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Essential Oil of Taxodium distichum (L.) Rich.: Chemical Diversity, Biological Activities, and Prospects for Standardized Applications—A Review

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Abstract

Taxodium distichum (L.) Rich., commonly known as bald cypress, produces chemically diverse essential oils in its leaves, twigs, and seed cones. Although the species is often associated with α-pinene-rich oil, published investigations also describe limonene-rich, β-phellandrene-rich, and oxygenated sesquiterpene- or diterpene-rich preparations. This narrative review examines the botanical context, extraction methods, compositional variability, biological activities, analytical requirements, and development prospects of these oils. Direct studies of *T. distichum* are considered separately from research on isolated terpenes, other essential oils, and nonvolatile Taxodium extracts. The evidence supports substantial dependence of oil composition on organ, provenance, season, and processing. Chiral analysis adds a further dimension because the abundance of a terpene does not specify its enantiomeric composition. Laboratory studies report antibacterial, antifungal, cytotoxic, anti-inflammatory, and antispasmodic effects, while more recent work offers a specific application in protecting paper against mould. These findings justify further investigation but do not establish clinical efficacy, routine food-use suitability, or safety of repeated exposure. Differences in extraction, concentration units, microbial assays, and constituent identification currently limit comparisons between studies. Progress requires authenticated plant material, independent biological replication, retention-index-supported chromatographic analysis, validated quantitative assays, and application-specific safety testing. A practical development strategy should prioritise reproducible oil types and clearly defined uses rather than treating all bald-cypress oils as equivalent products. Sustainable recovery from cultivated biomass, combined with controlled formulation and realistic efficacy testing, could provide a stronger basis for future industrial and biological applications.

Keywords: *Taxodium distichum*; essential oil; terpene composition; antimicrobial activity; chemical standardisation.

1. Introduction

Essential oils connect plant chemical ecology with applied natural-product research. Their constituents may influence microbial growth, interact with biological membranes, and contribute to the aroma and functional properties of plant-derived products. However, an essential oil is a complex mixture rather than a single active substance. Its behaviour depends on constituent identity, relative abundance, concentration, formulation, and exposure conditions. Broad reviews describe numerous biological responses to essential oils while emphasising that laboratory activity alone does not establish suitability as a medicine, food preservative, or commercial formulation (Bakkali et al., 2008; Burt, 2004).

Medicinal and aromatic plants provide a substantial reservoir of compounds for antimicrobial investigation. Singh et al. (2020) discuss this wider research context, including the pharmaceutical relevance of plant phytochemicals. Nevertheless, identifying a potentially useful plant source is only the beginning of product development. Botanical authentication, reproducible extraction, chemical characterisation, efficacy testing, and application-specific safety assessment remain necessary.

Bald cypress, *Taxodium distichum* (L.) Rich., illustrates these challenges particularly well. The term “bald-cypress oil” can suggest a uniform product, although oils obtained from leaves, twigs, cones, cone scales, and seeds may differ markedly. Odell’s (1912) investigation of southern-cypress oil demonstrates that scientific interest predates modern chromatographic analysis. Subsequent research has expanded into organ-specific composition, antimicrobial activity, cytotoxicity, enantiomeric analysis, extraction optimisation, and protection of materials against fungal growth (Al-Sayed, 2018; Djapic, 2022; El Tantawy et al., 1999; Flamini et al., 2000; Hosseinihashemi et al., 2024; Ogunwande et al., 2007; Padalia et al., 2016; Shyu et al., 2024).

The central question is therefore no longer whether the species produces an aromatic oil. It is which preparation is being investigated, how consistently its chemistry can be reproduced, and what evidence supports its proposed application. This review addresses these questions through a narrative synthesis of 54 references. It approaches *T. distichum* as a source of several potentially useful chemical profiles rather than one interchangeable essential-oil product. Evidence from related plants, isolated constituents, and general essential-oil research is included where it clarifies analytical, biological, or formulation principles.

2. Scope and Approach of the Review

This article is a narrative review rather than a systematic review or meta-analysis. The supplied literature encompasses historical investigations, compositional studies, biological assays, extraction research, and methodological publications. The discussion organises these sources into three categories: direct research involving *T. distichum* oils; related research on *Taxodium* extracts, tissues, or isolated compounds; and broader literature relevant to essential-oil analysis and application.

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The 54 references should not be interpreted as 54 independent investigations of bald-cypress essential oil. The species-specific evidence is substantially smaller than the general essential-oil literature. For example, studies involving *Juniperus communis*, *Pinus roxburghii*, *Thuja occidentalis*, or *Murraya koenigii* provide comparative context but cannot establish the activity of an untested *T. distichum* preparation (Singh, Pathak, et al., 2018; Vishwakarma & Singh, 2025).

Numerical findings are retained where the source material, experimental organism, or measurement basis is identifiable. Comparisons remain descriptive because the investigations differ in extraction methods, chemical profiles, assay designs, and concentration units. Pooling these results into a common effect estimate would obscure important differences in the tested preparations.

3. Botanical Identity and the Meaning of the Oil Preparation

The botanical name used throughout this review is *Taxodium distichum* (L.) Rich., a member of Cupressaceae. Older publications frequently place the genus in Taxodiaceae. Bald cypress is associated with wet habitats in the southeastern United States and is cultivated in other regions. Taxonomic treatments of *Taxodium* have varied, particularly in relation to pond cypress and Montezuma cypress. These differences make botanical identity and collection provenance important components of chemical reporting (Adams et al., 2012; Su et al., 2013).

Leaves, small branches, cones, cone scales, and seeds should be identified separately. A sample described as “branches with leaves” is not equivalent to isolated foliage, because the relative proportions of the tissues may influence the recovered oil. Similarly, cone scales and seeds should not automatically be combined under a single chemical description.

Gymnosperm reproductive structures are cones, although some earlier publications describe their oils as “fruit oils.” This wording can be retained in reference titles while using “cone oil” in the discussion where the source material is clear.

The genus-wide review by Su et al. (2013) provides ethnobotanical and phytochemical context. However, traditional uses of another *Taxodium* species, whole-plant preparations, or decoctions should not be attributed directly to distilled *T. distichum* oil. Activity demonstrated by a purified diterpenoid likewise concerns that molecule under the tested conditions rather than every preparation obtained from the tree.

Extraction introduces another distinction. Hydrodistillation and steam distillation recover an operationally defined volatile fraction, whereas organic solvents and supercritical carbon dioxide may recover a broader range of lipophilic compounds. Their products may share constituents without being chemically or functionally interchangeable. Tocopherols and resinous components should therefore be interpreted in relation to the process that recovered them.

4. Extraction Methods and Processing Variables

4.1. Hydrodistillation and Steam Distillation

Hydrodistillation remains a common laboratory method for investigating bald-cypress oils. It permits comparison with much of the existing literature and requires relatively accessible equipment. Nevertheless, the final preparation reflects both the plant material and the extraction procedure.

Distillation duration, tissue size, plant-to-water ratio, heating conditions, condensation efficiency, and oil-separation losses can affect yield and composition. A reproducible report should identify whether the material was fresh or dried, document moisture content where possible, and state whether yield is calculated on a fresh-mass or dry-mass basis.

Yield expressed as volume per mass cannot be compared directly with mass per mass without additional information. Independent plant samples should also undergo separate extractions. Repeated injections of one pooled oil establish analytical precision but do not demonstrate biological reproducibility.

Extraction should be evaluated against the intended application. Fragrance development may prioritise retention of volatile monoterpenes, whereas protection of a material may depend more strongly on retention of a less volatile active fraction. Green-extraction principles consequently recommend assessing product quality, energy use, solvent consumption, and waste generation together (Chemat et al., 2012, 2019).

4.2. Supercritical Carbon Dioxide Extraction

Djapic (2022) compared supercritical carbon dioxide extraction with hydrodistillation of winter foliage. The study reported a maximum modelled extraction yield of 3.97% at 17.79 MPa and 62.70 °C, while a different condition favoured α-tocopherol recovery. The hydrodistilled preparation contained 62 identified constituents and was dominated by caryophyllene oxide at 55.55%.

These findings demonstrate that extraction conditions should follow the target product. A higher total extract yield does not necessarily mean greater recovery of volatile oil or the desired active constituent. General supercritical-extraction research similarly shows that pressure, temperature, and operating conditions influence extraction selectivity (Yousefi et al., 2019).

Future comparisons should report calibrated marker recovery per unit biomass alongside total yield. Commercial assessment should also include equipment costs, carbon dioxide recycling, processing time, and scale-up requirements.

4.3. Harvest and Postharvest Handling

Seasonal variation should be assessed through both relative composition and constituent recovery per unit biomass. Adams (2012) reported that α-pinene accounted for approximately 63–69% of leaf oil, while oil yield increased from 3.45 mg/g dry matter in April to 6.64 mg/g in May before declining. A comparatively stable chromatographic percentage therefore does not imply stable production per gram of foliage.

Postharvest research should distinguish original tissue chemistry from changes introduced by drying and storage. A useful experiment would divide material from the same trees among fresh, shade-dried, and controlled-temperature treatments. Measuring oil yield, chemical markers, and biological activity together would help determine whether processing preserves the properties relevant to the intended use.

5. Chemical Composition and Sources of Diversity

5.1. Monoterpene-Rich Oils

α-Pinene is prominent in several investigations, including Egyptian cone oil, Italian organ oils, and Indian leaf oils (El Tantawy et al., 1999; Flamini et al., 2000; Padalia et al., 2016). These findings support describing certain preparations as pinene-rich, but this description should not be treated as a universal characteristic of the species.

Padalia et al. (2016) identified 17 constituents in leaf oils collected across five seasons in Uttarakhand, India. α-Pinene ranged from 81.9% to 94.3%, accompanied by smaller amounts of myrcene, β-pinene, limonene, camphene, and α-terpineol. Chiral analysis indicated an approximately racemic α-pinene composition, with about 49.3% positive and 50.7% negative enantiomer.

This result adds an important dimension to chemical characterisation. Reporting total α-pinene abundance does not distinguish an enantiomerically enriched oil from an approximately racemic preparation.

Flamini et al. (2000) compared female cones, leaves, and branches from Italy within a shared analytical framework. Such within-study comparisons are especially useful because they reduce methodological differences that complicate comparisons among laboratories. They also demonstrate why organ selection must be considered before attributing compositional differences entirely to geography.

5.2. Sesquiterpenes and Diterpenes

Ogunwande et al. (2007) reported a Nigerian cone oil dominated by α-pinene and thujopsene, whereas the leaf oil contained substantial thujopsene, pimara-8(14),15-diene, widdrol, and β-caryophyllene. This organ contrast challenges the expectation that foliage oil is always strongly α-pinene-dominant.

The winter-foliage study by Djapic (2022) adds a caryophyllene-oxide-rich preparation. Together, these findings demonstrate that bald-cypress oil research extends beyond monoterpene hydrocarbons.

Hosseinihashemi et al. (2024) examined cone scales, seeds, and thin branches with leaves from cultivated trees in northern Iran. Limonene was the principal constituent, at approximately 56.5%, 50.5%, and 43.8%, respectively. Separating the tissues revealed variation that could be concealed by analysing a whole cone or mixed sample.

Shyu et al. (2024) reported Taiwanese leaf oil containing substantial limonene and α-pinene, while cone oil contained 43.2% ferruginol and 12.5% caryophyllene oxide. The occurrence of diterpenes in an operationally defined hydrodistilled oil requires careful documentation because their volatility differs substantially from that of common monoterpenes.

5.3. Provenance and Chemotype Interpretation

Adams et al. (2012) described geographically associated variation, including β-phellandrene-rich profiles in some Texas Hill Country materials. Their comparison of materials with documented origins grown in a shared setting provides stronger evidence for provenance-related variation than comparisons among unrelated national reports.

Nevertheless, a single chemical profile does not establish a stable chemotype. Demonstrating a reproducible type requires repeated sampling of multiple trees, consistent tissue selection, comparable extraction methods, and preferably cultivation under shared conditions.

For product development, the immediate requirement is reliable batch composition. A supplier must be able to deliver an oil within an agreed chemical specification, whether or not that specification corresponds to a formally demonstrated genetic chemotype.

Table 1: Selected compositional evidence from direct oil studies.

Preparation	Reported markers	Interpretation	Source
Egyptian cone oil	α-Pinene, 87.3%	Steam-distilled preparation; yield, 0.8% v/w	El Tantawy et al. (1999)
Indian leaf oils	α-Pinene, 81.9–94.3%	Five-season sampling; approximately racemic α-pinene	Padalia et al. (2016)
Serbian winter foliage	Caryophyllene oxide, 55.55%	Hydrodistilled preparation differed from the carbon dioxide extract	Djapic (2022)
Iranian cone scales and seeds	Limonene, 56.5% and 50.5%	Reproductive tissues analysed separately	Hosseinihashemi et al. (2024)
Taiwanese leaves and cones	Leaf limonene, 39.8%; cone ferruginol, 43.2%	Marked organ-related variation	Shyu et al. (2024)
United States provenance comparison	β-Phellandrene-rich profiles in some Texas origins	Provenance-associated variation within *Taxodium*	Adams et al. (2012)

6. Analytical Identification and Quality Assurance

6.1. Gas Chromatography and Retention Indices

Gas chromatography–mass spectrometry is central to essential-oil characterisation, while flame ionisation detection is commonly used to estimate relative constituent abundance. Identification should combine mass-spectral information with retention behaviour rather than rely exclusively on library matching.

The temperature-programmed retention-index approach described by van den Dool and Kratz (1963) provides an established framework for comparing chromatographic retention data. A homologous n-alkane series should be analysed under the same conditions as the oil, and reports should specify stationary phase, column dimensions, temperature programme, injection conditions, and measured indices.

Important or unexpected constituents should be checked with authentic standards where feasible. Closely related isomers may produce similar spectra, making retention data especially valuable.

Sumner et al. (2007) distinguish confirmed identification from putative annotation. Applying this principle would make identification confidence explicit for each reported constituent. Unidentified peaks should remain visible, and uncertain minor constituents should not become the basis of detailed mechanistic claims.

6.2. Quantification and Chiral Analysis

Relative peak areas are useful descriptors but do not necessarily represent mass percentages. Detector responses vary, and an apparent increase in one constituent may reflect a decrease in another. Quality control should therefore combine relative profiles with calibrated concentrations for selected markers.

Chiral analysis deserves attention in pinene-rich preparations. The findings of Padalia et al. (2016), together with research on isolated pinene enantiomers, indicate that stereochemistry may influence biological behaviour (da Silva et al., 2012; de Sousa Eduardo et al., 2018; Ložienė et al., 2018).

An oil containing 85% total α-pinene cannot automatically be equated with a preparation containing 85% of one purified enantiomer. Where relevant, enantiomeric ratios should accompany abundance measurements.

A proposed release specification should document botanical identity, organ, provenance, extraction process, yield, marker concentrations, and storage stability. Biological applications would additionally require a reproducible activity assay. This is a development recommendation rather than an established pharmacopoeial standard for bald-cypress oil.

7. Biological Activities and Their Evidential Limits

7.1. Antibacterial Activity

El Tantawy et al. (1999) reported antibacterial activity of Egyptian cone oil against *Escherichia coli*, *Proteus mirabilis*, and *Staphylococcus aureus*. The preparation had a distillation yield of 0.8% v/w and contained 87.3% α-pinene. These findings provide direct evidence for that oil under the reported conditions.

Al-Sayed (2018) investigated leaf oil and reported minimum inhibitory concentrations of 9.8 µg/mL against *Bacillus subtilis* and 39 µg/mL against methicillin-resistant *S. aureus*. These observations justify replication with independently prepared, chemically characterised batches and a wider selection of isolates.

An additional direct investigation by Singh, et al. (2018) compared oils from *P. roxburghii*, *T. distichum*, and *T. occidentalis* against *Vibrio cholerae*. The paper reported a *T. distichum* oil MIC of 1.995 mg/mL and an IC_{50} of 0.914 mg/mL. However, although its title refers to synergy, the reported experimental arrangement primarily evaluates the oils individually. The result should therefore be interpreted as antibacterial screening evidence rather than conclusive demonstration of mixture synergy. The methods also contain an organism-name inconsistency that warrants clarification before replication.

Comparative gymnosperm research provides additional context. Singh, et al. (2018) evaluated *J. communis*, *P. roxburghii*, and *T. occidentalis* oils against *E. coli*. Because *T. distichum* was absent from that investigation, its findings cannot establish bald-cypress oil activity. Similarly, the *M. koenigii* study by Vishwakarma and Singh (2025) is relevant to the wider relationship between phytochemical profiling and antibacterial investigation, rather than direct evidence for *Taxodium*.

Antibacterial usefulness also depends on selectivity. An oil that inhibits bacteria through broadly disruptive physicochemical effects may affect host cells or application materials. Therapeutic proposals should consequently include cytotoxicity assessment, suitable reference agents, and controls for solvents or emulsifiers.

7.2. Antifungal Activity and Materials Protection

Ogunwande et al. (2007) reported a cone-oil MIC of 19.5 µg/mL against *Aspergillus niger*. This supports further investigation of fungal-growth control but does not establish broad-spectrum performance.

Component-level testing can clarify which substances contribute to antifungal activity. Hammer et al. (2003) demonstrated the usefulness of this approach for tea tree oil, providing a methodological example rather than direct evidence for bald cypress.

Shyu et al. (2024) investigated the anti-mildew properties of bald-cypress oils on paper. Cone oil showed the strongest performance among the tested organs, and fractionation identified an especially active fraction. Ferruginol completely inhibited the seven tested mould fungi at 200 µg/cm² under the study conditions.

This surface loading cannot be compared directly with a broth MIC expressed in µg/mL. Further paper-preservation research should examine ageing, colour changes, ink compatibility, mechanical strength, odour persistence, and repeated fungal challenge. Successful inhibition must be accompanied by preservation of the material itself (figure 1).

7.3. Anti-Inflammatory and Antispasmodic Findings

El Tantawy et al. (1999) reported anti-inflammatory and antispasmodic effects of Egyptian cone oil. These observations should remain distinct from mechanistic investigations of isolated constituents.

Kim et al. (2015) reported that α-pinene suppressed inflammatory responses involving MAPK and NF-κB pathways in mouse peritoneal macrophages. This suggests a mechanism worth investigating in appropriately characterised oils, but it does not establish that every bald-cypress preparation acts through the same pathway.

Gertsch et al. (2008) identified β-caryophyllene as a functional cannabinoid CB2 receptor agonist. Its occurrence in an oil provides a research lead, although actual constituent exposure and whole-mixture behaviour must be established.

Whole-oil experiments require concentration–response measurements and viability controls to distinguish specific signalling effects from general cell injury. Proposed respiratory or gastrointestinal uses also require formulation, pharmacokinetic, and safety evidence beyond isolated-organ or cellular observations.

7.4. Cytotoxicity and Anticancer Interpretation

Ogunwande et al. (2007) examined cytotoxic effects of leaf and cone oils. Cytotoxicity, however, is not synonymous with anticancer efficacy. Reduced survival in cultured cells may reflect general toxicity, solvent effects, or interference with the measurement system.

A stronger anticancer investigation would compare malignant and suitable nonmalignant cells, use complementary viability methods, and assess whether effective exposures are achievable.

Research on isolated *Taxodium* diterpenoids further illustrates the importance of identifying the preparation. Kusumoto et al. (2010) isolated cone compounds and investigated their antifungal activity. Findings involving purified substances or solvent extracts should not be reassigned to unfractionated essential oils. The available evidence supports further investigation rather than a clinical anticancer claim.

7.5. Antioxidant Potential

Antioxidant activity must be measured for the actual preparation. DPPH, ABTS, and FRAP assays evaluate different aspects of chemical reactivity and need not produce equivalent rankings (Benzie & Strain, 1996; Brand-Williams et al., 1995; Re et al., 1999).

Huang et al. (2005) explain the chemical basis of antioxidant-capacity assays, while Prior et al. (2005) discuss standardisation and interpretation. These publications support complementary testing and explicit reporting of reaction conditions.

Hydrophobic oils require suitable blanks for turbidity, colour, and solvent effects. A positive radical-scavenging result should not be described as established protection against oxidative stress in humans.

Application-focused experiments could assess lipid oxidation in a defined food, coating, or formulation. Phenolic-rich solvent extracts should be examined separately from distilled oil so that activity is not attributed to constituents absent from the intended product.

7.6. Insect-Related and Ecological Activities

Kusumoto et al. (2009) reported antitermitic and antifeedant effects of isolated abietane-type diterpenes from cones. Scheffrahn et al. (1988) investigated the chemical resistance of bald-cypress heartwood to subterranean termites.

These findings illuminate the species' chemical ecology but do not establish leaf or cone essential oil as an effective field insecticide. Product development would require a defined target organism, realistic exposure, persistence measurements, and non-target assessment.

Aquatic exposure is particularly relevant to outdoor use around wet habitats. Plant origin alone does not establish the environmental safety of a concentrated preparation.

8. Mechanistic Interpretation

Membrane interactions offer a useful starting point for antimicrobial research. Cox et al. (2000) investigated permeability and respiratory effects of tea tree oil, while Lambert et al. (2001) examined oregano oil, thymol, and carvacrol. These studies provide experimental approaches that can guide *Taxodium* research without establishing its mechanism.

Ultee et al. (1999) investigated carvacrol-associated changes in membrane bioenergetics in *Bacillus cereus*. Xu et al. (2008) examined carvacrol and thymol against *E. coli*, and Trombetta et al. (2005) studied antibacterial mechanisms of three monoterpenes. Collectively, these investigations support measuring permeability, ion leakage, energy status, and viability together.

For bald-cypress oil, mechanistic studies should begin with reproducible inhibition and killing measurements. Membrane effects should then be evaluated at matched concentrations and exposure times. Changes detected only after extensive cell death may be consequences rather than initiating mechanisms.

Mixture interactions require direct assessment. Bassolé and Juliani (2012) discuss synergy, additivity, and antagonism in essential-oil combinations. Fractionation, reconstitution, and omission experiments could reveal whether bald-cypress activity depends mainly on one constituent or on interactions among several.

A whole oil outperforming one isolated compound does not establish synergy unless component concentrations and an appropriate interaction model are considered. This distinction also applies to the terminology used in the comparative study by Singh, et al. (2018).

Pinene studies identify another variable. Different antimicrobial responses have been observed among enantiomers and preparations with differing enantiomeric composition (da Silva et al., 2012; de Sousa Eduardo et al., 2018; Ložienė et al., 2018). Stereochemistry should therefore be examined alongside minor constituents and total composition.

9. Improving the Reliability of Bioassays

Assay design can substantially influence apparent activity. Balouiri et al. (2016) review antimicrobial methods, while Hood et al. (2003) specifically evaluate screening approaches used in essential-oil research.

Diffusion assays are convenient for preliminary screening, but inhibition-zone diameter reflects movement through agar as well as microbial susceptibility. Poor diffusion can make an active oil appear weak.

Griffin et al. (2000) describe an agar-dilution approach for essential oils, and Klančnik et al. (2010) compare diffusion and dilution methods for plant extracts. Results from different exposure systems should not be ranked as though they share one measurement scale.

Reports should specify medium, dispersing agent, inoculum, incubation conditions, and endpoint determination. Bactericidal claims additionally require viable-organism recovery rather than growth inhibition alone (Verma, 2007).

Testing clinical isolates can improve relevance. LaPlante (2007) investigated tea tree oil alongside lysostaphin and mupirocin against clinical methicillin-resistant *S. aureus*. For *T. distichum*, recognised reference strains and independently obtained isolates would provide complementary evidence.

Reliable experiments should include independent oil batches, growth controls, sterility controls, solvent or emulsifier controls, and reference antimicrobials. Colour-based assays require checks for direct indicator interference, while killing assays should minimise oil carryover into recovery media.

Concentration units must also be explicit. Mass concentration, volume fraction, vapour exposure, and surface loading describe different exposure systems. Converting oil volume to mass requires density, while comparing surface and liquid doses requires defined geometry and exposure conditions.

10. Formulation, Stability, and Potential Applications

10.1. Storage Stability

Essential oils may change through oxidation, evaporation, and other reactions. Temperature, light, and oxygen exposure are important determinants of stability (Turek & Stintzing, 2013).

Bald-cypress storage studies should connect chemical changes with biological performance. Monitoring should include marker concentrations, new chromatographic peaks, physical properties, and activity in the intended application.

Packaging should be evaluated under realistic use conditions, including repeated opening where relevant. An expiry period requires product-specific data rather than assumptions based on essential oils generally.

10.2. Encapsulation and Controlled Delivery

Encapsulation may help where volatility, dispersion, or rapid release limits performance. Reis et al. (2022) discuss encapsulated oils in food preservation. Natrajan et al. (2015) investigated chitosan–alginate nanocapsules, while He et al. (2019) developed carvacrol-loaded solid lipid nanoparticles.

These studies provide formulation principles rather than a validated *T. distichum* delivery system. Carrier selection should follow the application: paper protection requires adhesion and compatibility; packaging requires migration and sensory assessment; topical use requires tolerability and suitable release. Small particle size alone does not demonstrate improvement. Oil loading, encapsulation efficiency, free-oil content, release behaviour, and retained activity should be measured.

Comparisons should include unformulated oil, empty carrier, and complete formulation at equivalent oil doses. Improved dispersion may explain better performance without changing intrinsic antimicrobial potency.



Figure 1: Graphical overview of Taxodium distichum essential oils showing plant sources, extraction and chemical profiling, representative constituents, and laboratory-supported biological activities, together with priorities for developing standardised applications.

10.3. Food and Packaging Research

Essential-oil activity can weaken in foods through interactions with proteins, lipids, and other matrix constituents (Burt, 2004; Hyldgaard et al., 2012). Aroma may also restrict acceptable concentrations.

For bald-cypress oil, food preservation remains a proposed application requiring direct evidence. Initial studies should investigate one chemically specified oil in a defined food or packaging system, measure microbial growth during realistic storage, and assess sensory effects.

Packaging applications additionally require migration and exposure measurements. Suitability must be established for the particular formulation and conditions of use.

10.4. Comparative Natural-Product Research

The investigations of other gymnosperm oils and *M. koenigii* illustrate the wider interest in chemically characterised plant antimicrobials (Singh, et al., 2018; Vishwakarma & Singh, 2025). Their value for bald-cypress development lies in informing comparative designs and highlighting the need to connect chemistry with biological outcomes.

The broader discussion by Singh et al. (2020) similarly places aromatic plants within pharmaceutical biotechnology. Such context supports investigating *T. distichum*, while product claims must remain grounded in evidence for its actual preparation.

11. Safety and Sustainable Sourcing

El Tantawy et al. (1999) reported an acute LD_{50} of 1,060 mg/kg for the tested oil. This historical result does not establish a human dose, repeated-exposure safety, or suitability for ingestion.

Essential-oil biological activity may include cytotoxic effects, making safety assessment inseparable from efficacy development (Bakkali et al., 2008). Therapeutic proposals require irritation, sensitisation, formulation-specific toxicity, and exposure assessment. Materials applications likewise require evaluation of user exposure and substrate compatibility.

Safety findings for a purified constituent cannot automatically be assigned to the whole mixture. A selective antimicrobial window would be more informative than microbial inhibition alone.

Sourcing should prioritise authenticated cultivated material with documented harvesting practices. Leaves and routine pruning residues may offer potential feedstocks, although seasonal variation in recovery must be considered (Adams, 2012).

Cone collection should be evaluated in relation to regeneration and plantation management. Economic and environmental comparisons should include energy, water, transport, residue handling, active-fraction recovery, and batch rejection rates (Chemat et al., 2012, 2019).

12. Research Gaps and Future Prospects

The principal gap is reproducibility across independently collected and processed batches. Many findings concern individual preparations whose consistency across trees, seasons, and laboratories remains uncertain.

A coordinated study should sample authenticated trees from several provenances, separate organs consistently, and apply a common extraction and analytical framework. Absolute marker recovery and relevant enantiomeric ratios should accompany relative peak areas.

A second priority is linking composition with function. The same batches should undergo chemical analysis, biological testing, and stability assessment. Fractionation and reconstitution can then test whether identified constituents reproduce whole-oil activity.

Application selection should follow the strongest direct evidence. Paper protection has a specific experimental basis in Shyu et al. (2024), whereas pharmaceutical, food, and agricultural proposals need additional development. Establishing one reproducible surface treatment may be more tractable than pursuing several applications simultaneously.

Future publications should make chromatograms, retention indices, identification confidence, batch descriptions, and assay controls available. The frameworks of van den Dool and Kratz (1963) and Sumner et al. (2007) support improved analytical reporting. Negative and poorly tolerated results should also be reported to define practical limits.

Table 2: Proposed priorities for future research.

Priority	Suggested investigation	Expected contribution
Source variability	Repeated organ-specific sampling across trees and seasons	Establish reproducible chemical specifications
Extraction selection	Compare calibrated marker recovery and processing inputs	Select a method for a defined product
Antimicrobial efficacy	Test independent batches using dilution and killing assays	Establish reproducible activity and selectivity
Active constituents	Conduct fractionation, reconstitution, and omission experiments	Resolve constituent and mixture contributions
Formulation	Compare free oil, empty carrier, and formulated oil	Measure release and retained performance
Paper protection	Assess ageing, mould challenge, colour, and strength	Determine preservation compatibility
Safety and environment	Perform exposure-based host and non-target testing	Define application-specific limits

13. Conclusion

Taxodium distichum provides chemically diverse oils whose composition varies with organ, provenance, season, and extraction process. Published preparations include monoterpene-rich oils and oils containing substantial oxygenated sesquiterpenes or diterpenes.

Direct laboratory studies support antibacterial and antifungal activity in selected systems, including an additional antibacterial investigation against *V. cholerae*. Research on paper protection offers a particularly identifiable application lead. Pharmacological and cytotoxic observations remain insufficient for clinical recommendations, while synergy requires explicit combination testing rather than inference from individual-oil comparisons.

Further development should integrate botanical authentication, calibrated chemical analysis, relevant chiral characterisation, independent batch replication, stability studies, and realistic efficacy and safety testing. Research on other aromatic plants and isolated compounds can guide this work, but cannot replace evidence for the actual bald-cypress preparation.

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