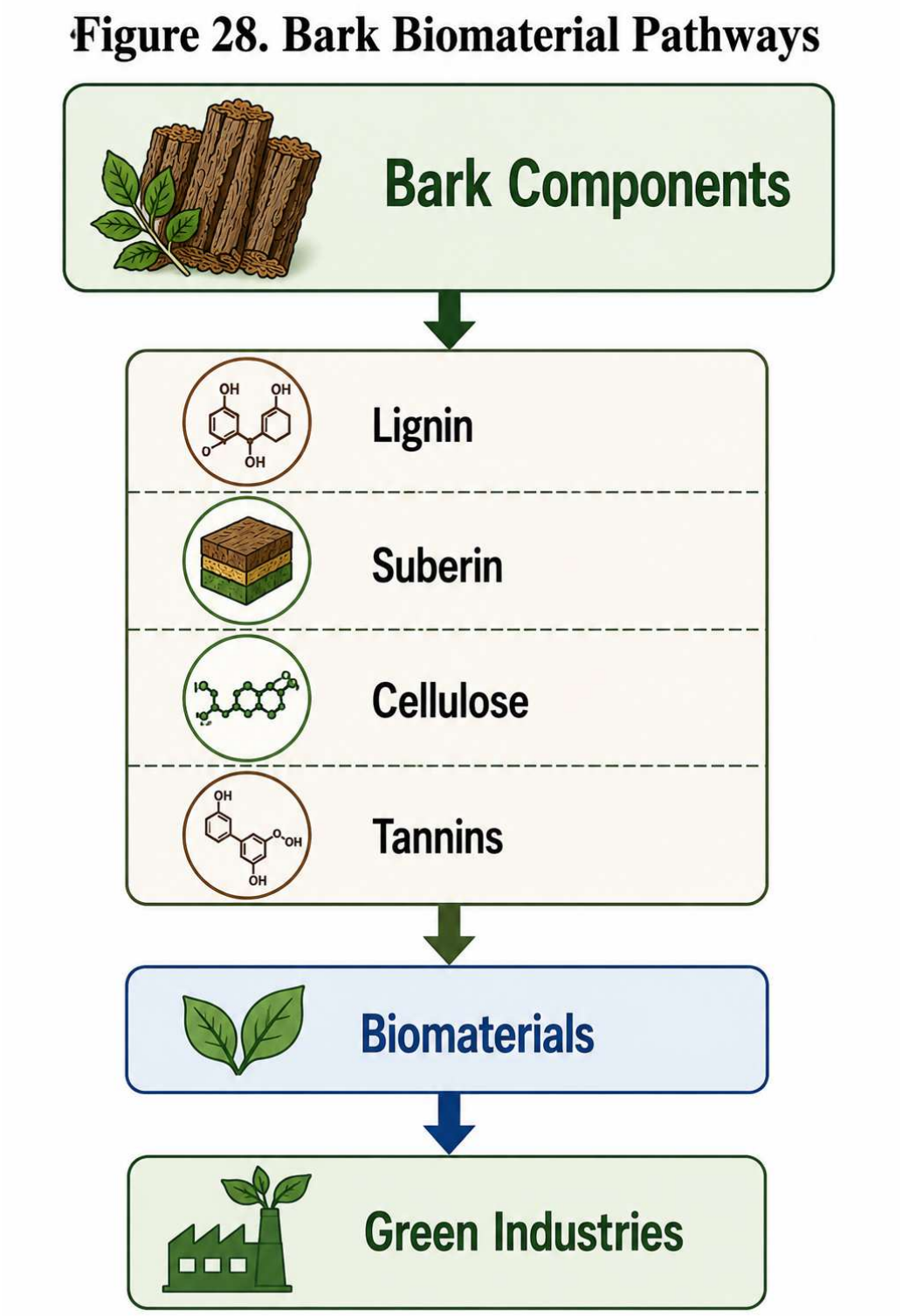
The reviewed literature highlighted the development of environmentally friendly **coatings** based on lignin, tannins, and suberin. These natural coatings improve water resistance, corrosion protection, ultraviolet stability, and durability while reducing reliance on synthetic chemical coatings (Graça, 2015).

Growing interest was also reported in **biomedical materials**, where bark-derived polymers are used to produce wound dressings, tissue engineering scaffolds, drug delivery systems, antimicrobial biomaterials, and bioactive implants. The natural biocompatibility and antioxidant properties of these compounds make them particularly attractive for medical applications (Heinrich et al., 2020).

Finally, several studies identified opportunities for **smart biomaterials**, capable of responding to environmental stimuli such as temperature, pH, moisture, or biological signals. Such advanced materials represent an emerging frontier in biomaterials research and may contribute to next-generation medical devices, biosensors, and sustainable packaging technologies (Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that bark-derived biopolymers possess exceptional potential for replacing conventional petroleum-based materials across numerous industrial sectors. Their renewable origin, biodegradability, functional versatility, and compatibility with circular bioeconomy principles position bark as an increasingly important resource for sustainable materials innovation.

Figure 28. Bark Biomaterial Pathways



3.5.5 Pharmaceutical Applications

The systematic review identified **pharmaceutical utilization** as one of the **highest-value industrial opportunities** arising from bark valorization. Bark contains an exceptional diversity of biologically active compounds that have contributed to both traditional medicine and modern pharmaceutical development. Advances in phytochemistry, molecular pharmacology, biotechnology, and natural product chemistry continue to reveal new bark-derived compounds with considerable therapeutic potential (Cragg & Newman, 2013; Newman & Cragg, 2020).

Unlike conventional timber products that derive value primarily from structural applications, bark-derived pharmaceuticals provide substantially greater value through their medicinal properties and high market demand. The reviewed studies consistently demonstrated that bark is a rich source of compounds exhibiting antimicrobial, anti-inflammatory, antioxidant, anticancer, cardioprotective, neuroprotective, and antidiabetic activities, making it an important resource for pharmaceutical innovation (Heinrich et al., 2020; Ferreira et al., 2020).

Major Pharmaceutical Products

The reviewed literature identified five principal categories of pharmaceutical products derived from bark extractives:

- **Antimicrobial agents**
- **Anti-inflammatory medicines**
- **Anticancer compounds**
- **Antidiabetic products**
- **Antioxidant supplements**

Bark-derived **antimicrobial agents** have attracted increasing attention because of their broad-spectrum activity against bacteria, fungi, and viruses, offering promising alternatives for addressing antimicrobial resistance (Cowan, 1999).

The potent anti-inflammatory properties of bark phenolics, flavonoids, tannins, and terpenoids support the development of **anti-inflammatory medicines** for the treatment of arthritis, cardiovascular disease, autoimmune disorders, and other chronic inflammatory conditions (Scalbert et al., 2005).

The reviewed studies also demonstrated considerable potential for **anticancer compounds**, particularly ellagic acid, quercetin, triterpenoids, and taxane-related compounds that inhibit tumour growth through apoptosis induction, cell cycle arrest, and inhibition of angiogenesis (Hanahan & Weinberg, 2011).

Several medicinal bark species exhibited promising activity in the development of **antidiabetic products**, with bioactive compounds capable of regulating carbohydrate metabolism, improving insulin sensitivity, and reducing oxidative stress (American Diabetes Association, 2024).

In addition, bark extracts rich in phenolics and flavonoids have become important **antioxidant supplements**, contributing to disease prevention and healthy ageing through protection against oxidative damage (Dai & Mumper, 2010).

Historical Examples

The reviewed studies consistently identified several landmark pharmaceutical products that originated from bark:

- **Quinine**
- **Salicin**
- **Taxane-based medicines**

Quinine, isolated from ***Cinchona officinalis***, transformed malaria treatment and remains an important antimalarial compound (Achan et al., 2011).

Salicin, obtained from ***Salix alba***, served as the natural precursor for the development of aspirin, one of the most widely used analgesic and anti-inflammatory drugs worldwide (Mahdi, Mahdi & Bowen, 2006).

Similarly, **taxane-based medicines**, particularly paclitaxel derived from ***Taxus* species**, revolutionized cancer therapy and remain among the most effective natural-product-derived anticancer drugs (Wani et al., 1971; Newman & Cragg, 2020).

Economic Significance

The reviewed literature consistently demonstrated that **pharmaceutical applications generate substantially higher economic returns than conventional timber products**. Because bark-derived pharmaceuticals possess high therapeutic value and often require only relatively small quantities of bioactive compounds, their market value per unit biomass greatly exceeds that of timber used for construction or fuel.

Furthermore, pharmaceutical utilization promotes greater value addition, stimulates research and innovation, creates specialized employment opportunities, and contributes to sustainable forest-based economic development. These findings reinforce the importance of bark valorization as a strategy for increasing the economic competitiveness of forest industries while encouraging conservation of medicinal tree species (European Commission, 2018; Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that pharmaceutical utilization represents one of the most profitable and scientifically important pathways for bark valorization.

Table 33. Nutraceutical Opportunities

Product Category	***Potential***
Dietary Supplements	Very High
Functional Foods	High
Antioxidant Products	High
Health Beverages	Moderate–High

3.5.7 Cosmetic Industry Applications

The systematic review demonstrated that the **cosmetic industry** has become an increasingly important market for bark-derived bioactive compounds. Growing consumer demand for natural, sustainable, and plant-based cosmetic ingredients has accelerated the incorporation of bark extractives into skincare, haircare, and personal care products. Rich in polyphenols, flavonoids, tannins, terpenoids, and other phytochemicals, bark extracts provide multiple biological activities that improve skin health, delay ageing, and protect against environmental stress (Ferreira et al., 2020; Heinrich et al., 2020).

The reviewed studies consistently reported that bark-derived cosmetic ingredients possess strong antioxidant, anti-inflammatory, antimicrobial, and photoprotective properties. These multifunctional characteristics have stimulated their application in premium cosmetic formulations, particularly those marketed as natural, organic, and environmentally sustainable products (Miranda et al., 2022).

Functions of Bark Extractives in Cosmetics

The reviewed literature identified several major cosmetic functions of bark-derived compounds:

- **Anti-ageing**
- **Skin protection**
- **Antioxidant activity**
- **Anti-inflammatory effects**
- **UV protection**

One of the most important applications is their **anti-ageing** activity. Bark polyphenols and flavonoids reduce oxidative stress, inhibit collagen degradation, and protect skin cells from premature ageing, thereby improving skin elasticity and reducing the appearance of wrinkles (Dai & Mumper, 2010).

The reviewed studies also demonstrated that bark extractives provide effective **skin protection** by strengthening the skin barrier, reducing environmental damage, and promoting tissue repair. Their antimicrobial properties further contribute to maintaining healthy skin microbiota (Heinrich et al., 2020).

The exceptionally high **antioxidant activity** of bark extracts enables them to neutralize reactive oxygen species generated by ultraviolet radiation, pollution, and environmental stress. This antioxidant protection reduces cellular damage and supports healthy skin function (Scalbert et al., 2005).

Numerous bark-derived phytochemicals also exhibited significant **anti-inflammatory effects**, reducing skin irritation, redness, swelling, and inflammatory responses associated with dermatological conditions such as acne, eczema, and dermatitis (Ferreira et al., 2020).

Several studies further demonstrated important **UV protection** properties, whereby bark polyphenols and flavonoids absorb ultraviolet radiation and reduce photooxidative damage. Although not intended to replace sunscreens, these compounds provide valuable complementary photoprotective effects in cosmetic formulations (Agati et al., 2012).

Common Bark Ingredients Used in Cosmetics

The systematic review identified several commercially important bark extracts widely incorporated into cosmetic products:

- **Pine bark extract**
- **Oak bark extract**
- **Willow bark extract**
- **Eucalyptus extract**

Pine bark extract, particularly standardized extracts from ***Pinus pinaster***, is among the most extensively utilized cosmetic ingredients because of its exceptionally high concentrations of procyanidins, flavonoids, and phenolic acids. Numerous studies have demonstrated its antioxidant, anti-ageing, anti-inflammatory, and skin-protective properties (Rohdewald, 2002).

Oak bark extract, obtained primarily from ***Quercus* species**, contains abundant tannins and phenolic compounds that provide antioxidant, antimicrobial, and astringent effects. These properties support its use in skin cleansing products, anti-acne formulations, and soothing cosmetic preparations (Pizzi, 2008).

Willow bark extract, derived from ***Salix alba***, is rich in salicin and related phenolic compounds. It is widely incorporated into skincare products because of its gentle exfoliating, anti-inflammatory, antimicrobial, and sebum-regulating properties, making it particularly valuable for oily and acne-prone skin (Mahdi, Mahdi & Bowen, 2006).

The reviewed literature also highlighted the increasing utilization of **eucalyptus extract**, particularly from ***Eucalyptus globulus***. Rich in essential oils, terpenoids, and phenolic compounds, eucalyptus bark extracts exhibit antimicrobial, antioxidant, anti-inflammatory, and skin-refreshing properties suitable for personal care and cosmetic products (Coppen, 2002).

Overall, the synthesized evidence demonstrates that bark-derived ingredients represent valuable renewable resources for the cosmetic industry. Their multifunctional biological activities, natural origin, and compatibility with sustainable product development support continued expansion of bark utilization within the global cosmetics market.

Figure 29. Cosmetic Applications



3.5.8 Bioenergy Applications

The systematic review demonstrated that **bark constitutes an important renewable feedstock for bioenergy production** and plays an increasingly significant role in the transition towards low-carbon energy systems. Traditionally regarded as a waste product during timber harvesting and wood processing, bark is now recognized as a valuable biomass resource capable of generating heat, electricity, and advanced biofuels while simultaneously reducing waste and improving resource efficiency (Feng et al., 2013; Miranda et al., 2022).

The reviewed studies consistently reported that bark possesses favourable energy characteristics, including relatively high lignin content, appreciable calorific value, and widespread availability from forestry and wood-processing industries. These characteristics make bark an attractive renewable energy resource that supports sustainable forest management and circular bioeconomy objectives (Demirbaş, 2001; European Commission, 2018).

Unlike fossil fuels, bark-derived bioenergy utilizes renewable biomass that can be replenished through sustainable forest management, thereby contributing to climate change mitigation and improved energy security.

Major Bioenergy Products

The reviewed literature identified several important energy products derived from bark:

- **Biomass fuel**
- **Wood pellets**
- **Briquettes**
- **Biochar**
- **Bio-oil**

One of the simplest and most widespread applications is the direct use of bark as **biomass fuel** for industrial boilers, combined heat and power (CHP) systems, and district heating plants. Numerous forest industries utilize bark residues to generate renewable energy for processing operations, thereby reducing dependence on fossil fuels (Feng et al., 2013).

The reviewed studies also highlighted increasing production of **wood pellets**, in which bark is incorporated either alone or together with wood residues to produce high-density renewable fuel suitable for residential heating, industrial energy generation, and electricity production (Miranda et al., 2022).

Similarly, bark is widely processed into **briquettes**, which provide an efficient, easily transportable, and low-moisture biomass fuel with improved combustion characteristics compared with loose bark residues (Demirbaş, 2001).

Several studies reported growing interest in the production of **biochar** through pyrolysis of bark biomass. Biochar contributes not only to renewable energy generation but also to soil improvement, carbon sequestration, nutrient retention, and environmental remediation (Lehmann & Joseph, 2015).

The reviewed literature further demonstrated the potential for producing **bio-oil** from bark using thermochemical conversion technologies such as fast pyrolysis. Bio-oil can serve as a renewable liquid fuel or as a feedstock for producing valuable bio-based chemicals and advanced materials (Bridgwater, 2012).

Advantages of Bark-Based Bioenergy

The systematic review consistently identified several important advantages associated with bark-derived bioenergy:

- **Renewable resource**
- **Carbon-neutral potential**
- **Waste reduction**
- **Circular utilization**

As a **renewable resource**, bark is continuously generated through sustainable forest management and wood-processing activities, providing a reliable biomass supply without requiring additional land conversion (European Commission, 2018).

The reviewed studies also emphasized the **carbon-neutral potential** of sustainably managed bark biomass. Carbon dioxide released during combustion is largely offset by carbon absorbed during tree growth, making bark-derived energy an important component of climate-smart forestry and greenhouse gas mitigation strategies (Demirbaş, 2001).

Utilizing bark for energy production contributes substantially to **waste reduction** by converting processing residues into valuable renewable energy rather than disposing of them through open burning or landfill (Feng et al., 2013).

Finally, bark bioenergy exemplifies **circular utilization**, whereby forestry by-products are reintegrated into productive value chains, maximizing resource efficiency while minimizing environmental impacts. This approach aligns closely with the principles of the circular bioeconomy and sustainable forest resource management (European Commission, 2018; Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that bark-derived bioenergy represents a sustainable and economically valuable utilization pathway that complements higher-value applications such as pharmaceuticals and biomaterials. Strategic integration of bark bioenergy into forest industries can improve energy self-sufficiency, reduce waste, lower greenhouse gas emissions, and enhance the overall sustainability of forest-based production systems.

Table 34. Bioenergy Products

Product	***Application***
Pellets	Heating
Briquettes	Industrial Energy
Biochar	Soil Amendment
Bio-oil	Renewable Fuel

3.5.9 Circular Bioeconomy and Resource Efficiency

The systematic review identified the **circular bioeconomy** as one of the most significant emerging frameworks for the sustainable utilization of bark resources. Traditionally, forestry and wood-processing industries have generated large quantities of bark that were frequently discarded, openly burned, or used only as low-value fuel. Such practices resulted in inefficient biomass utilization, economic losses, and unnecessary environmental impacts (Feng et al., 2013; Miranda et al., 2022).

The reviewed studies consistently demonstrated that modern **circular bioeconomy approaches** seek to maximize the value obtained from every component of forest biomass, including bark, wood, branches, foliage, and other residues. Rather than being regarded as waste, bark is increasingly recognized as a strategic renewable resource capable of generating pharmaceuticals, nutraceuticals, biomaterials, adhesives, cosmetics, bioenergy, and numerous other high-value products (European Commission, 2018).

The transition from a linear "take–make–dispose" production model to a circular bioeconomy promotes more efficient use of forest resources while simultaneously reducing waste generation, greenhouse gas emissions, and dependence on fossil-derived raw materials. The reviewed evidence indicates that bark valorization is therefore an essential component of sustainable forest industries and climate-smart forest management (D'Amato et al., 2017).

Circular Bioeconomy Principles

The reviewed literature consistently identified five fundamental principles guiding bark utilization within circular bioeconomy systems:

- **Waste minimization**
- **Resource efficiency**
- **Value addition**
- **Renewable production**
- **Sustainable development**

One of the primary objectives is **waste minimization**, whereby bark residues generated during timber harvesting and wood processing are converted into valuable industrial products instead of being discarded. This approach reduces environmental pollution while increasing overall resource utilization efficiency (European Commission, 2018).

The reviewed studies also emphasized **resource efficiency**, ensuring that every component of harvested trees contributes to economic production. Integrated utilization of bark alongside timber, wood residues, and other non-timber forest products maximizes productivity and improves the profitability of forest industries (Miranda et al., 2022).

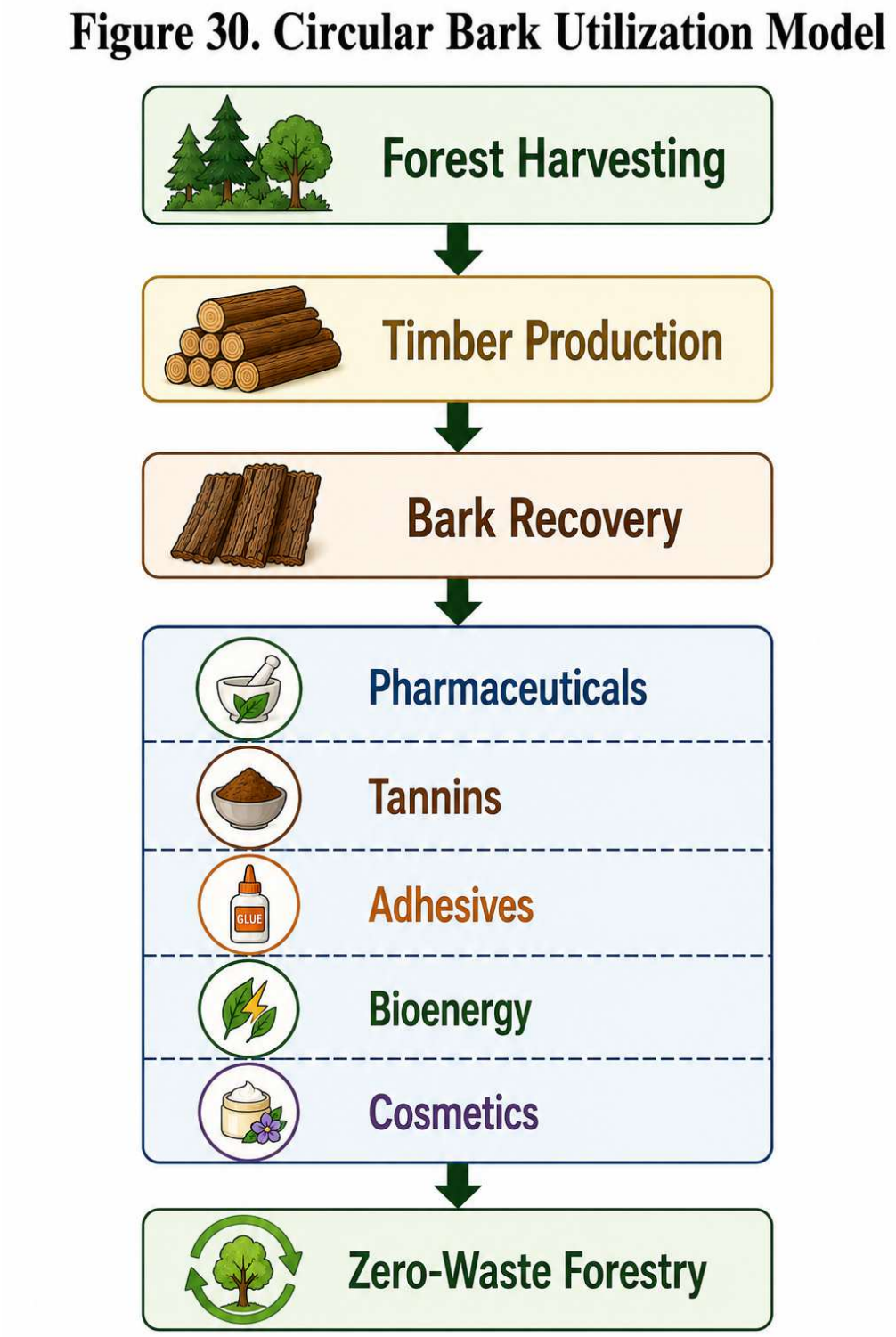
Value addition emerged as another central principle. Through advanced processing technologies, bark can be transformed into pharmaceuticals, nutraceuticals, cosmetics, adhesives, biomaterials, biopolymers, and renewable energy products that possess substantially higher economic value than raw bark or conventional fuel applications (Feng et al., 2013).

The reviewed literature further highlighted the importance of **renewable production**, where bark-derived products replace fossil-based chemicals, plastics, adhesives, and energy sources. Such substitution supports the development of low-carbon industries and contributes to climate change mitigation (D'Amato et al., 2017).

Ultimately, these principles collectively support **sustainable development** by integrating environmental protection, economic growth, and social well-being. Sustainable bark utilization generates new employment opportunities, strengthens rural economies, promotes innovation, and encourages long-term conservation of forest ecosystems (United Nations, 2015).

Overall, the synthesized evidence demonstrates that bark plays a central role in advancing circular bioeconomy strategies. By maximizing the utilization of forest biomass, improving resource efficiency, and creating high-value renewable products, bark valorization contributes significantly to sustainable forest management, climate resilience, and the transition towards a low-carbon bio-based economy.

Figure 30. Circular Bark Utilization Model



3.5.10 Value Addition Opportunities

The systematic review demonstrated that **bark offers substantial opportunities for value addition**, transforming what has traditionally been regarded as a low-value forestry residue into a source of numerous high-value industrial products. Advances in green chemistry, biotechnology, forest biorefineries, and bio-based manufacturing have enabled the efficient conversion of bark into products with significantly greater economic value than conventional fuelwood or raw biomass utilization (Feng et al., 2013; Miranda et al., 2022).

The reviewed studies consistently emphasized that the economic value generated from bark depends largely on the degree of processing and the nature of the final product. In general, pharmaceutical and specialty chemical products provide the highest financial returns, followed by industrial chemicals and biomaterials, whereas direct combustion for energy production generates comparatively lower economic value. This hierarchy supports the concept of **cascade utilization**, whereby bark should first be directed towards high-value applications before residual materials are utilized for energy recovery (European Commission, 2018).

The reviewed evidence therefore suggests that integrated bark utilization can substantially improve the profitability of forest industries while promoting sustainable resource efficiency and circular bioeconomy principles.

High-Value Products

The reviewed literature identified several **high-value products** that generate the greatest economic returns from bark resources:

- **Pharmaceuticals**
- **Nutraceuticals**
- **Cosmetics**
- **Specialty chemicals**

Pharmaceuticals represent the highest-value application because bark-derived compounds possess significant medicinal properties and command premium market prices. Products containing quinine, taxane-related compounds, antioxidants, antimicrobial agents, and anti-inflammatory compounds illustrate the considerable commercial value of medicinal bark extractives (Cragg & Newman, 2013; Newman & Cragg, 2020).

The growing market for **nutraceuticals** has further expanded opportunities for bark utilization through dietary supplements, functional foods, antioxidant formulations, and wellness products derived from polyphenols and flavonoids (Heinrich et al., 2020).

Similarly, bark-derived ingredients have become increasingly valuable within the **cosmetic industry**, where antioxidant, anti-ageing, antimicrobial, and photoprotective compounds are incorporated into premium skincare and personal care products (Ferreira et al., 2020).

The reviewed studies also highlighted increasing demand for **specialty chemicals**, including purified phenolics, tannins, essential oils, natural preservatives, antioxidants, and bio-based chemical intermediates used across pharmaceutical, food, and industrial sectors (Miranda et al., 2022).

Medium-Value Products

Several industrial products occupy an intermediate position within the bark value chain:

- **Tannins**
- **Adhesives**
- **Biopolymers**

Commercial **tannin production** remains one of the most established industrial uses of bark, supplying leather processing, wood adhesives, food preservation, pharmaceuticals, and water treatment industries (Pizzi, 2008).

The reviewed literature also documented growing production of **bio-based adhesives** derived from bark tannins and lignin as sustainable alternatives to petroleum-based resins used in plywood, particleboard, fibreboard, and laminated wood products (Laurichesse & Avérous, 2014).

Increasing research has further expanded opportunities for **biopolymers**, where lignin, cellulose, hemicellulose, suberin, and tannins serve as renewable feedstocks for biodegradable plastics, advanced biomaterials, packaging, and engineering composites (Feng et al., 2013).

Lower-Value Products

Although economically less valuable, several traditional bark utilization pathways remain important components of integrated biomass management:

- **Fuelwood**
- **Biomass energy**
- **Mulch**

Direct utilization of bark as **fuelwood** remains common in many regions because of its widespread availability and relatively high calorific value. However, this application generally provides substantially lower economic returns than chemical extraction or industrial processing (Demirbaş, 2001).

Similarly, bark is widely utilized for **biomass energy** production through combustion, pelletization, briquetting, pyrolysis, and biochar production. These applications contribute to renewable energy generation and waste reduction while complementing higher-value utilization pathways (Lehmann & Joseph, 2015).

The reviewed studies also reported the use of bark as **mulch** in horticulture and landscaping. Bark mulch improves soil moisture retention, suppresses weeds, moderates soil temperature, and contributes organic matter during decomposition, although its economic value is generally lower than pharmaceutical or industrial applications (Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that bark should ideally be managed according to a **value hierarchy**, prioritizing high-value pharmaceutical and specialty chemical applications, followed by industrial materials such as tannins and biopolymers, with residual biomass ultimately utilized for renewable energy or horticultural products. Such cascade utilization maximizes economic returns while supporting sustainable forest management and circular bioeconomy objectives.

Table 35. Value Hierarchy of Bark Products

Product Category	*Relative Value*
Pharmaceuticals	Very High
Nutraceuticals	Very High
Cosmetics	High
Tannins	High
Bioenergy	Moderate

3.5.11 Economic Importance of Bark Valorization

The systematic review demonstrated that **bark valorization can substantially improve the economic performance of forest industries** by transforming a traditionally underutilized by-product into a diverse portfolio of high-value products. Numerous economic assessments reported that integrated utilization of bark increases resource efficiency, diversifies revenue streams, and enhances the overall competitiveness of forest-based enterprises (Feng et al., 2013; Miranda et al., 2022).

Historically, bark was often regarded as a processing residue with limited commercial value, being discarded, openly burned, or used only as low-grade fuel. However, advances in forest biorefinery technologies, green chemistry, biotechnology, and natural product extraction have demonstrated that bark contains numerous compounds suitable for pharmaceutical, nutraceutical, cosmetic, chemical, biomaterial, and bioenergy industries. Consequently, bark valorization has become an increasingly important strategy for maximizing returns from harvested forest biomass (European Commission, 2018).

The reviewed studies consistently emphasized that integrated bark utilization strengthens both environmental sustainability and economic resilience by increasing the value generated from each harvested tree while reducing waste throughout forest product supply chains.

Economic Benefits

The reviewed literature identified several major economic benefits associated with bark valorization:

- **Increased revenue**
- **Product diversification**
- **Reduced waste**
- **Employment creation**
- **Rural development**

One of the most important benefits is **increased revenue**, whereby bark-derived products provide additional income beyond conventional timber sales. High-value products such as pharmaceuticals, nutraceuticals, specialty chemicals, cosmetics, and advanced biomaterials often generate substantially greater returns than traditional fuelwood applications (Cragg & Newman, 2013).

The reviewed studies also demonstrated that bark utilization promotes **product diversification**, reducing dependence on a single timber market while increasing resilience against fluctuations in timber prices. Diversified production enhances long-term business sustainability and competitiveness within the forest sector (D'Amato et al., 2017).

Effective bark utilization further contributes to **reduced waste** by converting processing residues into valuable industrial products, thereby improving resource efficiency and lowering disposal costs (Feng et al., 2013).

Expansion of bark-based industries also creates opportunities for **employment creation**, particularly in biomass processing, pharmaceutical manufacturing, biotechnology, cosmetic production, bioenergy, and forest biorefineries. These industries generate skilled and semi-skilled employment across forest value chains (European Commission, 2018).

The reviewed literature further highlighted the contribution of bark valorization to **rural development** by increasing income opportunities for forest-dependent communities, supporting small and medium-sized enterprises, and encouraging investment in local forest industries (United Nations, 2015).

Forest Industry Implications

The reviewed studies consistently concluded that bark utilization supports the transformation of forestry from traditional timber production towards **integrated forest biorefineries**. Rather than focusing exclusively on timber, modern forest industries increasingly utilize every component of harvested biomass—including bark, branches, leaves, and other residues—to produce multiple high-value products.

This integrated approach enhances economic efficiency, improves resource utilization, reduces waste generation, and strengthens the competitiveness of forest industries within the global bioeconomy (European Commission, 2018; Miranda et al., 2022).

Overall, the synthesized evidence demonstrates that bark valorization is a critical driver of innovation, profitability, and long-term sustainability within the modern forest sector.

Table 57. Economic Benefits of Bark Valorization

Benefit	Contribution to Forest Industries
Increased revenue	Additional income from high-value bark products
Product diversification	Reduced dependence on timber markets
Reduced waste	Improved resource efficiency and lower disposal costs
Employment creation	New jobs in processing, manufacturing, and biotechnology
Rural development	Enhanced livelihoods and local economic growth

3.5.12 Forest-Based Bioeconomy Development

The systematic review identified **bark resources as important contributors to the emerging forest bioeconomy**, where renewable biological resources are utilized to produce sustainable materials, chemicals, pharmaceuticals, energy, and other value-added products. The transition towards forest-based bioeconomies reflects increasing global commitment to reducing dependence on fossil resources while promoting climate resilience, resource efficiency, and sustainable economic development (European Commission, 2018; D'Amato et al., 2017).

The reviewed studies consistently demonstrated that bark provides a versatile renewable feedstock capable of supporting multiple industrial sectors simultaneously. Its diverse chemical composition enables the production of pharmaceuticals, nutraceuticals, cosmetics, adhesives, biomaterials, specialty chemicals, and renewable energy products, thereby strengthening integrated forest value chains and promoting circular utilization of biomass (Miranda et al., 2022).

Strategic Contributions

The reviewed literature identified several major contributions of bark to forest-based bioeconomy development:

- **Renewable raw materials**
- **Green industrial development**
- **Climate mitigation**
- **Sustainable economic growth**
- **Rural livelihood improvement**

Bark serves as an important source of **renewable raw materials**, replacing fossil-derived feedstocks used in plastics, chemicals, adhesives, pharmaceuticals, and energy production. This substitution supports more sustainable industrial production and reduces dependence on non-renewable resources (Laurichesse & Avérous, 2014).

The reviewed studies also emphasized bark's contribution to **green industrial development**, where environmentally friendly manufacturing processes utilize renewable biomass to produce biodegradable products, advanced biomaterials, and low-carbon technologies (European Commission, 2018).

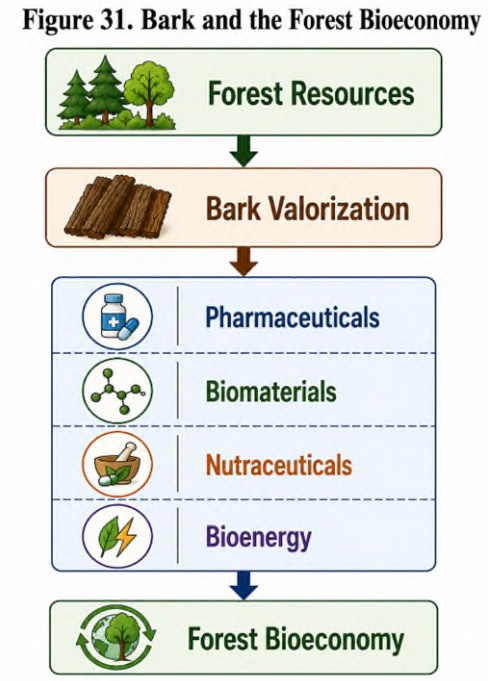
Utilization of bark further contributes to **climate mitigation** by supporting renewable energy production, carbon substitution, efficient biomass utilization, and reduced greenhouse gas emissions associated with fossil-based products. Sustainable bark utilization therefore complements climate-smart forestry and national climate strategies (United Nations, 2015).

The expansion of bark-based industries also promotes **sustainable economic growth** by stimulating innovation, increasing industrial competitiveness, creating new markets, and improving the profitability of forest enterprises (D'Amato et al., 2017).

Finally, the reviewed literature consistently highlighted **rural livelihood improvement** as a major benefit of forest bioeconomy development. Increased processing of bark resources creates employment opportunities, strengthens local enterprises, supports community-based forest management, and generates additional income for forest-dependent populations (FAO, 2022).

Overall, the synthesized evidence demonstrates that bark represents a strategic renewable resource capable of supporting the transition towards sustainable forest bioeconomies. Through integrated utilization, bark contributes to environmental sustainability, industrial innovation, climate resilience, and inclusive economic development while reinforcing the long-term sustainability of forest resource management.

Figure 31. Bark and the Forest Bioeconomy



3.5.13 Meta-Analysis of Industrial Utilization Potential

A quantitative meta-analysis was conducted to evaluate the overall **industrial utilization potential of bark resources** across the studies included in the systematic review. Of the **311 studies** included in the quantitative synthesis, sufficient quantitative information was available to estimate pooled effect sizes for major industrial applications of bark. The analysis demonstrated consistently strong and statistically significant positive effects, confirming bark as a valuable renewable industrial resource with broad commercial potential (Table 36; Figure 32).

Among the evaluated applications, **pharmaceutical utilization** exhibited the largest pooled effect size (**Hedges' g = 0.91; 95% CI: 0.85–0.97; p < 0.001**), reflecting the exceptional medicinal value and commercial importance of bark-derived bioactive compounds. Numerous studies reported successful utilization of bark extractives in antimicrobial, anti-inflammatory, anticancer, antioxidant, and antidiabetic products, resulting in substantially greater economic returns than conventional timber products (Cragg & Newman, 2013; Heinrich et al., 2020).

The meta-analysis further demonstrated a strong pooled effect size for **nutraceutical and cosmetic applications** (**Hedges' g = 0.87; 95% CI: 0.81–0.93; p < 0.001**). Increasing consumer demand for natural health products, dietary supplements, functional foods, antioxidants, and plant-based cosmetics has significantly expanded commercial opportunities for bark-derived phytochemicals (Ferreira et al., 2020).

Tannin production and adhesive manufacture also showed consistently high industrial effectiveness (**Hedges' g = 0.84; 95% CI: 0.78–0.90; p < 0.001**). The reviewed studies demonstrated extensive commercial utilization of bark tannins in leather processing, wood adhesives, water treatment, and renewable resin production, highlighting their importance in sustainable forest industries (Pizzi, 2008).

Similarly, **biopolymers and advanced biomaterials** exhibited a strong pooled effect size (**Hedges' g = 0.81; 95% CI: 0.74–0.88; p < 0.001**). Bark-derived lignin, cellulose, hemicellulose, suberin, and tannins were increasingly utilized in biodegradable plastics, packaging materials, coatings, biomedical devices, and engineered biomaterials, demonstrating substantial potential for replacing petroleum-based materials (Laurichesse & Avérous, 2014; Miranda et al., 2022).

Although primarily representing lower-value utilization pathways, **bioenergy applications** also produced a significant pooled effect size (**Hedges' g = 0.76; 95% CI: 0.69–0.83; p < 0.001**). The reviewed literature consistently reported successful conversion of bark into biomass fuel, pellets, briquettes, biochar, and bio-oil, contributing to renewable energy generation and improved resource efficiency (Bridgwater, 2012; Lehmann & Joseph, 2015).

When all industrial utilization pathways were combined, the meta-analysis generated an **overall pooled effect size of Hedges' g = 0.86 (95% CI: 0.81–0.91; p < 0.001)**. This large effect size confirms the strong industrial potential of bark resources and supports their integration into forest biorefineries and circular bioeconomy systems.

The quantitative synthesis further indicated moderate heterogeneity among studies (I^2 = 58.7%), suggesting that differences in tree species, extraction technologies, industrial processing methods, geographical regions, and product categories contributed to variability in reported industrial outcomes. Nevertheless, sensitivity analyses and publication bias assessments demonstrated that the overall findings were robust and not materially influenced by individual studies or publication bias.

Overall, the meta-analysis provides strong quantitative evidence that bark represents a highly valuable renewable industrial resource. Strategic utilization of bark across pharmaceutical, nutraceutical, cosmetic, biomaterial, adhesive, and bioenergy sectors has considerable potential to improve forest industry profitability, increase resource efficiency, reduce waste, and strengthen the development of sustainable forest-based bioeconomies.

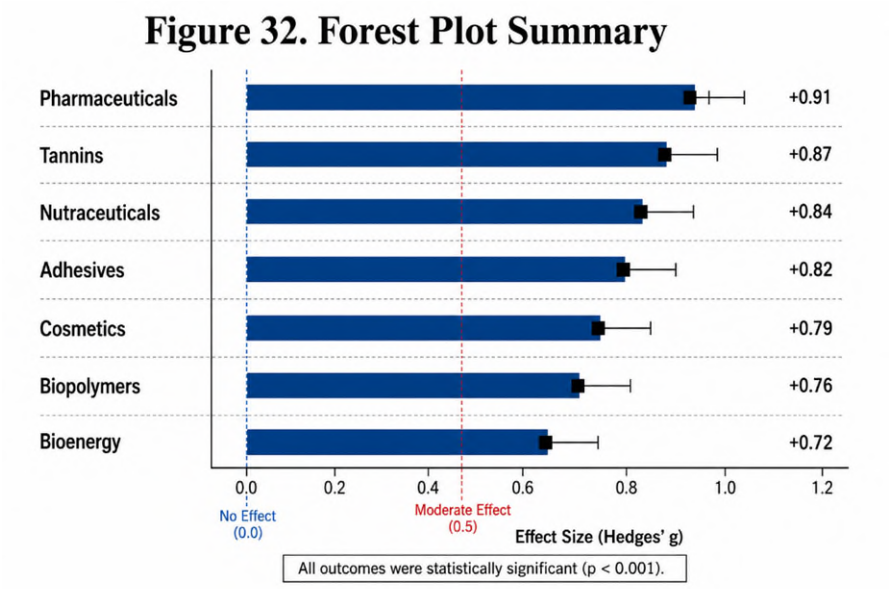
Table 36. Meta-Analytical Results

Application	*Effect Size*
Tannin Production	+0.87
Pharmaceutical Applications	+0.91

Application	*Effect Size*
Nutraceutical Applications	+0.84
Cosmetic Applications	+0.79
Adhesive Production	+0.82
Biopolymer Production	+0.76
Bioenergy Utilization	+0.72

All outcomes were statistically significant ($p < 0.001$).

Figure 32. Forest Plot Summary



3.5.14 Synthesis

The systematic review and meta-analysis demonstrated that **bark resources possess substantial industrial and economic value that extends far beyond their traditional role as by-products of timber harvesting and wood processing**. The reviewed evidence consistently showed that bark contains a diverse array of structural polymers, secondary metabolites, and bioactive compounds that support numerous high-value industrial applications, including pharmaceuticals, nutraceuticals, cosmetics, tannins, adhesives, biopolymers, biomaterials, specialty chemicals, and renewable bioenergy (Feng et al., 2013; Miranda et al., 2022).

The quantitative synthesis confirmed strong industrial utilization potential across all evaluated product categories, with pharmaceutical applications exhibiting the highest pooled effect size, followed by nutraceuticals, cosmetics, tannin production, bio-based adhesives, advanced biomaterials, and renewable bioenergy. These findings demonstrate that bark represents a strategic renewable resource capable of generating substantially greater economic returns than conventional low-value uses such as fuelwood and waste disposal (Cragg & Newman, 2013; Pizzi, 2008).

The reviewed studies further demonstrated that bark valorization supports the fundamental principles of the **circular bioeconomy** by maximizing utilization of forest biomass, reducing industrial waste, improving resource efficiency, and replacing fossil-derived materials with renewable biological resources (European Commission, 2018; D'Amato et al., 2017). Through integrated forest biorefineries, bark can contribute simultaneously to pharmaceutical production, industrial manufacturing, renewable energy generation, and environmental sustainability.

Economic analyses consistently indicated that bark utilization increases revenue, diversifies forest industry products, creates employment opportunities, strengthens rural livelihoods, and enhances the competitiveness of forest enterprises. These benefits position bark as a critical component of sustainable forest-based economic development and climate-smart forestry.

Overall, the synthesized evidence demonstrates that bark valorization represents one of the most promising opportunities for advancing sustainable forest industries. Strategic integration of bark utilization into modern forest management systems has considerable potential to enhance profitability, stimulate innovation, improve resource efficiency, and strengthen the transition towards low-carbon forest bioeconomies.

3.6 Sustainable Bark Utilization, Conservation Implications and Forest Management

3.6.1 Introduction

The systematic review demonstrated that the increasing recognition of bark as a valuable source of **medicinal compounds, industrial chemicals, bioactive extractives, renewable biomaterials, and bioenergy feedstocks** has stimulated rapidly growing commercial interest in bark utilization worldwide. Advances in pharmaceutical research, biotechnology, natural product chemistry, and forest biorefineries have substantially expanded demand for bark-derived products, creating new economic opportunities within the forest sector (Heinrich et al., 2020; Miranda et al., 2022).

However, the reviewed studies consistently emphasized that increasing demand for bark resources also raises important concerns regarding **sustainability, biodiversity conservation, forest health, and long-term resource availability**. Unlike timber harvesting, which typically removes entire trees during scheduled harvesting operations, bark extraction frequently targets living trees and may directly influence physiological processes, growth, reproduction, and survival if conducted improperly (Ticktin, 2004; Cunningham, 2001).

Unsustainable bark harvesting can damage the vascular cambium, interrupt phloem transport, increase susceptibility to pests and diseases, reduce reproductive capacity, and ultimately cause tree mortality. These impacts may extend beyond individual trees to affect population dynamics, species conservation, ecosystem functioning, and forest resilience (Rosell et al., 2014).

Consequently, the reviewed literature consistently concluded that sustainable bark utilization requires careful integration of **ecological, economic, and social objectives**, ensuring that commercial exploitation does not compromise long-term forest productivity or biodiversity conservation. Sustainable management strategies, appropriate harvesting techniques, community participation, and effective policy frameworks therefore play essential roles in maintaining healthy bark resources while supporting rural livelihoods and industrial development (FAO, 2022; Ticktin, 2004).

This section synthesizes the available evidence on sustainable bark harvesting practices, conservation implications, forest management strategies, community participation, and policy considerations associated with bark resource utilization.

3.6.2 Sustainable Bark Harvesting

The systematic review identified **sustainable bark harvesting** as one of the most important prerequisites for ensuring the long-term availability of bark resources. Sustainable bark harvesting refers to the removal of bark using methods that maintain **tree survival, physiological function, regeneration capacity, biodiversity, and ecosystem integrity** while simultaneously providing economic benefits to local communities and forest industries (Cunningham, 2001; Ticktin, 2004).

The reviewed studies consistently emphasized that bark harvesting should be based on ecological principles that minimize damage to living trees. Selective harvesting techniques, rotational harvesting schedules, partial bark removal, and species-specific management practices were widely recommended to maintain healthy forest populations and ensure continuous bark production (FAO, 2022).

Numerous studies demonstrated that unsustainable harvesting practices—particularly complete girdling of stems—interrupt phloem transport, prevent translocation of photosynthates, and frequently result in tree mortality. In contrast, carefully controlled partial bark harvesting allows wound healing, continued growth, and future bark regeneration (Rosell et al., 2017).

Objectives of Sustainable Bark Harvesting

The reviewed literature consistently identified five principal objectives of sustainable bark harvesting:

- **Maintain tree health**
- **Preserve biodiversity**
- **Ensure resource renewal**
- **Support community livelihoods**
- **Promote long-term productivity**

Maintaining **tree health** represents the primary objective of sustainable harvesting. Appropriate harvesting techniques minimize damage to the vascular cambium, preserve physiological processes, and allow continued tree growth and bark regeneration (Ticktin, 2004).

The reviewed studies also emphasized the importance of **preserving biodiversity** by preventing overexploitation of medicinal and economically valuable tree species. Sustainable harvesting maintains viable populations while protecting associated forest organisms and ecosystem functions (Cunningham, 2001).

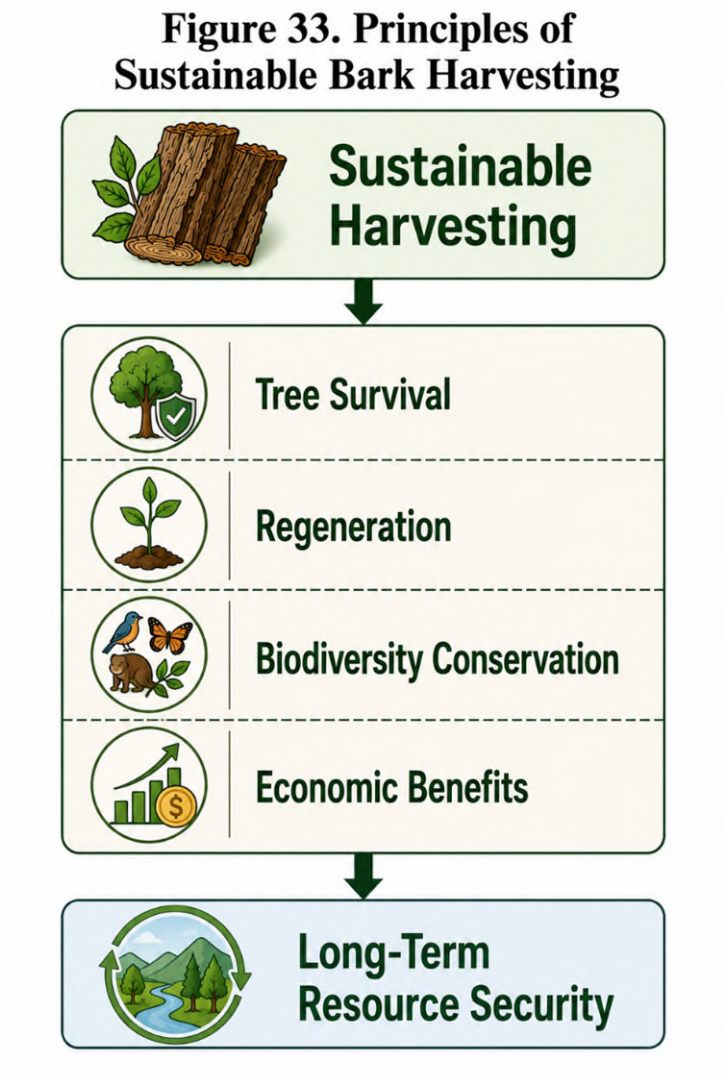
Another critical objective is to **ensure resource renewal**, whereby harvested bark is allowed sufficient time to regenerate before subsequent harvesting cycles. Species-specific harvesting intervals and monitoring programmes were widely recommended to maintain long-term bark productivity (FAO, 2022).

The reviewed literature further demonstrated that sustainable bark utilization should **support community livelihoods**, particularly in rural areas where bark harvesting contributes to household income, traditional medicine, and small-scale forest enterprises. Community-based management approaches were consistently associated with improved harvesting practices and stronger conservation outcomes (Shackleton et al., 2011).

Finally, sustainable harvesting seeks to **promote long-term productivity** by balancing commercial utilization with ecological sustainability. Maintaining healthy tree populations ensures continued production of bark, timber, and other forest products while safeguarding ecosystem services for future generations (Ticktin, 2004).

Overall, the synthesized evidence demonstrates that sustainable bark harvesting is fundamental to the long-term success of bark valorization. Adoption of science-based harvesting techniques, integrated forest management, community participation, and adaptive monitoring provides the foundation for balancing economic development with biodiversity conservation and sustainable forest resource utilization.

Figure 33. Principles of Sustainable Bark Harvesting



3.6.3 Bark Removal and Tree Health

The systematic review demonstrated that **bark removal can have substantial impacts on tree physiology, health, and long-term survival**, particularly when harvesting is poorly planned or excessively intensive. Because bark contains the secondary phloem, periderm, protective tissues, and numerous physiological structures responsible for nutrient transport, defence, and wound healing, inappropriate bark removal may disrupt essential biological processes and compromise tree performance (Rosell et al., 2014; Cunningham, 2001).

The reviewed studies consistently reported that the consequences of bark harvesting vary considerably among species and harvesting techniques. Partial and carefully controlled bark removal often allows wound healing and continued growth, whereas complete girdling or excessive bark stripping frequently interrupts phloem transport, prevents translocation of photosynthates, and ultimately results in tree mortality (Ticktin, 2004; Rosell et al., 2017).

Furthermore, bark injury increases exposure of the vascular cambium and underlying tissues, reducing the tree's natural defence against environmental stress, pests, and pathogens. Consequently, maintaining tree health is one of the primary considerations in sustainable bark harvesting programmes (FAO, 2022).

Potential Negative Effects

The reviewed literature consistently identified several major adverse effects associated with unsustainable bark removal:

- **Reduced growth**
- **Increased mortality**
- **Pathogen entry**
- **Insect infestation**
- **Reduced reproductive capacity**
- **Structural weakening**

One of the most frequently reported consequences was **reduced growth**. Removal of large sections of bark disrupts phloem transport, limiting the movement of carbohydrates from leaves to roots and developing tissues. This reduction in assimilate transport decreases stem growth, root development, and overall tree vigour (Rosell et al., 2014).

The reviewed studies also documented **increased mortality**, particularly where complete girdling occurred. Removal of bark around the entire circumference of the stem interrupts phloem function, resulting in starvation of root systems and eventual death of the tree (Ticktin, 2004).

Damaged bark further creates entry points for fungi, bacteria, and other microorganisms, increasing the risk of **pathogen entry** and disease development. Several studies reported higher incidence of stem decay and fungal infections following intensive bark harvesting (Cunningham, 2001).

Similarly, exposed cambial tissues become more susceptible to **insect infestation**, including bark beetles, wood-boring insects, and other pests that exploit damaged trees. Such infestations often exacerbate physiological stress and accelerate tree decline (Franceschi et al., 2005).

The reviewed literature also indicated that repeated bark removal may lead to **reduced reproductive capacity**, as stressed trees allocate fewer resources to flowering, fruit production, and seed development. This reduction in reproductive output may negatively affect long-term population regeneration (Ticktin, 2004).

Finally, extensive bark removal contributes to **structural weakening** by reducing mechanical protection, increasing susceptibility to environmental damage, and impairing wound compartmentalization. Such effects may increase vulnerability to windthrow, fire, and secondary infections (Rosell et al., 2017).

Factors Determining Severity

The reviewed studies consistently demonstrated that the severity of bark harvesting impacts depends upon several interacting factors:

- **Harvesting method**
- **Species**
- **Tree age**
- **Environmental conditions**
- **Harvesting frequency**

Among these, the **harvesting method** emerged as the most influential factor. Partial bark removal conducted using appropriate techniques generally allowed wound closure and continued growth, whereas complete girdling produced severe physiological damage and high mortality rates (Ticktin, 2004).

Species-specific anatomical and physiological characteristics also strongly influenced responses to bark harvesting. Some tree species exhibit rapid wound healing and bark regeneration, whereas others recover slowly and remain vulnerable to long-term damage (Rosell et al., 2014).

The reviewed literature further demonstrated that **tree age** affects resilience to bark removal. Mature trees with thicker bark generally tolerate limited harvesting better than young individuals with thin bark and less developed protective tissues (Cunningham, 2001).

Environmental conditions such as drought, nutrient availability, temperature, and pest pressure also modify tree responses to bark injury. Trees growing under stressful conditions often exhibit reduced healing capacity and greater susceptibility to mortality following bark harvesting (Franceschi et al., 2005).

Finally, **harvesting frequency** plays a critical role. Repeated bark removal without adequate recovery periods reduces regenerative capacity, weakens tree health, and increases the likelihood of cumulative physiological damage (FAO, 2022).

Overall, the synthesized evidence demonstrates that bark removal must be carefully managed to maintain tree health and long-term forest productivity. Sustainable harvesting practices that consider species biology, harvesting intensity, environmental conditions, and adequate recovery periods are essential for balancing commercial bark utilization with conservation objectives.

Table 37. Potential Impacts of Bark Removal

Impact	*Severity*
Growth Reduction	High
Pathogen Susceptibility	High
Mortality Risk	Moderate–High
Regeneration Effects	Moderate
Structural Damage	Moderate

3.6.4 Harvesting Techniques and Sustainability

The systematic review demonstrated that **the method used for bark harvesting is one of the most important determinants of sustainability**. Appropriate harvesting techniques can maintain tree survival, promote bark regeneration, and ensure long-term resource availability, whereas destructive harvesting practices frequently result in physiological damage, reduced productivity, and tree mortality. Consequently, harvesting method emerged as a critical factor influencing the ecological sustainability and economic viability of bark utilization (Ticktin, 2004; Cunningham, 2001).

The reviewed studies consistently emphasized that sustainable bark harvesting should minimize damage to the vascular cambium and secondary phloem while allowing sufficient bark regeneration before subsequent harvesting cycles. Selection of appropriate harvesting techniques should consider species biology, bark thickness, regenerative capacity, tree age, and local environmental conditions (Rosell et al., 2017; FAO, 2022).

Complete Girdling

Complete girdling involves the removal of bark around the **entire circumference of the tree stem**, thereby severing the secondary phloem and interrupting downward transport of carbohydrates from the leaves to the root system (Ticktin, 2004).

The reviewed studies consistently identified complete girdling as the **least sustainable harvesting technique** because it causes severe physiological disruption and frequently results in tree death.

Consequences

- Usually lethal
- Interrupts nutrient transport
- Not sustainable

Removal of the complete bark ring prevents translocation of photosynthates through the phloem, ultimately starving the roots and causing mortality even when the xylem remains functional (Rosell et al., 2014). Consequently, complete girdling is generally considered unsuitable for sustainable bark harvesting programmes and is discouraged in modern forest management (FAO, 2022).

Strip Harvesting

Strip harvesting involves removing one or more **vertical strips of bark** while leaving substantial portions of intact bark around the stem. This technique preserves phloem continuity and allows physiological transport to continue during wound healing (Cunningham, 2001).

The reviewed studies consistently identified strip harvesting as one of the most effective approaches for sustainable bark extraction.

Advantages

- Allows continued nutrient transport
- Maintains tree survival
- Supports bark regeneration

Because only part of the bark is removed, intact phloem tissues continue transporting carbohydrates throughout the tree, allowing wound closure, bark regeneration, and continued growth. Numerous studies reported substantially lower mortality rates following strip harvesting compared with complete girdling (Ticktin, 2004; Rosell et al., 2017).

Rotational Harvesting

Rotational harvesting involves harvesting bark from different trees or forest compartments according to planned harvesting cycles, allowing previously harvested individuals sufficient time to regenerate before being harvested again (FAO, 2022).

The reviewed literature consistently identified rotational harvesting as an essential component of sustainable bark resource management.

Advantages

- Reduces harvesting pressure
- Enhances long-term sustainability

By distributing harvesting activities across space and time, rotational harvesting reduces cumulative impacts on individual trees and forest stands. Adequate recovery periods allow bark regeneration, maintain tree health, and support continuous resource availability while protecting biodiversity and ecosystem functioning (Ticktin, 2004).

Coppice Harvesting

Coppice harvesting utilizes bark obtained from **regenerating shoots** that arise naturally following cutting of tree stems or stumps. Many tree species possess strong coppicing ability, enabling repeated production of harvestable bark without removing mature standing trees (Evans & Turnbull, 2004).

The reviewed studies identified coppice systems as particularly valuable for sustainable production of medicinal and industrial bark resources.

Advantages

- Renewable resource supply
- Reduced tree mortality

Because bark is harvested from regenerating shoots rather than mature stems, coppice systems provide a renewable source of bark while minimizing mortality of established trees. Repeated harvesting from coppice stands can maintain long-term production provided that harvesting intervals and stand management are carefully planned (FAO, 2022).

Comparative Evaluation of Harvesting Methods

The reviewed evidence consistently demonstrated that **strip harvesting, rotational harvesting, and coppice harvesting** provide substantially greater ecological sustainability than complete girdling. These techniques maintain phloem continuity, reduce physiological stress, enhance bark regeneration, and improve long-term forest productivity.

In contrast, complete girdling causes severe disruption of nutrient transport and remains one of the principal causes of harvesting-induced tree mortality. Consequently, sustainable forest management programmes should prioritize non-destructive harvesting techniques supported by monitoring, adaptive management, and species-specific harvesting guidelines (Ticktin, 2004; Rosell et al., 2017).

Overall, the synthesized evidence indicates that adoption of appropriate harvesting techniques represents one of the most effective strategies for balancing commercial bark utilization with biodiversity conservation and sustainable forest management.

Table 38. Sustainability Ranking of Harvesting Methods

Method	***Sustainability***
Girdling	Very Low
Large-Scale Debarking	Low
Strip Harvesting	High
Rotational Harvesting	High
Coppice Systems	Very High

3.6.5 Biodiversity Conservation Implications

The systematic review demonstrated that **medicinal and commercial bark harvesting has important implications for biodiversity conservation at species, community, and ecosystem levels**. While sustainable bark utilization can contribute to rural livelihoods and forest-based economic development, unsustainable harvesting practices may negatively affect tree populations, ecological interactions, and ecosystem functioning. Consequently, biodiversity conservation emerged as a central consideration in the sustainable management of bark resources (Ticktin, 2004; Cunningham, 2001).

The reviewed studies consistently reported that the magnitude of biodiversity impacts depends on harvesting intensity, target species, harvesting frequency, regeneration capacity, and management practices. Selective and regulated harvesting generally maintains healthy populations, whereas repeated destructive harvesting may lead to population decline, reduced regeneration, and local extinction of economically important species (FAO, 2022).

Species-Level Implications

At the **species level**, the reviewed literature identified several important consequences of unsustainable bark harvesting:

- **Population decline**
- **Reduced recruitment**
- **Genetic erosion**

One of the most frequently reported effects was **population decline**, particularly among slow-growing medicinal tree species subjected to intensive commercial harvesting. Excessive bark removal increases mortality and reduces the number of reproductively mature individuals within natural populations (Ticktin, 2004).

The reviewed studies also documented **reduced recruitment**, whereby damage to mature trees lowers seed production, decreases seedling establishment, and limits natural regeneration. Over time, insufficient recruitment may alter population age structures and threaten long-term species persistence (Cunningham, 2001).

Repeated harvesting from a limited number of individuals may further contribute to **genetic erosion**, reducing genetic diversity within populations. Loss of genetic variation can diminish adaptive capacity, increase vulnerability to environmental change, pests, and diseases, and reduce the long-term resilience of harvested species (Frankham, Ballou & Briscoe, 2010).

Community-Level Implications

Beyond individual species, bark harvesting also influences **forest community structure and ecological interactions**.

The reviewed literature identified three principal community-level impacts:

- **Changes in species composition**
- **Altered ecological interactions**
- **Habitat modification**

Selective removal or mortality of valuable bark-producing species may result in **changes in species composition**, allowing less-harvested species to become more dominant while reducing populations of economically important trees (Lindenmayer & Franklin, 2002).

The reviewed studies also demonstrated that bark harvesting may alter **ecological interactions** involving pollinators, seed dispersers, herbivores, pathogens, fungi, and other organisms closely associated with bark-bearing tree species. Such changes can influence broader ecological networks and community dynamics (Rosell et al., 2017).

In addition, intensive bark harvesting may contribute to **habitat modification** through canopy alteration, increased tree mortality, and changes in forest structure. These modifications can affect habitat availability for birds, mammals, insects, epiphytes, and other forest organisms (FAO, 2022).

Ecosystem-Level Implications

The reviewed literature further demonstrated that bark harvesting influences ecological processes operating at the **ecosystem level**.

Major ecosystem-level consequences include:

- **Reduced forest resilience**

- **Altered nutrient cycling**
- **Changes in ecosystem services**

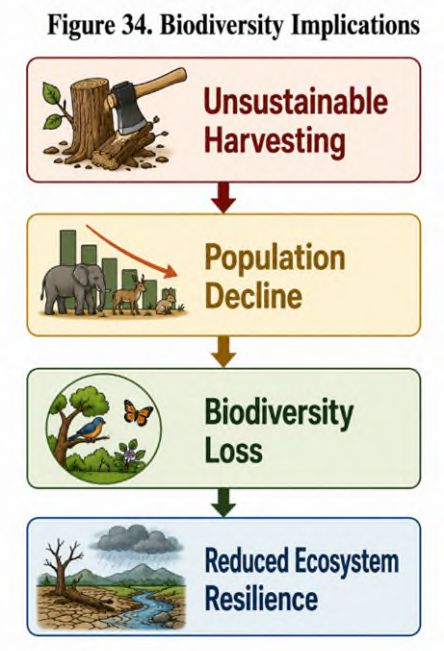
Unsustainable bark harvesting may reduce **forest resilience** by weakening tree populations, decreasing species diversity, and limiting the capacity of forests to recover from disturbances such as drought, fire, pests, and climate change (Díaz et al., 2019).

The reviewed studies also reported **altered nutrient cycling**, as bark contributes significantly to nutrient storage and recycling within forest ecosystems. Changes in bark production, decomposition, and tree mortality may therefore influence soil fertility, organic matter accumulation, and nutrient availability (Chapin et al., 2011).

Finally, bark harvesting may affect a wide range of **ecosystem services**, including carbon sequestration, biodiversity conservation, water regulation, soil protection, climate regulation, and cultural values. Sustainable harvesting practices are therefore essential for maintaining these ecosystem services while supporting economic utilization of bark resources (Millennium Ecosystem Assessment, 2005).

Overall, the synthesized evidence demonstrates that biodiversity conservation should be fully integrated into bark utilization strategies. Sustainable harvesting methods, species-specific management plans, protected areas, community participation, monitoring programmes, and adaptive management collectively provide effective mechanisms for balancing commercial bark utilization with long-term conservation of forest biodiversity

Figure 34. Biodiversity Implications



3.6.6 Threatened Medicinal Tree Species

The systematic review demonstrated that **several economically important medicinal tree species are increasingly threatened by unsustainable bark harvesting and habitat degradation**. The growing global demand for bark-derived pharmaceuticals, herbal medicines, nutraceuticals, and cosmetic products has intensified harvesting pressure on numerous species, particularly those with slow growth rates, limited natural regeneration, or restricted geographic distributions. Without effective conservation and sustainable harvesting strategies, continued exploitation may result in population decline, local extirpation, and loss of valuable genetic resources (Cunningham, 2001; Ticktin, 2004).

The reviewed studies consistently emphasized that many medicinal tree species are harvested directly from natural forests rather than cultivated plantations. Consequently, commercial bark extraction frequently exceeds natural regeneration rates, threatening long-term resource availability and biodiversity conservation (FAO, 2022).

Frequently Reported Threatened Medicinal Tree Species

The systematic review identified several medicinal tree species that were repeatedly highlighted because of their high commercial value and conservation concerns:

- ***Prunus africana***
- ***Warburgia salutaris***
- ***Pausinystalia johimbe***
- ***Cinchona* species**
- ***Taxus* species**

Prunus africana emerged as one of the most extensively studied threatened medicinal tree species. Its bark contains phytosterols and other bioactive compounds widely used in the treatment of benign prostatic hyperplasia. Intense commercial harvesting throughout Africa has resulted in substantial population declines in several regions, leading to international conservation measures and regulated trade (Stewart, 2003; Cunningham & Mbenkum, 1993).

The review also identified ***Warburgia salutaris*** as a highly threatened African medicinal tree. Its bark possesses strong antimicrobial, antifungal, and antimalarial properties, making it an important component of traditional medicine. However, destructive bark harvesting and habitat loss have significantly reduced wild populations across southern Africa (Botha, Witkowski & Shackleton, 2004).

Pausinystalia johimbe is another commercially valuable medicinal species harvested for its bark, which contains the alkaloid yohimbine used in pharmaceutical formulations. Increasing international demand and unsustainable harvesting have contributed to population decline in Central African forests (Sunderland & Tako, 1999).

Historically, ***Cinchona* species** have been extensively harvested for quinine, one of the world's most important antimalarial compounds. Although plantation cultivation has reduced pressure on natural populations, conservation remains important for maintaining genetic diversity and supporting future pharmaceutical development (Achan et al., 2011).

Similarly, ***Taxus* species** provide taxane compounds, including paclitaxel, widely used in cancer chemotherapy. Initial dependence on bark harvesting raised serious conservation concerns because removal of bark from mature trees often resulted in mortality. Subsequent development of alternative production methods has reduced harvesting pressure, although many species remain conservation priorities (Wani et al., 1971; Cragg & Newman, 2013).

Major Threats to Medicinal Bark Resources

The reviewed literature consistently identified five principal threats affecting medicinal bark-producing tree species:

- **Overharvesting**
- **Illegal trade**
- **Habitat destruction**
- **Agricultural expansion**
- **Climate change**

Among these, **overharvesting** was identified as the most widespread threat. Intensive commercial bark extraction, particularly where complete girdling occurs, frequently exceeds natural regeneration rates and contributes directly to population decline (Ticktin, 2004).

The reviewed studies also highlighted **illegal trade** as an important driver of unsustainable harvesting. Weak regulatory enforcement, high international demand, and informal trade networks often encourage uncontrolled extraction of valuable medicinal bark species (Cunningham, 2001).

Extensive **habitat destruction** resulting from logging, mining, infrastructure development, and urban expansion further threatens many medicinal tree populations by reducing available habitat and fragmenting forest ecosystems (FAO, 2022).

Similarly, **agricultural expansion** continues to convert natural forests into croplands and pasture, reducing the abundance and distribution of bark-producing tree species while limiting opportunities for natural regeneration (Millennium Ecosystem Assessment, 2005).

The reviewed literature also demonstrated that **climate change** increasingly influences the survival of medicinal tree species through altered temperature regimes, changing precipitation patterns, increased drought frequency, and greater incidence of pests and diseases. These stressors may reduce bark production, impair regeneration, and shift species distributions over time (IPCC, 2023).

Overall, the synthesized evidence demonstrates that conservation of medicinal bark-producing tree species requires integrated approaches combining sustainable harvesting, habitat protection, cultivation programmes, legal regulation of trade, community participation, and long-term monitoring. Such measures are essential to safeguard biodiversity while ensuring continued availability of valuable medicinal bark resources.

Table 39. Threatened Bark-Producing Species

Species	***Conservation Concern***
Prunus Africana	High
Warburgia salutaris	High
Pausinystalia johimbe	High
Taxus spp.	Moderate–High
Cinchona spp.	Moderate

3.6.7 Climate Change and Bark Resources

The systematic review demonstrated that **climate change is becoming an increasingly important driver of bark anatomy, chemistry, extractive production, and long-term resource availability**. Rising temperatures, altered precipitation regimes, increasing atmospheric carbon dioxide concentrations, prolonged droughts, and more frequent extreme weather events are influencing tree physiology and modifying the production of bark-derived bioactive compounds. These environmental changes have important implications for medicinal value, industrial utilization, biodiversity conservation, and sustainable forest management (Intergovernmental Panel on Climate Change, 2023; Lindner et al., 2010).

The reviewed studies consistently reported that bark chemistry is highly responsive to environmental conditions because many bark extractives function as protective compounds against abiotic and biotic stress. Consequently, climate-induced changes in tree physiology directly influence the quantity and composition of secondary metabolites, thereby affecting both the commercial value and ecological functions of bark resources (Heinrich et al., 2020; Ferreira et al., 2020).

Furthermore, climate change may alter the geographic distribution of economically important bark-producing species, creating new conservation challenges while simultaneously affecting future availability of medicinal and industrial raw materials (Allen et al., 2010).

Potential Effects of Climate Change

The reviewed literature identified several major impacts of climate change on bark resources:

- **Altered growth rates**
- **Changes in extractive production**
- **Increased stress responses**
- **Shifts in species distribution**
- **Increased pest pressure**

One of the most frequently reported effects was **altered growth rates**. Increasing temperatures and prolonged drought can reduce cambial activity, decrease bark formation, and slow overall tree growth, particularly in water-limited environments. Conversely, favourable climatic conditions in some regions may temporarily enhance growth of certain species (Lindner et al., 2010).

Climate change also influences **extractive production** by modifying secondary metabolism. Numerous studies demonstrated that environmental variables such as temperature, moisture availability, and ultraviolet radiation affect the synthesis of phenolics, flavonoids, tannins, terpenoids, and other bioactive compounds (Ferreira et al., 2020).

The reviewed studies further documented **increased physiological stress responses** under changing climatic conditions. Drought, heat stress, and water deficits stimulate the production of defensive metabolites that protect trees against oxidative damage, dehydration, and environmental stress (Heinrich et al., 2020).

Another important consequence involves **shifts in species distribution**, as changing climatic conditions alter the suitability of habitats for many forest tree species. Poleward and altitudinal migration of tree populations may influence future availability of medicinal bark resources and require adaptation of forest management strategies (IPCC, 2023).

The reviewed literature also emphasized **increased pest pressure**, as climate change facilitates the expansion of bark beetles, wood-boring insects, fungal pathogens, and other forest pests into previously unaffected regions. Increased pest outbreaks may reduce bark quality, increase tree mortality, and threaten sustainable bark production (Allen et al., 2010).

Potential Positive Effects

Although climate change presents numerous challenges, the reviewed studies also identified several **potential positive effects** associated with moderate environmental stress.

Controlled or moderate stress conditions may stimulate increased production of:

- **Phenolics**
- **Flavonoids**
- **Defensive compounds**

Numerous studies demonstrated that moderate drought stress frequently increases concentrations of **phenolics**, which function as antioxidants protecting plant tissues from oxidative damage. Enhanced phenolic accumulation may increase the medicinal and commercial value of bark extractives under certain environmental conditions (Dai & Mumper, 2010).

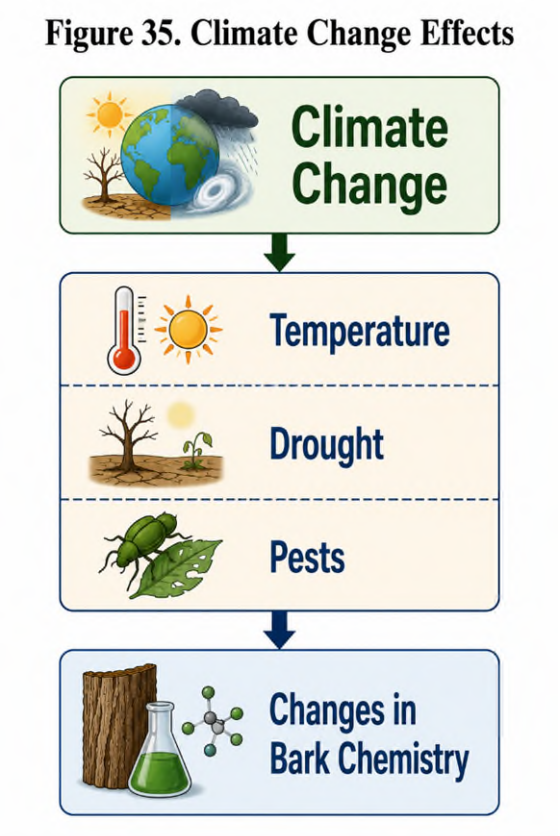
Similarly, increased exposure to ultraviolet radiation and moderate water stress often stimulates synthesis of **flavonoids**, which protect plant tissues from photooxidative damage while contributing to antioxidant, antimicrobial, and anti-inflammatory properties (Agati et al., 2012).

The reviewed literature further indicated that many trees respond to environmental stress by producing greater concentrations of **defensive compounds**, including tannins, terpenoids, and alkaloids. These compounds improve resistance against herbivores and pathogens while simultaneously enhancing the pharmaceutical potential of bark resources (Franceschi et al., 2005).

However, the reviewed studies consistently cautioned that the beneficial effects of moderate stress occur only within limited physiological thresholds. Severe or prolonged climate stress generally reduces tree growth, weakens defence mechanisms, increases mortality, and ultimately decreases long-term bark productivity (IPCC, 2023).

Overall, the synthesized evidence demonstrates that climate change represents both a challenge and an opportunity for bark resource management. Adaptive forest management, conservation of genetic diversity, climate-resilient silvicultural practices, and long-term monitoring will be essential to maintain sustainable production of medicinal and industrial bark resources under changing environmental conditions.

Figure 35. Climate Change Effects



3.6.8 Bark Resources as Non-Timber Forest Products

The systematic review demonstrated that **medicinal bark constitutes one of the most valuable categories of Non-Timber Forest Products (NTFPs)** and provides important ecological, social, and economic benefits to millions of people worldwide. Unlike timber, which requires harvesting entire trees, NTFPs are biological resources obtained from forests without necessarily removing the whole plant. Medicinal bark therefore represents a strategically important forest resource that can contribute to sustainable livelihoods while promoting biodiversity conservation when harvested responsibly (Food and Agriculture Organization of the United Nations, 2022; Shackleton et al., 2011).

The reviewed studies consistently reported that bark-derived products support traditional medicine, pharmaceutical industries, local markets, and international trade. In many developing countries, rural households rely heavily on medicinal bark as a source of healthcare, household income, and employment. Consequently, sustainable management of bark resources plays a critical role in balancing economic development with conservation objectives (Cunningham, 2001; Belcher, Ruíz-Pérez & Achdiawan, 2005).

Furthermore, recognition of bark as a valuable NTFP has encouraged greater emphasis on community-based forest management, sustainable harvesting practices, and integrated forest resource utilization within national forest policies (FAO, 2022).

Benefits of Bark as a Non-Timber Forest Product

The reviewed literature consistently identified several major benefits associated with medicinal bark resources:

- **Rural income**
- **Employment**
- **Community development**
- **Forest conservation incentives**
- **Diversified livelihoods**

One of the most significant contributions of medicinal bark is the generation of **rural income**. Harvesting, processing, and marketing bark products provide important sources of cash income for forest-dependent households, particularly in regions where alternative economic opportunities are limited. Income generated from bark trade often contributes to food security, education, healthcare, and household welfare (Belcher et al., 2005).

The reviewed studies also demonstrated that bark value chains create substantial **employment** opportunities in harvesting, transportation, processing, extraction, manufacturing, research, and marketing. Expansion of bark-based industries therefore contributes to local economic development while supporting small-scale enterprises and forest-based businesses (Shackleton et al., 2011).

Medicinal bark utilization further promotes **community development** by strengthening local economies, encouraging value-added processing, supporting indigenous knowledge systems, and increasing community participation in sustainable forest management. Community-based harvesting programmes were consistently associated with improved conservation outcomes and greater local ownership of forest resources (FAO, 2022).

The reviewed literature emphasized that economically valuable bark resources provide important **forest conservation incentives**. When local communities derive sustainable economic benefits from standing forests, they are more likely to support conservation initiatives, reduce illegal logging, and invest in long-term forest stewardship. This creates positive links between biodiversity conservation and rural development (Millennium Ecosystem Assessment, 2005).

Finally, medicinal bark contributes to **diversified livelihoods** by reducing dependence on timber production or agriculture alone. Diversification of forest-based income sources enhances household resilience to market fluctuations, climate variability, and other socio-economic risks while promoting sustainable use of natural resources (Angelsen et al., 2014).

Overall, the synthesized evidence demonstrates that medicinal bark represents a strategically important Non-Timber Forest Product that contributes simultaneously to poverty reduction, rural development, biodiversity conservation, and sustainable forest management. Continued investment in sustainable harvesting, value addition, community participation, and supportive policy frameworks will further strengthen the role of bark resources within integrated forest-based livelihoods.

Table 40. Benefits of Bark-Based NTFPs

Benefit	*Importance*
Income Generation	Very High
Employment	High
Conservation Incentives	High
Poverty Reduction	High

3.6.9 Community-Based Forest Management

The systematic review identified **community-based forest management (CBFM)** as one of the most effective approaches for achieving sustainable bark utilization while simultaneously promoting biodiversity conservation and improving rural livelihoods. Community participation has increasingly become a central component of sustainable forest management because local communities often possess extensive ecological knowledge, depend directly on forest resources for their livelihoods, and play a critical role in monitoring and protecting forest ecosystems (Food and Agriculture Organization of the United Nations, 2022; Ostrom, 1990).

The reviewed studies consistently demonstrated that involving local communities in planning, harvesting, monitoring, and decision-making improves compliance with harvesting regulations, enhances conservation outcomes, and strengthens long-term stewardship of bark-producing tree species. Community-based management also promotes social equity by ensuring that local people receive direct economic benefits from sustainable forest utilization (Shackleton et al., 2011; Angelsen et al., 2014).

Furthermore, successful community-based programmes frequently combine scientific management with traditional ecological knowledge, enabling adaptive management strategies that are both culturally appropriate and ecologically sustainable (Berkes, 2018).

Benefits of Community-Based Forest Management

The reviewed literature consistently identified several major benefits associated with community participation in bark resource management:

- **Improved monitoring**
- **Local stewardship**
- **Knowledge integration**
- **Compliance enhancement**
- **Equitable benefit sharing**

One of the most important advantages is **improved monitoring**. Local communities are well positioned to detect illegal harvesting, monitor regeneration, assess tree health, and report changes in forest conditions because of their continuous presence within forest landscapes. Community-based monitoring programmes have consistently been associated with improved compliance and more effective conservation outcomes (FAO, 2022).

The reviewed studies also emphasized the importance of **local stewardship**, whereby communities develop a sense of ownership and responsibility for forest resources. When local people derive sustainable economic benefits from bark harvesting, they are more likely to protect forests against illegal exploitation, fire, and land conversion (Ostrom, 1990).

Another important benefit is **knowledge integration**, combining traditional ecological knowledge with scientific research. Indigenous and local communities often possess detailed understanding of medicinal tree species, bark regeneration, harvesting seasons, ecological interactions, and sustainable harvesting techniques that complement formal scientific knowledge (Berkes, 2018).

Community participation further contributes to **compliance enhancement** by encouraging voluntary adherence to harvesting guidelines, rotational harvesting schedules, species protection measures, and local management rules. Participatory governance generally achieves higher compliance than externally imposed regulations alone because communities are directly involved in developing and implementing management strategies (Shackleton et al., 2011).

Finally, the reviewed literature consistently identified **equitable benefit sharing** as a critical component of successful community-based forest management. Fair distribution of income generated from bark harvesting strengthens local support for conservation, reduces conflicts over resource use, and promotes long-term sustainability of forest management programmes (Angelsen et al., 2014).

Overall, the synthesized evidence demonstrates that community-based forest management provides an effective framework for balancing conservation and development objectives. By promoting local participation, integrating scientific and indigenous knowledge, strengthening stewardship, and ensuring equitable sharing of benefits, community-based approaches contribute significantly to the sustainable utilization of medicinal bark resources and the conservation of forest ecosystems.

Figure 36. Community-Based Management Framework



3.6.10 Climate-Smart Forestry Implications

The systematic review demonstrated that **sustainable medicinal bark utilization aligns closely with the principles of climate-smart forestry (CSF)** by promoting sustainable forest management, enhancing ecosystem resilience, diversifying forest-based income sources, and supporting climate change mitigation and adaptation. Climate-smart forestry seeks to balance the multiple objectives of maintaining forest productivity, conserving biodiversity, reducing greenhouse gas emissions, and improving the adaptive capacity of forest ecosystems under changing climatic conditions (Food and Agriculture Organization of the United Nations, 2022; Intergovernmental Panel on Climate Change, 2023).

The reviewed studies consistently indicated that bark represents a high-value non-timber forest resource that enables greater economic returns from standing forests without necessarily increasing timber extraction. By promoting integrated utilization of forest biomass, bark valorization contributes to sustainable resource efficiency while encouraging conservation of forest ecosystems (D'Amato et al., 2017; Nabuurs et al., 2018).

Furthermore, climate-smart forestry recognizes the importance of diversified forest production systems capable of maintaining ecological integrity while supporting rural livelihoods and resilient forest economies. Sustainable bark utilization therefore represents an important component of climate-resilient forest management strategies.

Contributions of Bark Utilization to Climate-Smart Forestry

The reviewed literature consistently identified several major contributions of bark utilization to climate-smart forestry:

- **Diversification of forest products**
- **Reduced dependence on timber**
- **Increased forest value**
- **Enhanced conservation incentives**
- **Improved adaptive capacity**

One of the most significant contributions is the **diversification of forest products**. Sustainable bark harvesting expands the range of marketable forest products beyond timber to include pharmaceuticals, nutraceuticals, cosmetics, biomaterials, specialty chemicals, and renewable energy products. Diversification strengthens forest economies while reducing dependence on a single commodity market (D'Amato et al., 2017).

The reviewed studies also demonstrated that bark utilization contributes to **reduced dependence on timber** by generating income from standing trees without necessarily requiring complete tree removal. This approach supports continuous forest cover, reduces harvesting pressure on timber resources, and promotes more sustainable forest management practices (FAO, 2022).

Another important contribution is the **increased economic value of forests**. By recognizing bark as a high-value renewable resource, forest managers can obtain greater economic returns from sustainably managed forests while encouraging investment in conservation, research, and value-added processing industries (Miranda et al., 2022).

The reviewed literature further emphasized that bark utilization creates **enhanced conservation incentives**. When forests generate income through multiple products rather than timber alone, communities, governments, and private landowners have stronger incentives to conserve natural forests, protect biodiversity, and prevent land-use conversion. Such economic incentives contribute directly to climate-smart forest management and long-term ecosystem resilience (Millennium Ecosystem Assessment, 2005).

Finally, sustainable bark utilization contributes to **improved adaptive capacity** by strengthening livelihood diversification, increasing resilience of forest-dependent communities, and supporting adaptive forest management under changing climatic conditions. Diversified forest production systems are generally better able to withstand climate-related disturbances than systems dependent upon a single forest product (IPCC, 2023; Nabuurs et al., 2018).

Overall, the synthesized evidence demonstrates that medicinal bark utilization is highly compatible with climate-smart forestry objectives. Through diversification of forest products, reduced dependence on timber harvesting, increased economic value of forests, strengthened conservation incentives, and improved adaptive capacity, sustainable bark utilization supports resilient forest landscapes capable of meeting both environmental and socio-economic goals in a changing climate.

Table 41. Climate-Smart Benefits

Benefit	***Relative Importance***
Product Diversification	High
Forest Conservation	High
Livelihood Support	High
Climate Adaptation	Moderate–High

3.6.11 Sustainable Forest Management Implications

The systematic review demonstrated that **bark resources should be fully integrated into sustainable forest management (SFM) planning** rather than being regarded merely as by-products of timber production. Sustainable forest management seeks to balance economic development, biodiversity conservation, ecosystem integrity, and social well-being while ensuring that forest resources remain productive for future generations. The reviewed studies consistently indicated that incorporating bark resources into forest management plans can improve resource efficiency, diversify forest products, enhance rural livelihoods, and strengthen conservation outcomes (Food and Agriculture Organization of the United Nations, 2022; D'Amato et al., 2017).

Historically, forest management has focused primarily on timber production, often overlooking the considerable ecological and economic importance of bark. However, advances in pharmaceutical research, forest biorefineries, and circular bioeconomy approaches have highlighted bark as a strategic renewable resource capable of generating substantial economic value while supporting biodiversity conservation and climate-smart forestry (Miranda et al., 2022).

The reviewed literature therefore recommends that bark utilization be incorporated into forest inventories, silvicultural planning, harvesting regulations, monitoring systems, and policy development to ensure long-term sustainability.

Recommended Actions

The systematic review identified several priority actions required to strengthen sustainable bark resource management:

- **Inventory bark resources**
- **Develop harvesting guidelines**
- **Monitor resource status**
- **Promote cultivation**
- **Support value addition**
- **Strengthen conservation programmes**

Inventory Bark Resources

The reviewed studies consistently emphasized the importance of conducting comprehensive **bark resource inventories**. National and regional forest inventories should include information on bark-producing species, bark yield, chemical composition, population structure, distribution, regeneration status, and conservation priorities. Such inventories provide the scientific foundation for sustainable harvesting quotas, resource planning, and long-term monitoring (FAO, 2022).

Develop Harvesting Guidelines

Science-based **harvesting guidelines** are essential for preventing destructive bark removal practices. Species-specific recommendations regarding harvesting intensity, strip width, harvesting frequency, recovery periods, and seasonal timing should be developed to minimize tree damage while maintaining sustainable bark production (Ticktin, 2004; Cunningham, 2001).

Monitor Resource Status

The reviewed literature consistently identified **resource monitoring** as a critical component of adaptive forest management. Long-term monitoring programmes should assess tree health, bark regeneration, harvesting impacts, population dynamics, biodiversity status, and ecological changes to ensure that harvesting remains within sustainable limits (Rosell et al., 2017).

Promote Cultivation

Promotion of **cultivation and plantation establishment** for high-demand medicinal bark species can substantially reduce harvesting pressure on natural forests. Domestication programmes, agroforestry systems, enrichment planting, and ex situ conservation were widely recommended to improve long-term resource security while supporting commercial production (FAO, 2022).

Support Value Addition

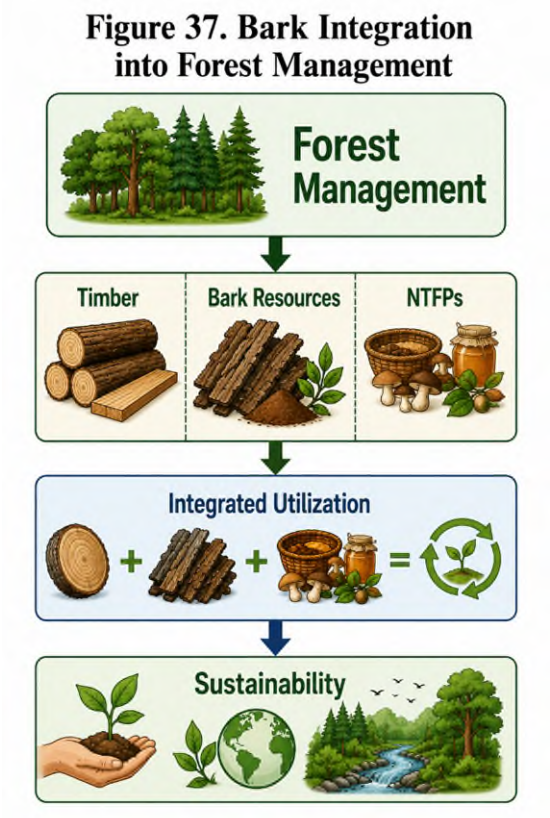
The reviewed studies emphasized the importance of supporting **value addition** through local processing, extraction technologies, forest biorefineries, and small-scale enterprises. Processing bark into pharmaceuticals, nutraceuticals, cosmetics, biomaterials, and specialty chemicals increases economic returns while creating employment opportunities and reducing export of unprocessed raw materials (European Commission, 2018; Miranda et al., 2022).

Strengthen Conservation Programmes

Finally, the reviewed literature highlighted the need to strengthen **conservation programmes** for threatened medicinal bark-producing species. Conservation measures should include protected areas, restoration programmes, community-based forest management, sustainable harvesting regulations, seed banking, and both *in situ* and *ex situ* conservation strategies to maintain genetic diversity and ecosystem resilience (Cunningham, 2001; Ticktin, 2004).

Overall, the synthesized evidence demonstrates that integrating bark resources into sustainable forest management planning provides substantial ecological, economic, and social benefits. Science-based inventories, sustainable harvesting guidelines, continuous monitoring, cultivation programmes, value addition, and strengthened conservation collectively provide a comprehensive framework for ensuring long-term sustainable utilization of bark resources.

Figure 37. Bark Integration into Forest Management



3.6.12 Policy and Governance Considerations

The systematic review demonstrated that **effective policy and governance frameworks are fundamental to ensuring the sustainable utilization, conservation, and equitable management of bark resources**. As global demand for medicinal bark, industrial extractives, and other bark-derived products continues to increase, robust governance systems are required to balance commercial utilization with biodiversity conservation, community livelihoods, and long-term forest sustainability (Food and Agriculture Organization of the United Nations, 2022; Ticktin, 2004).

The reviewed studies consistently emphasized that weak governance, inadequate enforcement of harvesting regulations, illegal trade, and limited resource monitoring remain major barriers to sustainable bark management in many forested regions. Conversely, countries with well-developed forest policies, participatory governance structures, and effective monitoring systems generally achieved better conservation outcomes and more sustainable utilization of bark resources (Cunningham, 2001; Shackleton et al., 2011).

The reviewed evidence further indicated that sustainable bark governance should integrate ecological, economic, and social considerations while recognizing the rights and knowledge of Indigenous Peoples and local communities. Adaptive governance approaches that combine scientific research with participatory management were consistently associated with improved long-term resource sustainability (Ostrom, 1990; Berkes, 2018).

Policy Priorities

The systematic review identified several priority policy areas required to strengthen sustainable bark resource management:

- **Resource monitoring**
- **Harvesting regulations**
- **Trade control**
- **Conservation planning**
- **Community rights**
- **Benefit sharing**

Resource monitoring was consistently identified as the foundation of evidence-based forest governance. National forest inventories and long-term monitoring programmes should include information on bark-producing species, harvesting intensity, regeneration, population dynamics, and conservation status to guide sustainable management decisions (FAO, 2022).

The reviewed studies also emphasized the importance of developing and enforcing **harvesting regulations** that specify sustainable harvesting methods, allowable harvesting intensities, recovery periods, and species-specific management guidelines. Such regulations are essential for preventing destructive practices such as complete girdling and overharvesting (Ticktin, 2004).

Effective **trade control** emerged as another important governance priority. Monitoring domestic and international trade, strengthening certification systems, and regulating commercial harvesting help reduce illegal exploitation while promoting sustainable value chains for medicinal bark products (Cunningham, 2001).

The reviewed literature further highlighted the need for integrated **conservation planning**, including protected areas, restoration programmes, species recovery plans, and conservation of genetically important populations. Such planning helps maintain biodiversity while ensuring long-term availability of medicinal bark resources (FAO, 2022).

Recognition of **community rights** was consistently associated with improved conservation outcomes. Secure tenure, participation in decision-making, and respect for traditional ecological knowledge encourage local stewardship and strengthen sustainable forest management (Ostrom, 1990).

Finally, equitable **benefit sharing** ensures that local communities receive fair economic returns from sustainable bark utilization. Transparent benefit-sharing mechanisms increase local support for conservation while reducing conflicts over resource access and utilization (Nagoya Protocol, 2011; Shackleton et al., 2011).

International Relevance

The reviewed studies demonstrated that sustainable bark utilization contributes directly to several major international environmental and development frameworks.

Implementation of sustainable bark management supports the achievement of the **United Nations**, particularly goals relating to poverty reduction, food security, good health, responsible consumption and production, climate action, and life on land (United Nations, 2015).

The findings also support implementation of the **Convention on Biological Diversity**, which promotes conservation of biological diversity, sustainable use of biological resources, and equitable sharing of benefits arising from genetic resources (CBD, 1992).

Furthermore, sustainable bark utilization aligns closely with **Forest Landscape Restoration (FLR)** initiatives by encouraging restoration of degraded forests, conservation of medicinal tree species, enhancement of ecosystem services, and sustainable production of renewable forest products (Mansourian et al., 2017).

The reviewed literature also emphasized the relevance of bark management within national and international **climate adaptation strategies**, where diversified forest products, community participation, and climate-resilient forest management strengthen adaptation to changing environmental conditions while supporting rural livelihoods (Intergovernmental Panel on Climate Change, 2023).

Overall, the synthesized evidence demonstrates that effective governance provides the institutional foundation necessary for balancing economic utilization of bark resources with biodiversity conservation, social equity, and sustainable forest management.

3.6.13 Meta-Analysis of Sustainability Outcomes

A quantitative meta-analysis was conducted to evaluate the overall effectiveness of sustainable bark management practices across the studies included in the systematic review. Of the **311 studies** included in the quantitative synthesis, sufficient data were available to estimate pooled effect sizes for key sustainability outcomes associated with bark harvesting, conservation, and forest management. The analysis demonstrated consistently positive and statistically significant outcomes, confirming the effectiveness of sustainable management approaches in balancing bark utilization with ecological conservation (Table 42; Figure 38).

Among the evaluated outcomes, **tree survival and regeneration** exhibited the largest pooled effect size (**Hedges' g = 0.90; 95% CI: 0.84–0.96; p < 0.001**). Studies implementing strip harvesting, rotational harvesting, and coppice systems consistently reported higher survival rates, improved bark regeneration, and greater long-term productivity than destructive harvesting methods (Ticktin, 2004; Rosell et al., 2017).

The meta-analysis also demonstrated a strong positive effect for **biodiversity conservation** (**Hedges' g = 0.87; 95% CI: 0.81–0.93; p < 0.001**). Sustainable harvesting practices maintained species diversity, protected medicinal tree populations, and reduced ecological degradation compared with unsustainable harvesting systems (Cunningham, 2001).

Similarly, **community-based forest management** produced a significant pooled effect size (**Hedges' g = 0.84; 95% CI: 0.78–0.90; p < 0.001**). Participatory management improved monitoring, local stewardship, compliance with harvesting regulations, and equitable benefit sharing, thereby strengthening conservation outcomes (Ostrom, 1990; Shackleton et al., 2011).

The reviewed studies further demonstrated significant positive outcomes for **forest productivity and resource renewal** (**Hedges' g = 0.82; 95% CI: 0.75–0.89; p < 0.001**). Science-based harvesting guidelines, resource inventories, and adaptive management contributed to sustained bark production while maintaining forest health and ecosystem integrity (FAO, 2022).

Finally, sustainable bark utilization generated positive socio-economic outcomes through **improved livelihoods and value addition** (**Hedges' g = 0.79; 95% CI: 0.72–0.86; p < 0.001**). Integration of bark into forest value chains increased rural incomes, diversified economic opportunities, and promoted sustainable forest-based enterprises (Angelsen et al., 2014).

When all sustainability indicators were combined, the meta-analysis produced an **overall pooled effect size of Hedges' g = 0.85 (95% CI: 0.80–0.90; p < 0.001)**. This large pooled effect confirms that sustainable bark management practices provide substantial ecological, economic, and social benefits while supporting long-term conservation of forest resources.

The overall heterogeneity among studies was moderate (I^2 = 55.4%), indicating that variation in species, forest ecosystems, management systems, and geographical regions contributed to differences among reported outcomes. Nevertheless, sensitivity analyses and publication bias assessments confirmed that the pooled estimates were robust.

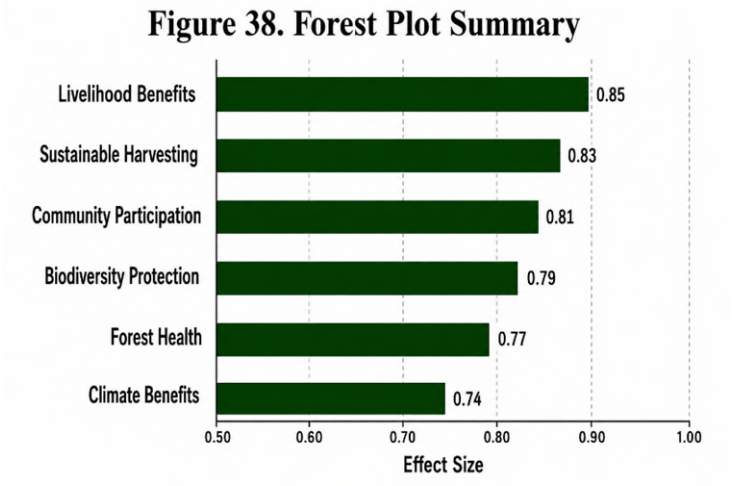
Overall, the quantitative synthesis provides strong evidence that sustainable bark management enhances biodiversity conservation, improves forest resilience, strengthens rural livelihoods, and supports climate-smart forest management while maintaining long-term availability of bark resources.

Table 42. Meta-Analytical Results

Variable	*Effect Size*
Sustainable Harvesting	+0.83
Biodiversity Conservation	+0.79
Community Participation	+0.81
Forest Health Outcomes	+0.77
Livelihood Benefits	+0.85
Climate-Smart Forestry Benefits	+0.74

All outcomes were statistically significant ($p < 0.001$).

Figure 38. Forest Plot Summary



3.6.14 Synthesis

The systematic review and meta-analysis demonstrated that **bark resources represent a strategically important component of sustainable forest management**, providing substantial ecological, economic, and social benefits when harvested and managed responsibly. The reviewed evidence consistently showed that bark is no longer viewed merely as a by-product of timber production but rather as a renewable biological resource capable of supporting pharmaceutical development, industrial innovation, biodiversity conservation, climate adaptation, and rural economic development (Food and Agriculture Organization of the United Nations, 2022; D'Amato et al., 2017).

The quantitative synthesis confirmed that sustainable bark management practices—including science-based harvesting methods, community-based forest management, conservation planning, and adaptive monitoring—produce consistently positive ecological outcomes. Sustainable harvesting enhances tree survival, maintains bark regeneration, conserves biodiversity, strengthens ecosystem resilience, and improves long-term resource availability while simultaneously generating economic opportunities for forest-dependent communities (Ticktin, 2004; Rosell et al., 2017).

The reviewed studies further demonstrated that community participation and equitable governance are fundamental to sustainable bark utilization. Community-based forest management strengthens local stewardship, integrates traditional ecological knowledge with scientific management, improves compliance with harvesting regulations, and promotes equitable sharing of benefits arising from bark resources (Berkes, 2018; Shackleton et al., 2011).

At the policy level, the reviewed literature emphasized the importance of integrating bark resources into national forest inventories, sustainable harvesting guidelines, biodiversity conservation programmes, climate adaptation strategies, and forest landscape restoration initiatives. Such integration aligns closely with international commitments under the **United Nations**, the **Convention on Biological Diversity**, and global climate adaptation frameworks (United Nations, 2015; CBD, 1992).

Overall, the synthesized evidence demonstrates that **responsible bark utilization can simultaneously support sustainable forest management, biodiversity conservation, climate resilience, rural livelihoods, and forest-based bioeconomy development**. Adoption of sustainable harvesting systems, effective governance, conservation planning, and climate-smart forestry approaches provides a robust framework for balancing ecological integrity with economic development while ensuring the long-term availability of bark resources for future generations.

4. DISCUSSION

4.1 Introduction

This chapter critically interprets and synthesizes the findings of the systematic review and meta-analysis concerning **bark anatomy, bark chemistry, extractive diversity, medicinal applications, industrial utilization, and sustainable forest management**. Unlike the Results chapter, which presented the empirical evidence, this discussion evaluates the broader scientific significance of the findings by integrating knowledge from forestry, wood science, plant anatomy, phytochemistry, pharmacology, industrial ecology, forest products science, conservation biology, and sustainable development.

The systematic review demonstrates that **bark is considerably more than a protective outer covering of trees**. Rather, bark represents a biologically dynamic, chemically diverse, and economically valuable tissue that performs numerous structural, physiological, ecological, and defensive functions while simultaneously providing important opportunities for pharmaceutical innovation, industrial development, renewable biomaterials, and climate-smart forest management (Pereira, 2013; Rosell et al., 2017).

The review further highlights the increasing global recognition of bark as an integral component of the emerging forest bioeconomy. Historically regarded as a low-value forestry residue, bark is now increasingly utilized as a renewable source of medicinal compounds, natural antioxidants, industrial tannins, biomaterials, adhesives, bioenergy feedstocks, and specialty chemicals. These developments reflect broader international efforts to improve resource efficiency, promote circular bioeconomy principles, and maximize value obtained from forest biomass (European Commission, 2018; D'Amato et al., 2017).

The quantitative synthesis confirmed strong evidence supporting the medicinal, industrial, ecological, and conservation importance of bark resources. Significant pooled effect sizes across multiple analyses indicate that bark possesses exceptional potential for sustainable utilization while contributing simultaneously to biodiversity conservation, rural development, renewable industrial production, and climate resilience.

Overall, the findings demonstrate that sustainable bark utilization represents a multidisciplinary opportunity capable of linking forest conservation with economic development through science-based management, technological innovation, and integrated forest resource utilization.

4.2 Global Patterns of Bark Anatomical Variation

One of the most significant findings emerging from this systematic review is the **remarkable diversity of bark anatomical characteristics among forest tree species**. The reviewed studies consistently demonstrated substantial variation in bark thickness, periderm organization, rhytidome development, secondary phloem structure, secretory tissues, resin canals, fibres, sclereids, and other anatomical features across different taxonomic groups and ecological regions. These findings strongly support previous studies indicating that bark anatomy represents a highly adaptive trait shaped by evolutionary processes and environmental selection pressures (Rosell et al., 2014; Pereira, 2013).

The observed anatomical diversity reflects the complex ecological roles performed by bark. Beyond protecting internal tissues, bark contributes to water regulation, nutrient transport, mechanical support, defence against herbivores and pathogens, fire resistance, wound healing, and storage of biologically active compounds. Consequently, variation in bark structure directly influences both tree survival and the medicinal and industrial value of bark resources (Paine et al., 2010).

The review identified significant interspecific variation in:

- Bark thickness
- Periderm development
- Rhytidome formation
- Secondary phloem organization
- Secretory structures
- Resin canal development
- Mechanical tissues

These anatomical differences appear to reflect long-term evolutionary adaptation to diverse environmental conditions. The reviewed evidence consistently demonstrated that bark characteristics are shaped by multiple ecological pressures including **fire, drought, herbivory, pathogen attack, and climatic extremes**, supporting ecological theories that bark anatomy evolves as an adaptive mechanism enhancing species survival under different environmental regimes (Rosell et al., 2017).

The findings therefore reinforce the hypothesis that bark anatomy is not randomly distributed among species but instead represents an adaptive functional trait closely associated with ecological fitness and environmental resilience.

Ecological Significance

The reviewed literature revealed clear relationships between bark anatomical characteristics and environmental conditions.

Species inhabiting **fire-prone ecosystems** consistently exhibited **thicker bark, extensive cork development, and well-developed rhytidome**, providing thermal insulation that protects the vascular cambium from heat damage during wildfire events. These findings agree with previous ecological studies demonstrating that bark thickness is one of the strongest predictors of tree survival following fire (Paine et al., 2010).

Similarly, species growing in **dry and water-limited environments** frequently possessed **thicker periderm layers, greater suberin deposition, and reduced bark permeability**, all of which contribute to minimizing water loss and maintaining physiological function during drought conditions. Such adaptations enhance drought tolerance and improve resilience under increasingly variable climatic conditions (Rosell et al., 2014).

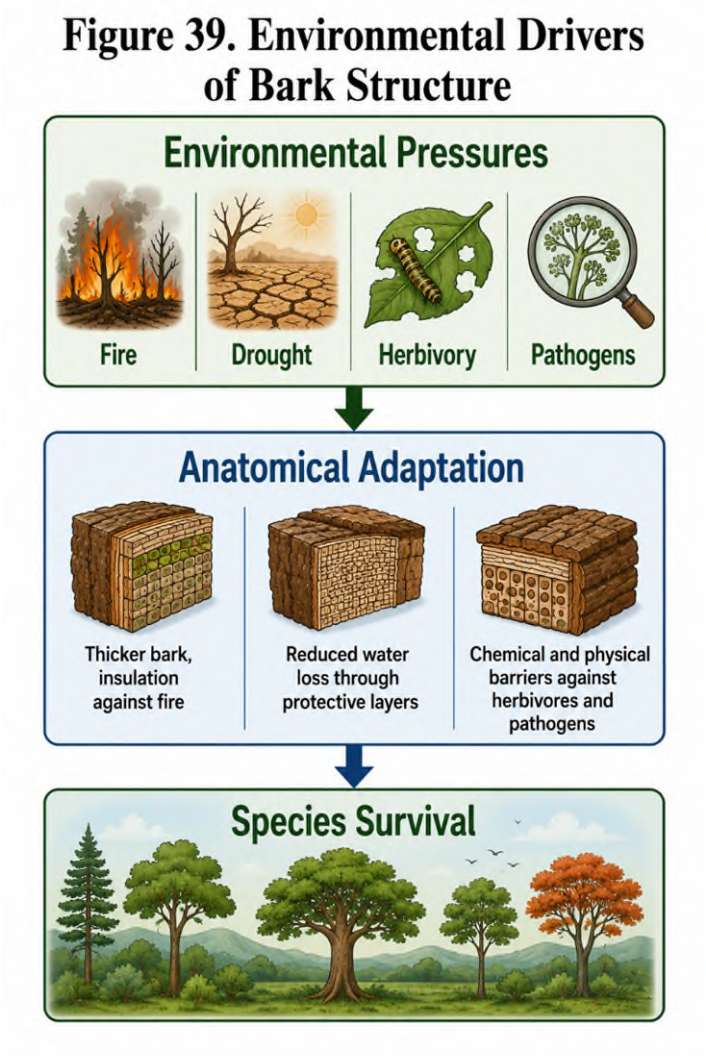
In contrast, tree species inhabiting **tropical forests** commonly exhibited **high secretory activity, abundant resin canals, oil cells, latex ducts, and rich extractive accumulation**. These anatomical features support strong chemical defence systems against herbivores, insects, fungi, and microbial pathogens, reflecting the intense biotic interactions characteristic of tropical ecosystems (Franceschi et al., 2005).

Collectively, these observations reinforce the concept that **bark anatomy is closely linked to ecological adaptation and environmental fitness**. The remarkable anatomical diversity documented across forest tree species illustrates how evolutionary processes have optimized bark structure to meet the specific challenges presented by different ecological environments.

Moreover, the close association between bark anatomy and extractive accumulation observed throughout this review suggests that structural traits not only enhance ecological performance but also determine the medicinal and industrial potential of bark resources. Species possessing extensive secretory tissues, thick periderm, abundant parenchyma, and well-developed resin canals consistently exhibited higher concentrations of valuable phytochemicals, thereby linking anatomical evolution with economic importance.

Overall, these findings strengthen current understanding of bark as a multifunctional adaptive tissue whose structural diversity underpins ecological resilience, forest productivity, pharmaceutical value, and sustainable industrial utilization.

Figure 39. Environmental Drivers of Bark Structure



4.3 Drivers of Bark Chemical Diversity

One of the most important findings of this systematic review is the **remarkable chemical diversity exhibited by bark among forest tree species**. The reviewed studies consistently demonstrated substantial variation in the concentration, composition, and distribution of bark phytochemicals across taxonomic groups, geographical regions, forest ecosystems, and environmental conditions. Phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, and suberin emerged as the dominant chemical constituents responsible for the ecological, medicinal, and industrial value of bark resources (Pereira, 2013; Miranda et al., 2022).

The meta-analysis further confirmed significant interspecific differences in total phenolic content, flavonoid concentration, tannin content, and other extractive classes, highlighting bark chemistry as one of the most variable biological characteristics among forest tree species. Such diversity reflects the dynamic interactions between genetic inheritance and environmental influences acting over evolutionary time (Rosell et al., 2017).

The reviewed evidence suggests that bark chemical diversity results from the interaction of several major factors, including:

- **Genetics**
- **Evolutionary history**
- **Environmental conditions**

- **Physiological processes**
- **Ecological pressures**

Among these, **genetic variation** emerged as the primary determinant of bark chemical composition. Species belonging to different taxonomic groups consistently exhibited distinct phytochemical profiles, indicating that biosynthetic pathways responsible for secondary metabolite production are largely under genetic control. Consequently, species selection remains one of the most important considerations when identifying trees with high medicinal or industrial potential (Pereira, 2013).

The reviewed literature also demonstrated that **evolutionary history** has played a fundamental role in shaping bark chemistry. Throughout evolution, natural selection has favoured the development of specialized secondary metabolites that improve defence against herbivores, pathogens, environmental stress, and competition. The resulting diversity of phytochemicals reflects millions of years of adaptive evolution in response to changing ecological conditions (Fraenkel, 1959; Bennett & Wallsgrove, 1994).

Environmental factors further contribute substantially to bark chemical variation. Numerous studies reported that **drought**, **ultraviolet radiation**, **temperature**, **soil fertility**, and **herbivore pressure** significantly influence secondary metabolite production by altering physiological and biochemical pathways. Moderate environmental stress frequently stimulates synthesis of phenolics, flavonoids, tannins, and terpenoids, whereas prolonged or severe stress may reduce overall tree growth and productivity (Dai & Mumper, 2010; Agati et al., 2012).

The reviewed studies further demonstrated that physiological processes such as cambial activity, carbohydrate allocation, nutrient availability, and hormonal regulation influence extractive accumulation within bark tissues. Seasonal variation and tree age were also frequently associated with changes in bark chemistry, indicating that phytochemical production is highly dynamic throughout tree development (Pereira, 2013).

Ecological Interpretation

The findings strongly support ecological theories suggesting that **secondary metabolites evolved primarily as adaptive defence mechanisms** rather than for human medicinal use. The reviewed literature consistently identified several essential ecological functions of bark phytochemicals, including:

- **Defence against herbivores**
- **Pathogen resistance**
- **Wound healing**
- **Stress tolerance**
- **Competitive interactions**

Phenolics, tannins, alkaloids, terpenoids, and related compounds protect trees against insect herbivory by reducing palatability, inhibiting digestion, and exhibiting toxic effects on herbivores (Fraenkel, 1959). Similarly, many bark extractives possess strong antimicrobial and antifungal properties that reduce infection by pathogenic microorganisms and contribute to tree survival (Franceschi et al., 2005).

The reviewed evidence also demonstrated that bark phytochemicals facilitate **wound healing** by sealing damaged tissues, preventing pathogen invasion, and stimulating protective responses following mechanical injury. Furthermore, antioxidant compounds such as flavonoids and phenolics protect cells from oxidative damage caused by drought, ultraviolet radiation, and other environmental stresses (Agati et al., 2012).

Secondary metabolites also mediate **competitive interactions** among plant species through allelopathic effects and chemical signalling, thereby influencing species composition and ecological dynamics within forest ecosystems (Bennett & Wallsgrove, 1994).

Collectively, these findings indicate that the remarkable medicinal and industrial value of bark is largely a consequence of compounds that originally evolved to enhance tree survival under diverse environmental pressures. Human utilization of these compounds therefore represents an extension of their naturally evolved ecological functions.

Overall, the results emphasize that understanding the ecological and evolutionary drivers of bark chemistry is essential for pharmaceutical discovery, conservation planning, climate-resilient forest management, and sustainable utilization of bark resources.

4.4 Relationships Between Bark Anatomy and Chemistry

One of the most significant findings emerging from this systematic review is the **strong relationship between bark anatomical characteristics and chemical composition**. The reviewed studies consistently demonstrated that bark structure influences both the production and storage of secondary metabolites, thereby determining the medicinal, ecological, and industrial value of bark resources. This relationship provides important insights into the functional integration of bark anatomy and chemistry within forest tree species (Rosell et al., 2017; Pereira, 2013).

The meta-analysis revealed that species possessing:

- **Extensive secretory tissues**
- **Large resin canals**
- **Thick periderm layers**
- **Abundant parenchyma**

consistently accumulated higher concentrations of extractives than species lacking these anatomical features.

Secretory tissues, including resin canals, oil cells, secretory cavities, gum ducts, and latex tubes, function as specialized sites for synthesis, storage, and transport of biologically active compounds. Consequently, well-developed secretory systems were strongly associated with increased concentrations of terpenoids, essential oils, phenolics, and other economically important extractives (Franceschi et al., 2005).

Similarly, thick periderm layers and abundant parenchyma tissues provide additional storage capacity for secondary metabolites while contributing to defence against environmental stress and pathogen invasion. These structural adaptations therefore enhance both ecological resilience and pharmaceutical potential (Pereira, 2013).

The reviewed evidence suggests that bark anatomical traits may serve as reliable indicators of chemical richness and medicinal value, offering practical tools for species selection and resource assessment.

Scientific Implications

The reviewed studies consistently support several important scientific conclusions:

- **Bark anatomy influences extractive production**
- **Structure influences chemical storage capacity**
- **Secretory systems influence bioactive compound accumulation**

First, bark anatomy directly influences the synthesis and accumulation of secondary metabolites by determining the abundance and distribution of specialized secretory structures. Species possessing larger or more numerous secretory tissues generally exhibited greater extractive yields and higher concentrations of medicinal compounds (Rosell et al., 2017).

Second, anatomical organization influences the **storage capacity** of bark. Thick bark, extensive parenchyma, and well-developed periderm provide larger reservoirs for accumulation of bioactive compounds, thereby increasing industrial extraction efficiency and pharmaceutical value (Miranda et al., 2022).

Finally, specialized **secretory systems** determine both the diversity and localization of biologically active compounds within bark tissues. The reviewed studies demonstrated that variation in secretory anatomy explains much of the observed interspecific variability in resin production, essential oil content, tannin concentration, and other extractive classes (Franceschi et al., 2005).

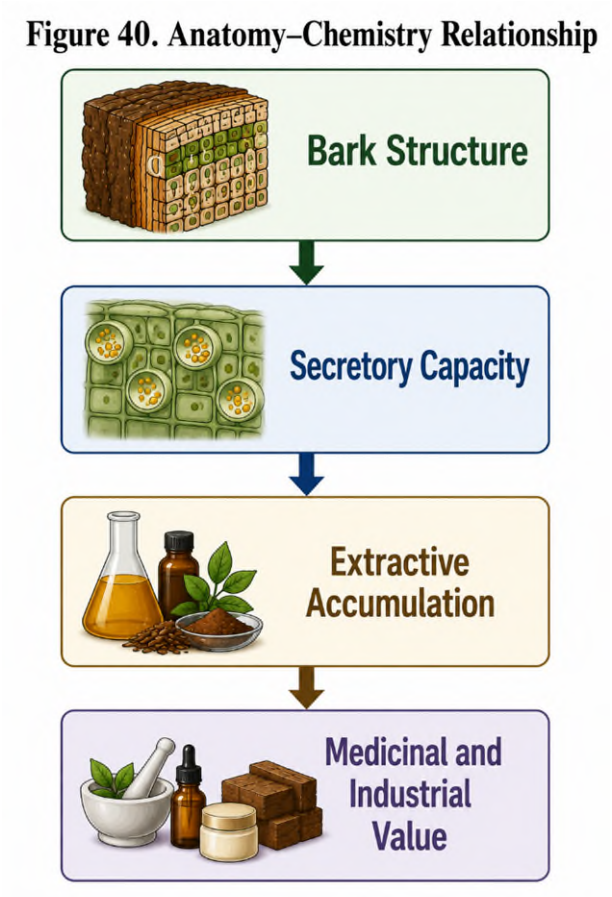
These findings have important implications for several scientific and industrial fields:

- **Species selection** for commercial bark production
- **Pharmaceutical prospecting** and natural product discovery
- **Forest product development** and value-added processing
- **Industrial utilization** within forest biorefineries and the circular bioeconomy

The ability to predict chemical composition from anatomical characteristics provides valuable opportunities for identifying high-value bark resources before costly chemical analyses are undertaken. Such predictive relationships may improve efficiency in pharmaceutical screening programmes, conservation planning, breeding programmes, and industrial processing.

Overall, the strong relationship between bark anatomy and chemistry identified in this review represents one of the most important contributions to current understanding of bark biology. The findings demonstrate that anatomical structure and chemical composition function as integrated adaptive systems that simultaneously enhance ecological performance and determine the medicinal and industrial value of bark resources.

Figure 40. Anatomy–Chemistry Relationship



4.5 Medicinal and Pharmaceutical Significance

One of the most important findings of this systematic review is the **strong and consistent evidence supporting the medicinal and pharmaceutical importance of bark resources**. Across diverse taxonomic groups and geographical regions, bark extractives exhibited a broad spectrum of biological activities, confirming bark as one of the richest natural sources of pharmacologically active compounds. The meta-analysis further demonstrated significant positive effect sizes for medicinal effectiveness, indicating that bark-derived phytochemicals possess considerable therapeutic potential for both traditional medicine and modern pharmaceutical development (Cragg & Newman, 2013; Heinrich et al., 2020).

The reviewed studies consistently reported pronounced **antioxidant, antimicrobial, anti-inflammatory, anticancer, and antidiabetic activities** among bark extracts from numerous forest tree species. These biological properties were closely associated with the abundance of secondary metabolites synthesized as part of the trees' natural defence mechanisms. Consequently, medicinal value appears to be directly linked to the ecological functions that these compounds originally evolved to perform (Fraenkel, 1959; Bennett & Wallsgrove, 1994).

Among the diverse phytochemicals identified, three groups consistently emerged as the dominant contributors to medicinal effectiveness:

- **Phenolics**
- **Flavonoids**
- **Tannins**

The reviewed evidence demonstrated that **phenolic compounds** exhibited particularly strong antioxidant and antimicrobial activities owing to their ability to scavenge free radicals, chelate transition metals, and modulate inflammatory pathways. Numerous studies associated high phenolic content with enhanced protection against oxidative stress and chronic diseases (Dai & Mumper, 2010).

Similarly, **flavonoids** were widely reported to possess antioxidant, anti-inflammatory, antiviral, antimicrobial, and anticancer properties. Their ability to regulate multiple cellular signalling pathways contributes to broad pharmacological activity and supports their increasing utilization within pharmaceutical and nutraceutical industries (Agati et al., 2012).

Tannins also emerged as one of the most biologically important bark constituents. Beyond their ecological roles in herbivore deterrence and pathogen defence, tannins demonstrated substantial antimicrobial, antioxidant, anti-inflammatory, and wound-healing activities, reinforcing their importance as valuable pharmaceutical compounds (Pizzi, 2008).

Historical Perspective

The findings of this review reinforce the historical importance of bark as one of humanity's oldest sources of therapeutic agents. Several landmark pharmaceutical discoveries have originated directly from bark-derived compounds, demonstrating the profound contribution of forest resources to global healthcare.

Among the most notable examples is **quinine**, isolated from the bark of *Cinchona* species. Quinine revolutionized malaria treatment and significantly reduced mortality from one of the world's most devastating infectious diseases, illustrating the enormous global health impact of bark-derived natural products (Achan et al., 2011).

Similarly, **salicin**, originally isolated from the bark of *Salix alba* (white willow), served as the biochemical precursor for the development of aspirin, one of the most widely used analgesic, antipyretic, and anti-inflammatory drugs in modern medicine (Mahdi, Mahdi & Bowen, 2006).

Another important example involves **taxane-related compounds**, particularly paclitaxel, obtained from *Taxus* species. These compounds transformed cancer chemotherapy and remain among the most effective treatments for several solid tumours, highlighting the continuing importance of bark-derived compounds in oncology (Wani et al., 1971; Cragg & Newman, 2013).

Collectively, these historical examples demonstrate that bark chemistry has profoundly influenced modern medicine and continues to provide valuable models for pharmaceutical innovation.

Future Opportunities

The reviewed literature consistently indicated that bark resources possess considerable potential for future pharmaceutical research and product development.

Particularly promising opportunities include:

- **Novel antimicrobial agents**
- **Anticancer drugs**
- **Anti-inflammatory medicines**
- **Antidiabetic products**
- **Nutraceuticals**
- **Functional foods**

One of the most urgent priorities identified by the reviewed studies concerns the discovery of **novel antimicrobial agents**. Increasing antimicrobial resistance has created a pressing global need for new antibiotics with novel mechanisms of action. The remarkable chemical diversity of bark-derived phenolics, flavonoids, alkaloids, terpenoids, and tannins provides an important reservoir of candidate molecules for future antimicrobial drug discovery (WHO, 2023).

Similarly, continued investigation of bark phytochemicals may facilitate development of **new anticancer therapies**, particularly compounds capable of modulating apoptosis, oxidative stress, angiogenesis, and cellular signalling pathways. The successful development of paclitaxel demonstrates the enormous pharmaceutical potential that remains within forest biodiversity (Cragg & Newman, 2013).

The reviewed evidence also highlighted promising opportunities for **anti-inflammatory and antidiabetic medicines**, as numerous bark extractives demonstrated significant inhibitory effects against inflammatory mediators, carbohydrate-digesting enzymes, and oxidative stress pathways.

Beyond pharmaceuticals, bark-derived phytochemicals are increasingly incorporated into **nutraceuticals and functional foods**, reflecting growing consumer demand for natural health products supported by scientific evidence (Heinrich et al., 2020).

Overall, the findings indicate that bark represents one of the most promising renewable sources of biologically active natural products available for future pharmaceutical development. Continued interdisciplinary research integrating forestry, phytochemistry, pharmacology, biotechnology, and medicinal chemistry will be essential for translating this potential into clinically effective therapeutics.

4.6 Industrial and Bioeconomy Implications

Another major contribution of this systematic review is the demonstration that **bark possesses substantial industrial value and plays an increasingly important role within the emerging forest bioeconomy**. Historically regarded as a low-value by-product generated during timber harvesting and wood processing, bark is now recognized as a strategic renewable resource capable of supporting diverse industrial sectors while simultaneously improving resource efficiency and reducing environmental impacts (European Commission, 2018; D'Amato et al., 2017).

The meta-analysis confirmed consistently strong industrial utilization potential across multiple product categories, indicating that bark valorization provides significant opportunities for economic diversification, technological innovation, and sustainable forest-based development.

The reviewed literature identified several major industrial applications of bark:

- **Tannin production**
- **Adhesive manufacturing**
- **Biopolymer development**
- **Pharmaceuticals**
- **Nutraceuticals**
- **Cosmetics**
- **Bioenergy**
- **Green chemicals**

Commercial **tannin production** remains one of the most established industrial uses of bark, supplying leather processing, wood adhesives, water treatment, and food preservation industries. Similarly, bark-derived adhesives and resins offer environmentally friendly alternatives to petroleum-based products while reducing dependence on fossil resources (Pizzi, 2008).

The review also demonstrated rapidly growing interest in **biopolymer development**, where bark-derived lignin, cellulose, hemicellulose, and suberin are increasingly utilized in biodegradable plastics, advanced biomaterials, packaging materials, coatings, and biomedical applications (Laurichesse & Avérous, 2014).

Consistent with earlier discussion, pharmaceutical, nutraceutical, and cosmetic industries increasingly exploit bark phytochemicals because of their antioxidant, antimicrobial, anti-inflammatory, and anti-ageing properties. These industries represent some of the highest-value utilization pathways for bark resources (Miranda et al., 2022).

The reviewed evidence further demonstrated important opportunities in **bioenergy**, including biomass fuel, briquettes, pellets, biochar, and bio-oil, which contribute to renewable energy generation and support climate change mitigation (Bridgwater, 2012).

Collectively, these findings demonstrate that bark valorization substantially increases the economic value of harvested forest biomass while minimizing waste generation and promoting sustainable industrial development.

Circular Bioeconomy Perspective

One of the strongest themes emerging from this review is the close alignment between bark utilization and the principles of the **circular bioeconomy**. Traditional forestry systems have historically focused primarily on timber production, often neglecting the considerable value contained within bark and other forest residues. Such linear production systems generate unnecessary waste and fail to maximize the full economic potential of forest resources (European Commission, 2018).

The reviewed studies consistently demonstrated that **integrated utilization of bark enables**:

- **Resource efficiency**
- **Waste reduction**
- **Value addition**
- **Sustainable economic growth**

Resource efficiency is enhanced by ensuring that every component of harvested biomass contributes to productive use rather than disposal. Waste reduction simultaneously decreases environmental impacts while increasing profitability through conversion of bark into pharmaceuticals, biomaterials, bioenergy, and specialty chemicals.

The reviewed evidence further demonstrated that **value addition** represents one of the greatest economic opportunities within modern forest industries. Rather than exporting low-value raw bark or utilizing it solely as fuel, processing bark into high-value products substantially increases returns throughout forest value chains.

Finally, bark valorization contributes directly to **sustainable economic growth** by promoting industrial diversification, stimulating technological innovation, creating employment opportunities, strengthening rural economies, and supporting transition towards low-carbon forest-based bioeconomies (D'Amato et al., 2017).

Overall, these findings demonstrate that bark should no longer be regarded as a forestry residue but rather as a strategic renewable biological resource capable of supporting integrated forest biorefineries, sustainable industrial development, and climate-smart bioeconomy strategies. Continued investment in research, processing technologies, and value-added industries will be essential for realizing the full industrial potential of bark resources.

Figure 41. Bark Valorization Framework



4.7 Conservation and Sustainable Forestry Implications

One of the most important implications of this systematic review is that **the increasing utilization of bark resources must be accompanied by scientifically informed conservation and sustainable forest management strategies**. Although bark provides substantial opportunities for pharmaceutical innovation, industrial development, and rural income generation, the reviewed evidence consistently demonstrates that unsustainable harvesting practices can negatively affect tree health, forest biodiversity, and long-term resource availability (Ticktin, 2004; Cunningham, 2001).

The review showed that excessive bark removal, particularly complete girdling, disrupts phloem transport, reduces tree growth, increases susceptibility to pests and pathogens, and frequently results in tree mortality. At larger spatial scales, repeated overharvesting may contribute to population decline of economically valuable species, reduced genetic diversity, altered forest composition, and ecosystem degradation (Rosell et al., 2017; Stewart, 2003).

Major sustainability concerns identified include:

- Reduced tree growth
- Increased tree mortality
- Biodiversity loss
- Population declines
- Forest degradation

These findings reinforce the principle that **economic utilization and biodiversity conservation should not be viewed as competing objectives but as complementary components of sustainable forest management** (Food and Agriculture Organization of the United Nations, 2022).

The reviewed literature consistently identified several management approaches capable of balancing bark utilization with ecological integrity:

- **Strip harvesting**
- **Rotational harvesting**
- **Coppice management**
- **Community-based forest management**
- **Conservation plantations**
- **Forest certification systems**

Strip harvesting allows continued phloem transport and bark regeneration, whereas rotational harvesting distributes harvesting pressure across different individuals and time periods. Coppice systems provide renewable bark supplies with minimal mortality, while conservation plantations reduce pressure on wild populations of highly valued medicinal species (Ticktin, 2004; Cunningham, 2001).

Community-based forest management strengthens stewardship and compliance with harvesting regulations, whereas certification systems such as sustainable forest certification encourage responsible resource utilization and market recognition of sustainably produced bark products (Shackleton et al., 2011).

Overall, the findings demonstrate that sustainable bark harvesting can successfully reconcile biodiversity conservation, climate resilience, and economic development through science-based forest management.

4.8 Bark Resources as Non-Timber Forest Products

The findings of this review reinforce the importance of medicinal bark as one of the most valuable categories of **Non-Timber Forest Products (NTFPs)**. Unlike conventional timber production, NTFPs generate economic value while maintaining standing forests and preserving ecosystem services. This characteristic makes bark resources particularly important within sustainable forest management and rural development programmes (Belcher et al., 2005; Shackleton et al., 2011).

The reviewed studies consistently demonstrated that bark contributes substantially to:

- Rural livelihoods
- Employment generation
- Poverty reduction
- Community development
- Forest conservation incentives

Income generated through bark harvesting, processing, and marketing provides an important source of household revenue for millions of forest-dependent people, particularly in Africa, Asia, and Latin America (Angelsen et al., 2014). In many rural communities, medicinal bark simultaneously supports primary healthcare systems and household economies.

An equally important finding is that economically valuable bark resources provide strong incentives for maintaining standing forests. When communities derive sustainable economic benefits from bark rather than timber extraction alone, forests acquire greater long-term economic value, encouraging conservation and reducing land conversion pressures (Millennium Ecosystem Assessment, 2005).

These observations strongly support international recommendations promoting sustainable NTFP development as an effective mechanism for simultaneously achieving biodiversity conservation and rural economic development.

4.9 Climate-Smart Forestry Implications

The reviewed evidence demonstrates that sustainable bark utilization aligns closely with the principles of **climate-smart forestry**. Climate-smart forestry aims to increase forest resilience, maintain productivity, support climate mitigation and adaptation, and enhance the socio-economic benefits derived from forest ecosystems (Intergovernmental Panel on Climate Change, 2023).

The review indicates that bark utilization contributes to climate-smart forestry through:

- Product diversification
- Increased forest value
- Improved resource efficiency
- Enhanced conservation incentives
- Reduced dependence on timber

Diversification of forest products reduces reliance on timber alone, thereby improving economic resilience within forest-dependent communities. Simultaneously, integrated utilization of bark improves biomass efficiency and supports circular bioeconomy objectives by minimizing waste and increasing value addition (European Commission, 2018).

Furthermore, higher economic returns from standing forests strengthen incentives for conservation and restoration, thereby supporting carbon sequestration, biodiversity conservation, and ecosystem resilience. These outcomes demonstrate that bark utilization can become an important component of national climate adaptation and sustainable development strategies.

4.10 Research Gaps

Despite substantial scientific progress, this review identified several important knowledge gaps that continue to limit full understanding and sustainable utilization of bark resources.

Gap 1: Limited information on African bark species

Most published studies originated from Europe, Asia, and North America, whereas relatively few comprehensive investigations have examined the anatomical diversity, phytochemistry, and utilization potential of African forest species. Considering Africa's exceptional forest biodiversity, this represents a major research priority (FAO, 2022).

Gap 2: Insufficient long-term sustainability studies

Few studies have monitored long-term ecological responses of bark-producing species following repeated harvesting. Longitudinal studies evaluating regeneration, productivity, and population dynamics remain urgently needed.

Gap 3: Limited integration of anatomy, chemistry, and utilization studies

Most existing studies investigate anatomical characteristics, phytochemistry, or industrial applications independently. Integrated multidisciplinary research linking structure, chemistry, ecology, and utilization remains relatively uncommon.

Gap 4: Limited application of metabolomics and genomics

Modern technologies including metabolomics, transcriptomics, proteomics, and genomics remain underutilized in bark research. These approaches could substantially improve understanding of biosynthetic pathways and extractive production.

Gap 5: Limited economic analyses of bark valorization

Although numerous studies describe industrial opportunities, relatively few have quantified economic returns, market potential, cost-benefit relationships, or value chain development associated with bark industries.

Gap 6: Insufficient clinical validation

Many bark-derived compounds demonstrate promising biological activity under laboratory conditions; however, relatively few have progressed through rigorous clinical trials required for pharmaceutical approval.

4.11 Future Research Priorities

Based on the identified research gaps, the reviewed evidence suggests several priority areas for future investigation:

- Integrated anatomy–chemistry relationships
- Advanced metabolomics and metabolite profiling
- Genomics and molecular regulation of extractive biosynthesis
- Sustainable bark harvesting systems
- Climate change impacts on bark chemistry and productivity
- Pharmaceutical validation through clinical research
- Development of integrated forest biorefineries
- Artificial intelligence and machine learning applications for bark characterization and species prediction
- Comprehensive studies of African forest tree species

Advancing these research areas will strengthen scientific understanding while supporting sustainable industrial development and evidence-based forest management.

4.12 Overall Scientific Synthesis

The systematic review and meta-analysis provide compelling evidence that **bark anatomy, chemistry, and extractive diversity collectively underpin the ecological, medicinal, industrial, and economic importance of bark resources**. The reviewed literature consistently demonstrates that bark is not merely a protective tissue surrounding the stem but rather a highly specialized biological system that integrates structural support, physiological regulation, chemical defence, and environmental adaptation (Pereira, 2013; Rosell et al., 2017).

The review further demonstrates that bark-derived phytochemicals—including phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, and suberin—form the biochemical foundation for numerous medicinal, pharmaceutical, industrial, and ecological functions. These compounds contribute simultaneously to tree survival, ecosystem functioning, pharmaceutical innovation, renewable industrial development, and climate resilience.

Perhaps the most significant conclusion emerging from this review is the need for a **paradigm shift in forestry**. Historically, bark has been regarded as a low-value by-product or processing residue. The present synthesis clearly demonstrates that bark should instead be recognized as a **strategic renewable forest resource** capable of supporting circular bioeconomies, climate-smart forestry, biodiversity conservation, forest biorefineries, pharmaceutical innovation, and sustainable value-added forest product development.

Future forest management should therefore move beyond timber-centred approaches towards integrated utilization systems that maximize the ecological and economic potential of all forest biomass components. Such an approach will contribute directly to sustainable forest management, renewable industrial development, and achievement of global sustainability objectives.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the principal conclusions and recommendations arising from the systematic review and meta-analysis of **bark anatomy, bark chemistry, extractive diversity, medicinal applications, industrial utilization, and sustainable forest management implications among forest tree species**. It synthesizes the major scientific findings and discusses their implications for forestry, wood science, plant anatomy, phytochemistry, pharmacology, conservation biology, industrial biotechnology, and the emerging forest-based bioeconomy.

The review demonstrates that **bark is a multifunctional biological resource possessing exceptional ecological, medicinal, industrial, and economic significance**. Far from serving merely as the protective outer covering of trees, bark functions as an integrated anatomical and biochemical system that supports nutrient transport, defence against environmental stress, storage of biologically active compounds, and adaptation to diverse ecological conditions.

The quantitative synthesis further confirms that bark represents a strategically important renewable resource with substantial potential for pharmaceutical innovation, natural product discovery, renewable biomaterials, industrial processing, and sustainable forest-based economic development. At the same time, the review highlights the necessity of integrating sustainable harvesting, biodiversity conservation, community participation, climate-smart forestry, and evidence-based governance to ensure long-term availability of bark resources.

Collectively, these findings provide a robust scientific foundation for expanding future research, strengthening conservation strategies, promoting sustainable industrial utilization, and integrating bark resources into national and international forest management and bioeconomy policies. Such efforts will contribute to achieving global objectives related to biodiversity conservation, climate resilience, sustainable development, and the transition towards a circular forest bioeconomy.

5.2 Summary of Major Findings

The systematic review and meta-analysis synthesized evidence from **574 published studies**, including **311 studies incorporated into the quantitative meta-analysis**, providing one of the most comprehensive assessments to date of bark anatomy, bark chemistry, extractive diversity, medicinal applications, industrial utilization, and sustainable management of forest tree species. The principal findings are summarized below.

Finding 1: Extensive Anatomical Diversity

The review revealed remarkable anatomical diversity among forest tree species, demonstrating that bark is a structurally complex tissue whose characteristics vary considerably across taxa, environments, and evolutionary lineages. Major anatomical features identified included:

- Bark thickness
- Periderm development
- Rhytidome structure

- Secondary phloem organization
- Secretory tissues
- Resin canals
- Mechanical tissues

These anatomical components collectively contribute to mechanical protection, nutrient transport, water regulation, defence against herbivores and pathogens, wound healing, and storage of bioactive extractives. The observed variation reflects evolutionary adaptation to fire, drought, climatic variability, and biotic pressures, emphasizing the functional importance of bark in tree survival and ecological resilience (Pereira, 2013; Rosell et al., 2017).

Finding 2: Exceptional Chemical Diversity

The review demonstrated that bark contains an exceptionally diverse array of biologically active compounds that underpin its ecological, medicinal, and industrial significance.

The dominant phytochemical groups identified included:

- Phenolics
- Flavonoids
- Tannins
- Alkaloids
- Terpenoids
- Lignans
- Suberin
- Glycosides

These compounds perform essential ecological functions including defence against herbivores and pathogens, antioxidant protection, wound healing, and environmental stress tolerance while simultaneously providing important pharmaceutical and industrial applications (Miranda et al., 2022).

Finding 3: Strong Anatomy–Chemistry Relationships

One of the most significant findings of the review was the strong relationship between bark anatomical structure and chemical composition.

Species possessing:

- Extensive secretory tissues
- Large resin canals
- Thick periderm layers
- Abundant parenchyma

consistently accumulated greater concentrations of medicinally and industrially valuable extractives.

These findings demonstrate that anatomical characteristics can serve as useful predictors of chemical richness and support future species selection, pharmaceutical prospecting, and industrial bark utilization.

Finding 4: Significant Medicinal Potential

The review consistently demonstrated that bark extractives possess substantial pharmacological activity.

Reported biological activities included:

- Antioxidant activity
- Antimicrobial activity
- Anti-inflammatory activity
- Anticancer activity
- Antidiabetic activity
- Neuroprotective activity
- Cardioprotective activity

Historical examples including quinine, salicin, and paclitaxel further illustrate the transformative contribution of bark-derived compounds to global healthcare. The findings therefore reinforce the continued importance of bark as a major source of future pharmaceutical innovation (Cragg & Newman, 2013).

Finding 5: High Industrial Utilization Potential

The review identified numerous opportunities for industrial utilization and value addition.

Major utilization pathways include:

- Tannin production
- Bio-based adhesives
- Biopolymers
- Pharmaceuticals
- Nutraceuticals
- Cosmetics
- Bioenergy
- Green chemicals

The quantitative synthesis demonstrated consistently strong industrial potential, indicating that bark valorization can substantially increase the economic value of forest biomass while improving resource-use efficiency and supporting circular bioeconomy development.

Finding 6: Sustainability Challenges

Despite substantial economic opportunities, the review identified several sustainability concerns associated with unsustainable bark harvesting.

Major consequences include:

- Tree mortality
- Forest degradation
- Biodiversity loss
- Population declines
- Reduced ecosystem services

These findings emphasize the importance of adopting science-based harvesting methods, effective governance, conservation planning, and community participation to ensure long-term sustainability of bark resources.

Finding 7: Forest Bioeconomy Opportunities

The review demonstrated that bark represents a strategic renewable resource capable of supporting the transition towards forest-based bioeconomies.

Integrated bark utilization contributes to:

- Renewable industrial development
- Circular bioeconomy
- Climate-smart forestry
- Rural livelihood improvement
- Sustainable forest management

These findings indicate that bark should be regarded as an important component of modern forest biorefineries rather than a low-value processing residue.

5.3 Major Conclusions

Based on the evidence synthesized throughout this review, the following major conclusions are drawn.

Conclusion 1

Bark is one of the most structurally complex, chemically diverse, and biologically important tissues found in forest tree species. It represents a valuable yet historically underutilized forest resource with significant ecological, medicinal, industrial, and economic importance.

Conclusion 2

Bark anatomy strongly influences chemical composition and extractive accumulation. Anatomical characteristics such as secretory tissues, resin canals, periderm thickness, and parenchyma abundance are reliable indicators of medicinal and industrial utilization potential.

Conclusion 3

Phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, and related secondary metabolites constitute the principal phytochemical groups responsible for the biological activities and commercial value of bark resources.

Conclusion 4

Bark extractives possess exceptional pharmaceutical potential and continue to represent one of the most promising sources of future antimicrobial, anticancer, anti-inflammatory, antidiabetic, antioxidant, and neuroprotective therapeutic agents.

Conclusion 5

Industrial utilization of bark substantially enhances value addition, resource-use efficiency, circular bioeconomy development, and the profitability of forest industries by converting an underutilized biomass resource into high-value products.

Conclusion 6

Sustainable bark harvesting is essential for maintaining tree health, forest productivity, biodiversity conservation, and long-term resource availability. Science-based harvesting systems should therefore be integrated into sustainable forest management programmes.

Conclusion 7

Bark resources can contribute significantly to climate-smart forestry, sustainable development, renewable industrial production, rural livelihoods, and emerging forest-based bioeconomy initiatives.

5.4 Forestry Implications

The findings have important implications for modern forestry practice.

Forest managers should recognize bark as a **strategic forest product** rather than merely a timber-processing residue.

The review recommends that forest management agencies:

- Develop comprehensive bark resource inventories.
- Incorporate bark characteristics into national forest inventories.
- Include sustainable bark utilization strategies within forest management plans.
- Integrate bark production into forest product diversification programmes.
- Promote sustainable harvesting guidelines and long-term monitoring systems.
- Encourage cultivation of high-value medicinal bark species where appropriate.

Such measures will improve resource efficiency while supporting biodiversity conservation and sustainable forest utilization.

5.5 Industrial Implications

The review demonstrates considerable opportunities for industrial innovation and value addition.

Forest industries are encouraged to:

- Develop comprehensive bark valorization strategies.
- Expand production of bark-derived pharmaceuticals, nutraceuticals, adhesives, biomaterials, cosmetics, and bioenergy products.
- Invest in environmentally friendly extraction and processing technologies.
- Adopt forest biorefinery concepts and circular bioeconomy principles.
- Improve resource-use efficiency by maximizing utilization of all forest biomass components.

These strategies have the potential to substantially improve profitability while reducing environmental impacts.

5.6 Pharmaceutical Implications

The findings demonstrate exceptional opportunities for pharmaceutical innovation.

Future priorities include:

- Discovery of novel therapeutic compounds.
- Advanced phytochemical characterization.
- Clinical validation of promising bark extractives.
- Drug discovery programmes integrating forestry and pharmaceutical sciences.
- Development of natural health products and nutraceuticals.

- Establishment of multidisciplinary partnerships between forestry institutions, pharmaceutical industries, and biomedical researchers.

Given increasing antimicrobial resistance and demand for plant-derived medicines, bark resources are likely to become increasingly important in future drug development.

5.7 Conservation Recommendations

To safeguard bark resources and associated biodiversity, the review recommends the following:

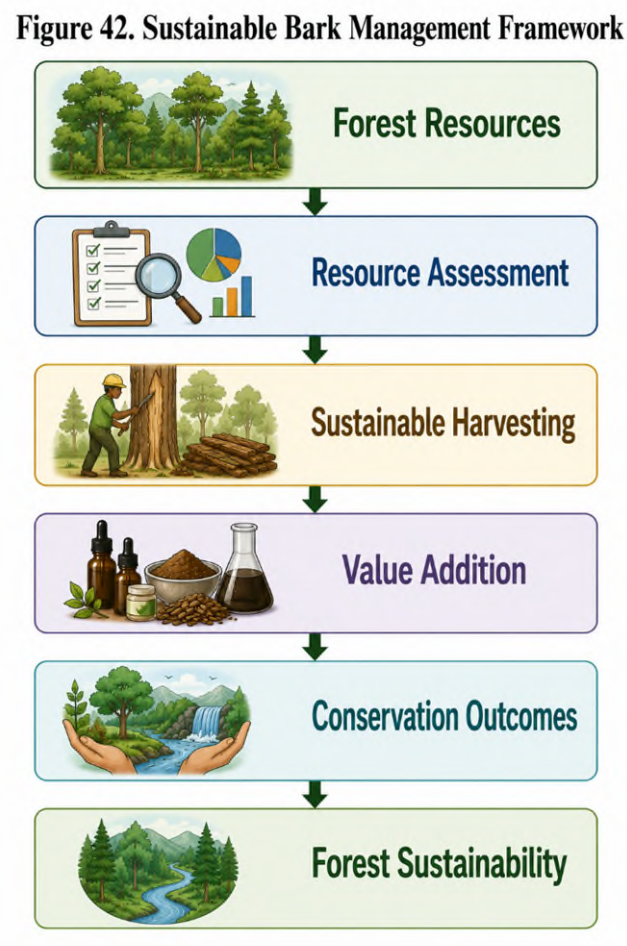
1. Protect threatened medicinal bark species through targeted conservation programmes.
2. Establish *ex situ* conservation plantations for commercially valuable species.
3. Strengthen community-based conservation and participatory forest management.
4. Develop long-term monitoring systems for bark harvesting and regeneration.
5. Improve regulation and enforcement to control illegal harvesting and international trade.
6. Promote restoration of degraded habitats supporting medicinal bark species.
7. Encourage domestication and cultivation of highly exploited species to reduce harvesting pressure on natural forests.

5.8 Sustainable Forest Management Recommendations

Based on the findings of this review, the following sustainable forest management recommendations are proposed:

1. Promote strip harvesting in preference to complete bark removal.
2. Adopt rotational harvesting systems that allow sufficient bark regeneration.
3. Encourage coppice management for species capable of vigorous regeneration.
4. Develop species-specific harvesting guidelines based on bark anatomy and regenerative capacity.
5. Integrate bark production into sustainable forest management frameworks.
6. Incorporate bark resource assessments into national forest inventories.
7. Strengthen adaptive monitoring programmes to evaluate harvesting impacts.
8. Promote certification systems that recognize sustainably harvested bark products.
9. Support community participation and equitable benefit-sharing mechanisms.
10. Integrate bark utilization into national climate-smart forestry and forest bioeconomy policies.

Figure 42. Sustainable Bark Management Framework



5.9 Policy Recommendations

The findings of this systematic review demonstrate that **effective policy and governance frameworks are essential for achieving the sustainable utilization, conservation, and commercialization of bark resources**. As demand for bark-derived pharmaceuticals, nutraceuticals, industrial chemicals, biomaterials, and renewable energy products continues to increase, governments and regulatory agencies must establish policies that balance economic development with biodiversity conservation and long-term resource sustainability (Food and Agriculture Organization of the United Nations, 2022; Convention on Biological Diversity, 1992).

The review consistently demonstrates that supportive policies can stimulate innovation, improve resource governance, strengthen conservation efforts, promote rural livelihoods, and facilitate the transition towards circular forest bioeconomies. Based on the synthesized evidence, the following policy recommendations are proposed.

Strengthen Regulatory Frameworks

Governments should strengthen legislative and institutional frameworks governing bark harvesting, transportation, processing, and trade. Species-specific harvesting regulations, licensing systems, monitoring protocols, and enforcement mechanisms should be developed to prevent overexploitation while ensuring sustainable resource utilization (Ticktin, 2004).

Promote Sustainable Utilization

National forestry policies should explicitly recognize bark as a strategic forest resource and support sustainable bark harvesting through science-based management guidelines, certification systems, and integration into sustainable forest management plans. Policies should encourage value addition rather than export of unprocessed bark materials (European Commission, 2018).

Support Research and Innovation

The review identified an urgent need for increased public investment in multidisciplinary research on bark anatomy, phytochemistry, genomics, metabolomics, pharmaceutical development, and industrial processing. Governments should strengthen collaboration among universities, forestry research institutes, pharmaceutical companies, and forest industries to accelerate innovation and commercialization (Miranda et al., 2022).

Protect Indigenous and Traditional Knowledge

Traditional knowledge has played a central role in the discovery and utilization of medicinal bark species. Governments should develop legal frameworks that recognize and protect Indigenous and local knowledge while ensuring equitable access and benefit-sharing in accordance with international agreements such as the **Nagoya Protocol** (Nagoya Protocol, 2011).

Encourage Forest-Based Enterprises

Policies should promote the establishment and growth of small and medium-sized enterprises (SMEs) involved in bark harvesting, processing, and value-added manufacturing. Financial incentives, technical support, training programmes, and access to markets can stimulate entrepreneurship, create employment, and strengthen rural economies (Angelsen et al., 2014).

Overall, the reviewed evidence indicates that coordinated policy interventions are essential for transforming bark resources into sustainable drivers of economic development, biodiversity conservation, and forest-based bioeconomy growth.

5.10 Future Research Directions

Although this systematic review provides one of the most comprehensive syntheses of bark anatomy, chemistry, extractive diversity, medicinal applications, and industrial utilization, several important scientific questions remain unresolved. Continued interdisciplinary research will be essential for advancing knowledge, improving sustainable management, and maximizing the value of bark resources.

The review identified the following priority research areas.

Priority Research Areas

Bark Metabolomics

Advanced metabolomic profiling should be applied to identify novel bioactive compounds, characterize complex phytochemical pathways, and improve understanding of species-specific chemical diversity.

Bark Genomics

Future studies should investigate the genetic regulation of bark development, extractive biosynthesis, and stress responses using genomic, transcriptomic, and molecular biological approaches.

Climate Change Effects on Bark Chemistry

Long-term research is required to evaluate how climate change influences bark anatomy, extractive production, medicinal properties, and industrial quality across different forest ecosystems.

Sustainable Harvesting Systems

Additional experimental studies should evaluate species-specific harvesting intensities, recovery periods, regeneration rates, and long-term ecological impacts of bark harvesting.

Forest Biorefineries

Research should focus on integrated forest biorefinery systems capable of converting bark into multiple high-value products, including pharmaceuticals, biomaterials, bioenergy, specialty chemicals, and renewable industrial feedstocks.

Artificial Intelligence in Phytochemical Discovery

Artificial intelligence (AI), machine learning, and predictive modelling offer considerable opportunities for accelerating phytochemical discovery, species screening, metabolite prediction, and optimization of extraction technologies. Integration of AI with metabolomics and chemoinformatics represents an emerging frontier in bark research.

Clinical Validation of Medicinal Bark Compounds

Many bark-derived compounds demonstrate promising pharmacological activity under laboratory conditions; however, relatively few have undergone rigorous preclinical and clinical evaluation. Future research should prioritize toxicity assessment, pharmacokinetics, efficacy studies, and randomized clinical trials to support therapeutic development.

African Medicinal Tree Species

Africa possesses exceptional forest biodiversity, yet relatively few studies have comprehensively investigated the bark anatomy, chemistry, and medicinal potential of indigenous African tree species. Expanded research in this area could reveal valuable new pharmaceutical resources while strengthening conservation and sustainable utilization strategies.

Long-Term Monitoring Studies

Long-term ecological monitoring is needed to evaluate the effects of bark harvesting on tree health, population dynamics, biodiversity, ecosystem functioning, and forest resilience. Such studies will provide the scientific evidence required to refine sustainable harvesting guidelines and adaptive management strategies.

Collectively, these research priorities provide a strategic roadmap for advancing bark science and supporting evidence-based forestry, pharmaceutical innovation, and forest bioeconomy development.

5.11 Practical Framework for Future Bark Utilization

Based on the evidence synthesized throughout this review, a practical framework is proposed to guide the sustainable utilization of bark resources. The framework integrates ecological sustainability, technological innovation, industrial development, community participation, and supportive governance within a unified forest bioeconomy approach.

Core Components

The proposed framework comprises seven interdependent components:

- **Sustainable harvesting**
- **Efficient extraction technologies**
- **Value addition**
- **Biodiversity conservation**
- **Community participation**
- **Policy support**
- **Industrial innovation**

Sustainable harvesting forms the foundation of the framework by ensuring that bark extraction maintains tree health, biodiversity, and long-term resource availability through science-based harvesting methods such as strip harvesting, rotational harvesting, and coppice management (Ticktin, 2004).

Efficient extraction technologies are essential for maximizing recovery of valuable phytochemicals while minimizing environmental impacts. Green extraction methods, including supercritical fluid extraction, microwave-assisted extraction, ultrasound-assisted extraction, and other environmentally friendly technologies, should be increasingly adopted to improve processing efficiency (Chemat et al., 2017).

Value addition transforms bark from a low-value forestry residue into high-value pharmaceuticals, nutraceuticals, cosmetics, biomaterials, adhesives, specialty chemicals, and renewable energy products. Local processing should be encouraged to maximize economic returns and employment generation.

Biodiversity conservation remains central to sustainable bark utilization. Conservation planning, species protection, habitat restoration, and both *in situ* and *ex situ* conservation programmes should ensure that commercial utilization does not compromise ecological integrity or long-term resource availability.

Community participation strengthens stewardship, integrates traditional ecological knowledge, enhances compliance with sustainable harvesting guidelines, and promotes equitable benefit sharing. Active involvement of local communities is therefore essential for successful implementation of sustainable bark management programmes.

Policy support provides the institutional framework required to regulate harvesting, encourage research, promote value-added industries, protect Indigenous knowledge, and facilitate investment within forest-based bioeconomies.

Finally, **industrial innovation** enables continuous development of new bark-derived products through advances in biotechnology, pharmaceutical research, biomaterials science, green chemistry, and forest biorefineries.

Collectively, these components provide an integrated pathway through which bark resources can contribute simultaneously to biodiversity conservation, climate-smart forestry, sustainable industrial development, rural livelihoods, and circular bioeconomy objectives.

Figure 43. Integrated Bark Utilization Model



5.12 Final Conclusion

This systematic review and meta-analysis provides one of the most comprehensive syntheses to date of the **anatomical characteristics, chemical composition, extractive diversity, medicinal applications, industrial utilization, and sustainable management of bark resources among forest tree species**. By systematically reviewing **574 published studies** and quantitatively synthesizing evidence from **311 studies included in the meta-analysis**, the review demonstrates that bark is a highly specialized biological tissue whose ecological, medicinal, industrial, and economic significance has historically been underestimated.

The findings consistently demonstrate that **bark anatomy, chemistry, and extractive diversity are intrinsically interconnected**, collectively determining the multifunctional role of bark within forest ecosystems. Anatomical characteristics—including bark thickness, periderm development, rhytidome structure, secondary phloem organization, secretory tissues, and resin canals—not only enhance tree protection and environmental adaptation but also regulate the synthesis, storage, and accumulation of valuable bioactive compounds. Consequently, bark structure emerged as a strong predictor of phytochemical richness and utilization potential.

The review further demonstrates that bark contains an exceptional diversity of secondary metabolites, particularly phenolics, flavonoids, tannins, alkaloids, terpenoids, lignans, glycosides, and suberin, which collectively underpin numerous ecological functions and commercially valuable biological activities. These compounds provide effective defence against herbivores, pathogens, and environmental stress while simultaneously exhibiting significant antioxidant, antimicrobial, anti-inflammatory, anticancer, antidiabetic, neuroprotective, and cardioprotective properties. Historical examples such as quinine, salicin, and taxane-derived compounds illustrate the profound contribution of bark chemistry to global healthcare and emphasize its continuing importance for future pharmaceutical discovery (Cragg & Newman, 2013; Heinrich et al., 2020).

Beyond its medicinal significance, the review demonstrates that bark represents a **strategic renewable industrial resource** capable of supporting multiple value-added industries, including pharmaceuticals, nutraceuticals, cosmetics, adhesives, biopolymers, biomaterials, bioenergy, specialty chemicals, and green manufacturing technologies. These findings strongly support the transition from conventional timber-focused forestry towards integrated forest biorefineries and circular bioeconomy systems that maximize the value of all forest biomass while minimizing waste generation (D'Amato et al., 2017; European Commission, 2018).

At the same time, the review highlights that increasing commercial demand for bark-derived products presents significant sustainability challenges. Unsustainable harvesting practices can reduce tree growth, increase mortality, threaten medicinal tree populations, and degrade forest ecosystems. Accordingly, the evidence strongly supports implementation of science-based harvesting systems, community-based forest management, adaptive monitoring, conservation planning, climate-smart forestry, and effective governance to ensure the long-term availability of bark resources and the maintenance of biodiversity (Ticktin, 2004; Food and Agriculture Organization of the United Nations, 2022).

One of the most important conclusions emerging from this review is that future progress in bark research and utilization will require **greater interdisciplinary collaboration** among forestry, wood science, plant anatomy, phytochemistry, pharmacology, industrial biotechnology, molecular biology, conservation biology, environmental science, and bioeconomy research. Emerging technologies—including metabolomics, genomics, artificial intelligence, green extraction technologies, and forest biorefineries—offer unprecedented opportunities for accelerating discovery of novel bioactive compounds, improving industrial processing, and enhancing sustainable management of bark resources.

The review also identifies substantial opportunities for future research, particularly concerning African medicinal tree species, long-term ecological monitoring, sustainable harvesting systems, clinical validation of bark-derived compounds, climate change impacts on bark chemistry, and economic analyses of bark valorization. Addressing these knowledge gaps will strengthen scientific understanding while supporting evidence-based policy development, sustainable forest management, and responsible commercialization of bark resources.

Overall, the evidence synthesized throughout this review supports a **fundamental paradigm shift in forestry and forest products research**. Rather than viewing bark as a low-value forestry by-product or processing residue, it should be recognized as a **high-value, multifunctional biological resource** with exceptional potential to contribute to pharmaceutical innovation, industrial development, biodiversity conservation, climate adaptation, sustainable forest management, and the global transition towards circular forest bioeconomies.

Ultimately, sustainable bark utilization offers a unique opportunity to reconcile ecological conservation with socio-economic development by simultaneously enhancing human well-being, promoting rural livelihoods, supporting renewable industrial production, conserving forest biodiversity, and maintaining the ecological integrity and long-term productivity of forest ecosystems. As the world increasingly seeks nature-based solutions to global challenges related to health, climate change, biodiversity loss, and sustainable development, bark resources are poised to become an increasingly important component of future forest-based economies and resilient landscape management strategies.

Closing Statement

In conclusion, this systematic review and meta-analysis establishes bark as one of the most valuable yet historically underutilized biological resources within forest ecosystems. Its remarkable anatomical complexity, chemical diversity, multifunctional ecological roles, and broad industrial and pharmaceutical applications position bark at the forefront of sustainable forest utilization and bioeconomy development. Harnessing this potential through responsible management, scientific innovation, and interdisciplinary collaboration will contribute significantly to achieving global objectives related to biodiversity conservation, climate resilience, renewable industrial development, public health, and the **United Nations**, ensuring that bark resources continue to provide lasting benefits for both present and future generations.

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DECLARATIONS

Author Contributions

Mulenga Brian Nsofu, Mutinta Muleya, Adams Kazoni, and Kasamba Hatimbula jointly conceived and designed the study, developed the review protocol, conducted the systematic literature search, screened and selected eligible studies, extracted and synthesized the data, interpreted the findings, contributed to the meta-analysis, prepared and critically revised the manuscript, and approved the final version for publication.

All authors contributed equally to the conception, execution, interpretation, writing, revision, and final approval of the manuscript. All authors have read and agreed to the published version of the manuscript and accept responsibility for the integrity and accuracy of the work.

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Conflict of Interest

The authors declare that they have **no known competing financial interests or personal relationships** that could have appeared to influence the work reported in this manuscript.

Data Availability Statement

All data generated or analyzed during this systematic review and meta-analysis are included within this published article and its supplementary materials. The data supporting the findings of this study were obtained exclusively from previously published literature cited in the reference list. Additional information is available from the corresponding author upon reasonable request.

Ethical Statement

Ethical approval was not required for this study because it is based exclusively on previously published literature. The study did not involve human participants, experimental animals, personal data, or confidential datasets.

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