Bioactive Terpenoids from Desert Shrubs for Durable Wood Protection: Chemistry, Delivery Systems, and Circular Bioresource Integration

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The demand for low-toxicity wood protectants is accelerating the search for plant-derived alternatives. Terpenoids from desert-adapted shrubs combine antimicrobial, insecticidal, hydrophobic, and photoprotective functions yet remain underused in wood protection. This review brings together the chemistry, bioactivity, and application potential of guayule (*Parthenium argentatum*), creosote bush (*Larrea tridentata*), physic nut (*Jatropha curcas*), spurges (*Euphorbia* spp.), and gum rockrose (*Cistus ladanifer*). Key terpenoids are classified by structure and mechanisms of action are mapped against decay fungi and termites. Delivery platforms, including solvent-free resin-oil blends, micro/nanoencapsulation, and biopolymer matrices, were evaluated with emphasis on persistence, UV stability, and substrate compatibility. A solvent-free valorization example using guayule resin illustrates circular-bioeconomy integration. Environmental and regulatory considerations, commercial readiness, and research gaps (standardized field trials, fractionation for consistency, genotype/agronomy improvements) are highlighted. Desert-shrub terpenoids emerge as multifunctional, eco-friendly agents for durable wood protection and pest management, offering a scalable pathway toward circular bioresource innovation.

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INTRODUCTION

The wood preservation industry faces mounting pressure from rising global wood consumption and the substantial economic losses caused by biodeterioration. Traditional wood preservatives such as chromated copper arsenate (CCA) and pentachlorophenol (PCP) have long been valued for efficacy against decay and pests (Schultz *et al.* 2007; Emenike *et al.* 2024). However, such agents raise serious environmental and health concerns due to their toxicity and persistence (Katz and Salem 2005; Morais *et al.* 2021). Conventional preservative systems also set a high durability benchmark. Under severe ground-contact exposure in southern Mississippi, CCA and pentachlorophenol showed exceptional long-term performance, with zero failures reported among 125 CCA-treated posts and 75 pentachlorophenol-treated posts after 50 years (Lebow *et al.* 2015). Long-duration stake trials likewise reported no failures for CCA-treated stakes after 40 to 61 years, depending on formulation type (Lebow *et al.* 2013). In addition, pentachlorophenol-treated posts have been reported to achieve durability exceeding 60 years (Cooper *et al.* 2001). These outcomes were obtained from sites characterized as AWPA Deterioration Zone 5 (Severe Hazard) (Lebow *et al.* 2013). In contrast, untreated controls failed within 2 to 4 years under the same conditions (Lebow *et al.* 2013), indicating that >60-year durability reflects performance under highly aggressive exposure rather than moderate service environments. Therefore, while terpenoid-based treatments are promising, replacement products must be designed not only for initial bioactivity but also for long-term persistence under weathering and ground-contact conditions. More broadly, pressure-treated wood remains essential for mitigating biological deterioration, particularly where moisture exposure is expected (Lebow *et al.* 2019). These benchmarks provide a durability reference point for interpreting reported terpenoid performance ranges and for defining the stabilization needed for field-ready bio-based systems. Simultaneously, wood-boring insects and decay fungi threaten wood and wooden structures worldwide, often acting synergistically; with insects vectoring pathogenic fungi that amplify damage (Aukema *et al.* 2011; Hulcr and Dunn 2011; Linnakoski and Forbes 2019). Climate change and global trade further exacerbate their spread and impact (Jactel *et al.* 2020).

Wood composites are increasingly used in construction but remain vulnerable to biological attack when unprotected (Smith and Wu 2005). These materials are particularly susceptible to decay fungi and termite damage, with Formosan subterranean termites responsible for hundreds of millions of dollars in losses in affected regions (Smith and Wu 2005). Resistance varies across composite types, with medium-density fiberboard (MDF) and particleboard generally exhibiting higher natural resistance than oriented strand board (OSB), plywood, and softwood plywood (Taşçıoğlu and Tsunoda 2010; Taşçıoğlu *et al.* 2013). Recent research is shifting toward eco-friendly alternatives in wood protection and biodeterioration prevention, including silicone-oil thermal modification and plant-derived resins (Okon *et al.* 2020, 2021a, b; Aguma 2024). Natural compounds/biocides from plant extracts, such as essential oils, tannins, and phenols; show promise as sustainable bioprotectants (Adenaiya *et al.* 2016; Broda 2020; Adedeji *et al.* 2023; Calovi *et al.* 2024), delivering multiple mechanisms with minimal harm to non-target organisms (Pavela and Benelli 2016). Nonetheless, practical hurdles remain, including inconsistent efficacy, susceptibility to photo-degradation, and limited persistence (Romani *et al.* 2022). Such drawbacks underscore the need for novel plant-derived protectants that pair environmental safety with reliable performance. Accordingly, durability claims for bio-based systems are most credible when evaluated using standardized protocols that simulate long-term environmental exposure, including leaching/weathering and decay/insect challenge conditions (*e.g.*, AWPA soil-block and related laboratory/field methods), because these better reflect service environments for treated wood products. At the same time, the literature cautions that some standardized leaching methods are designed to accelerate loss and may not reliably estimate in-service behavior, reinforcing the need to interpret results in the context of realistic exposure scenarios (Lebow 2014). Different test formats can also impose markedly different decay hazards (*e.g.*, laboratory soil jars *vs.* field modules *vs.*

roof-deck exposures), underscoring the complexity of comparing durability outcomes across methods (De Groot 1994). Consistent with this, comparisons of laboratory and field performance across multiple modified wood products have shown that durability classifications can be broadly consistent across environments, but only when exposure factors and evaluation endpoints are appropriately considered (Alfredsen and Westin 2009). In this review, "low-toxicity" and "eco-friendly" are used cautiously to indicate reduced persistence, bioaccumulation, and heavy-metal burden relative to legacy preservatives where evidence supports such claims; however, toxicity and ecotoxicity remain compound- and formulation-specific, and natural origin alone does not guarantee environmental safety.

Desert-adapted shrubs, including guayule (*Parthenium argentatum*), creosote bush (*Larrea tridentata*), physic nut (*Jatropha curcas*), spurges (*Euphorbia* spp.), and gum rockrose (*Cistus ladanifer*, also known as the labdanum shrub, produce diverse secondary metabolites, particularly terpenoids; these structurally varied compounds span mono-, sesqui-, and diterpenoid classes that underpin their environmental adaptation (Tahri *et al.* 2022; Aguma 2024). The compounds have been found to display antimicrobial, insecticidal, and water-repellent properties (Nakayama *et al.* 2000; Jara *et al.* 2019). Although guayule resin has been investigated recently for wood-preservative activity, broader attention to this class of compounds remains limited. These five shrubs were prioritized as representative arid-/semi-arid-adapted taxa that (i) are documented to produce terpenoid-rich resins, latex, or extractives relevant to moisture stress and herbivore/pathogen defense, (ii) include species with published evidence of antifungal and/or insect/termite-relevant activity, and (iii) offer practical translational relevance through identifiable coproduct streams and scalable biomass supply chains (*e.g.*, resin and bagasse co-products from guayule cultivation). This review aims to:

i. Highlight the chemical diversity and potential of terpenoids sourced from underutilized desert shrubs.
ii. Compare their modes of action against decay agents and wood pests.
iii. Assess feasible delivery systems and propose formulation strategies suited to wood protection.
iv. Evaluate environmental benefits, regulatory considerations, and commercial scalability.
v. Identify priorities for future research, including field trials, pathway elucidation, and integration into circular-bioeconomy models.

By integrating insights from plant biochemistry, wood science, entomology, and sustainable materials engineering, the review has a forward-looking premise: bioactive terpenoids from desert shrubs can serve next-generation wood protectants and pest management agents.

DESERT SHRUBS AS BIOCHEMICAL RESERVOIRS

Desert environments, characterized by prolonged drought, extreme temperature fluctuations, and high solar irradiation, exert profound evolutionary pressures on resident plant species. To adapt, desert plants have evolved specialized metabolic pathways, producing a rich diversity of secondary metabolites (Chae *et al.* 2014; Tahri *et al.* 2022), giving rise to complex chemical defense systems. Among these, terpenoids, derived from five-carbon isoprene units, represent the most extensive and diverse family of plant metabolites, encompassing more than 80,000 identified structures (Nes and Zhou 2001; Rudolf *et al.* 2021; Li and Tao 2024). They contribute significantly to plant growth and development while mediating ecological communication and defense (Cheng *et al.* 2007; Tholl 2015). Terpenoids are synthesized in various plant organelles and can be classified as monoterpenes, sesquiterpenes, and diterpenes (Zhang and Lu 2017). These compounds display broad bioactivity: spanning antioxidant, antimicrobial, and anticancer effects; positioning them as valuable ingredients for the pharmaceutical, food, and cosmetic sectors (Câmara *et al.* 2024). While tropical plants and forest tree barks have long been sources of bioactive compounds, recent research highlights the untapped potential of arid and semi-arid species. Despite their resilience and high metabolic output, arid-zone flora remains underexplored (Simpson *et al.* 2016). These plants, adapted to harsh conditions, produce unique metabolites with diverse biological activities (Dávila-Rangel *et al.* 2024). Arid plants have demonstrated antiviral, antimicrobial, and anticancer properties (Harlev *et al.* 2012; Naz *et al.* 2024). These species exhibiting thermal stability, low volatility, and long-term bioactivity under environmental stress, offer a virtually untapped reservoir of bioactive terpenoids, well-suited for application in wood preservation and pest control due to their chemical richness and ecological resilience (Bohlmann and Keeling 2008; Tholl 2015; Dutta *et al.* 2017; Kirker *et al.* 2024). These compounds exhibit thermal stability, low volatility, and long-term bioactivity under environmental stress, making them well-suited for such applications (Dutta *et al.* 2017; Kirker *et al.* 2024).

A key motivation for targeting desert shrubs is that their extractive profiles can complement those of widely used construction softwoods. Pine oleoresins are complex chemical defense systems that commonly include substantial monoterpene fractions (*e.g.*, α-/β-pinene and limonene) together with resin acids, contributing to deterrence against insect pests and associated pathogens (Phillips and Croteau 1999). Variation in pine monoterpene composition has also been linked to genetic control in xylem tissues (Smith 2000), and terpene profiles can shift in response to biotic stress (Celedon and Bohlmann 2019). In *Pinus edulis*, for example, volatile oils in resinous seed cone samples were reported to be dominated by α-pinene (mean 75.6%) (Wilson *et al.* 2023). By contrast, several desert shrubs emphasized here are characterized by higher proportions of less-volatile or more specialized bioactives, including sesquiterpene esters and triterpenoid-rich resin fractions in guayule; labdanum (Cistus) resins containing labdane-type diterpenes (Papaefthimiou *et al.* 2014); and creosote bush (Larrea) rich in phenolic metabolites such as NDGA (Herrera-Medina *et al.* 2021). This chemical differentiation reinforces the potential of desert shrubs as an underutilized source of multifunctional protectants, consistent with the broader observation that plants in harsh environments may evolve efficient protective secondary-metabolite systems (Harlev *et al.* 2012). The key advantage lies not only in bioactivity but also in the possibility of enhancing persistence through strategic formulation and delivery design. To translate this biochemical potential into practice, the following subsections survey five desert shrubs, highlighting their principal terpenoids, documented bioactivity, and relevance to wood preservation.

Guayule (*Parthenium argentatum*)

Guayule, a drought-tolerant shrub native to arid regions of the southwestern US and northern Mexico, is cultivated for hypoallergenic natural rubber production (Cornish and Brichta 2002; Rousset *et al.* 2021). However, its resin by-product is now gaining attention due to its rich composition of sesquiterpenes, many with proven antimicrobial and insecticidal activity. Recent research by Aguma (2024) identified several bioactive compounds β-caryophyllene, β-guaiene, and cumanin, using solvent-free extraction methods like steam distillation and dialysis. These compounds demonstrate termite resistance and low environmental toxicity, supporting guayule resin's potential as a sustainable, plant-based wood preservative.

Creosote Bush (*Larrea tridentata*)

Creosote bush, a dominant shrub in North American deserts, produces various bioactive compounds, most notably nordihydroguaiaretic acid (NDGA) and related lignans (Reyes-Melo *et al.* 2021). These metabolites exhibit diverse biological effects, notably antibacterial, antifungal, antiviral, and antioxidant (Gamboa-Alvarado *et al.* 2003; Líra-Saldivar *et al.* 2003; Herrera-Medina *et al.* 2021). Extracts from *L. tridentata* have demonstrated significant inhibition of several plant pathogens, indicating strong potential for use as natural fungicides (Lira-Saldivar *et al.* 2006).

Physic Nut (*Jatropha curcas*)

Native to Mesoamerica, physic nut; hereafter *J. curcas*, is now pantropical and often naturalized in disturbed sites; it performs best in warm, seasonally dry regions and is frost sensitive. *Jatropha* species, particularly *J. curcas*, contain various bioactive compounds with significant insecticidal and antifungal properties. Diterpenoids such as curcusone B and jatrophone, isolated from *J. curcas* and *J. gossypifolia*, respectively, exhibit strong antimicrobial activity (Sahidin *et al.* 2012). These lipophilic terpenoids readily integrate with plant oils and can be formulated into hydrophobic wood coatings or oil-resin blends, enhancing durability under moisture exposure.

Spurges (*Euphorbia* spp.)

Euphorbia, collectively known as spurges, is cosmopolitan yet especially prominent across arid and semi-arid belts, comprising latex-bearing shrubs and succulents that can be locally dominant in North and East Africa, the Mediterranean Basin, and parts of Southwest Asia and the Americas. The plants often occupy rocky, disturbed, and drought-prone sites. Many *Euphorbia* spp. from semi-arid regions secrete milky latex rich in diterpenes and phorbol esters. These species are particularly noted for latex-derived compounds such as phorbol esters and related diterpenes (Kemboi *et al.* 2021; Benjamaa *et al.* 2022). These compounds display diverse biological activities, encompassing cytotoxic, anti-inflammatory, and insecticidal properties (Mazoir *et al.* 2008; Anju *et al.* 2018), supporting their potential use in controlled-release insect-deterrent systems, especially when embedded in biopolymers or applied to wood surfaces.

Gum Rockrose (*Cistus ladanifer*), Also Known as Labdanum Shrub

Gum rockrose, a Mediterranean shrub, produces labdanum resin that is rich in labdane-type diterpenes and other bioactive compounds with antimicrobial, antioxidant, and UV-protective properties (Papaefthimiou *et al.* 2014; Frazão *et al.* 2022). The species demonstrates strong drought resilience, adapting well to stressful Mediterranean conditions (Frazão *et al.* 2018; Haberstroh *et al.* 2018). Gum rockrose's potential extends beyond traditional perfumery applications in skincare, pharmaceuticals, and biorefineries (Alves-Ferreira *et al.* 2022; Frazão *et al.* 2022). Resin from this species may offer hydrophobic and photoprotective benefits when used as a finish or sealant for exterior wood. Table 1 summarizes the principal desert-adapted shrubs, their representative terpenoids, and associated bioactivities relevant to eco-friendly wood preservation and pest management

Table 1. Comparative Overview of Desert-Adapted Shrubs, Their Key Terpenoids, and Major Bioactivities Relevant to Wood Preservation and Pest Management

Desert Shrub	Representative Terpenoids / Compounds	Primary Bioactivities	Reported Test Systems / Target Organisms (Examples)
Guayule (*Parthenium argentatum*)	β-Caryophyllene, β-Guaiene, Cumanin, Naphthalenes	Termiticidal, Antifungal, Hydrophobic	Subterranean termites (*e.g.*, *Coptotermes formosanus*); laboratory wood mass-loss / feeding-deterrence assays; wood-decay fungi (*e.g.*, *Gloeophyllum trabeum*, *Trametes versicolor*)
Creosote Bush (*Larrea tridentata*)	Nordihydroguaiaretic acid (NDGA), Monoterpenes, Sesquiterpenes	Antifungal, Anti-xylophagous insect, UV Protective	Antifungal assays (including inhibition of plant pathogens); UV/weathering studies reporting reduced surface weathering/color loss (NDGA-related compounds)
Physic Nut (*Jatropha curcas*)	Jatrophone, Curcusone (Diterpenoids	Insecticidal, Fungistatic, Water-repellent potential	Antimicrobial assays; insect bioassays (reported toxicity of phorbol ester-containing oils toward cockroaches and termites)
Spurges (*Euphorbia* spp.)	Phorbol Esters, Diterpenes	Cytotoxic, Insect Deterrent, Potential Biocide	Insect deterrence/toxicity reported toward wood-feeding beetles and subterranean termites
Gum Rockrose (*Cistus ladanifer*)	Labdane Diterpenes	Antimicrobial, Antioxidant, UV Stabilizer	Antimicrobial assays; UV/oxidative stabilization studies; proposed as exterior finish/sealant to reduce weathering

Table adapted from Selassie *et al.* (2002), Pasha *et al.* (2008), Sadgrove *et al.* (2021), Masyita *et al.* (2022), Tahri *et al.* (2022), Aguma (2024), and Câmara *et al.* (2024)

Summary and Implications for Wood Protection

Despite their geographic limitations, desert shrubs present strategic advantages. They provide high yields of secondary metabolites whose ecological functions mirror the requirements of durable wood protection (Ofir 2020; Tahri *et al.* 2022). These plants also exhibit natural resistance to desiccation, photooxidation, and pest attack, traits that are particularly desirable in long-lasting preservative systems (Yosef Friedjung *et al.* 2013). Furthermore, they demonstrate compatibility with other biobased components such as plant oils, thereby allowing for formulation versatility (González-Laredo *et al.* 2015; Teacă *et al.* 2019; Aguma, 2024). By valorizing these underutilized resources, it becomes possible not only to reduce dependence on synthetic preservatives but also to encourage bioregional economic models in which local vegetation supports localized wood preservation industries (Ofir 2020; Calovi *et al.* 2024). As summarized in Table 1, the terpenoid spectrum across these desert shrubs spans mono-, sesqui-, and diterpenes whose structural diversity underpins antifungal, insecticidal, and UV-protective activities central to durable wood preservation.

BIOACTIVE TERPENOIDS: CLASSIFICATION AND FUNCTIONS

Terpenoids, also known as isoprenoids, make up the most abundant and chemically diverse group of natural products, comprising over 80,000 known compounds (Nes and Zhou, 2001; Rudolf *et al.* 2021). Their biosynthesis originates from C_5 isoprene units, proceeding through either the mevalonate (MVA) or methylerythritol phosphate (MEP) route (Bohlmann and Keeling 2008; Pattanaik and Lindberg 2015).

As key plant secondary metabolites, terpenoids play essential ecological roles in desert shrubs and other plants (Cheng *et al.* 2007; Tahri *et al.* 2022). They act as antimicrobial agents, herbivore deterrents, allelopathic chemicals, and protectants against abiotic stress (Tholl 2015; Huang and Osbourn 2019). These same properties make them highly relevant to wood preservation and pest management applications.

Table 2 categorizes the major terpenoid classes by carbon count, highlighting representative compounds commonly found in desert-adapted species. Each class is associated with specific roles in wood preservation and pest deterrence.

Table 2. Bioactivity-Relevant Terpenoid Classes Found in Desert Shrubs

Terpenoid Class	Carbon Count	Common in Desert Shrubs	Relevance to Wood Protection
Monoterpenes	C_{10}	Limonene, α-pinene	Volatile, initial pest deterrents
Sesquiterpenes	C_{15}	β-caryophyllene, β-guaiene	Antitermitic, antifungal, hydrophobic
Diterpenes	C_{20}	Ingenol, curcusone, labdanes	Persistent biocides, UV stabilizers
Triterpenes	C_{30}	Lupeol, betulinic acid	Surface protectants, water repellents
Polyterpenes	(C_5) n	Rubber-related polymers	Coatings, adhesives

Table adapted from Sadgrove *et al.* (2021), Tahri *et al.* (2022), Aguma (2024), and Câmara *et al.* (2024)

Classification by Structure

Sesquiterpenes and diterpenes are abundant in guayule, physic nut, spurges, and labdanum, offering both chemical durability and bioactivity. Physic nut is a rich source of diterpenes with diverse biological activities, including cytotoxic effects (Souza *et al.* 2024; Srivastava *et al.* 2025). *Cistus* species contain labdane-type diterpenes with antioxidant, antibacterial, and anticancer properties (Papaefthimiou *et al.* 2014). Guayule yields guayulins, sesquiterpene esters with potential as fungicides, miticides, and insecticides (Jara *et al.* 2019; Rozalén *et al.* 2021; Aguma, 2024). These terpenes exhibit diverse biological effects, including antifeedant activity and antiparasitic action against insect pests (Bailén *et al.* 2020).

Functional Roles Relevant to Wood Protection

Antifungal activity

Terpenoids from plants exhibit potent antifungal properties through a range of mechanisms. They are known to disrupt cell membranes, inhibit hyphal growth, and suppress spore germination across diverse fungal species (Singh *et al.* 2006; Park *et al.* 2009; Scariot *et al.* 2020). For instance, β-caryophyllene has been reported as active against wood-decay fungi such as *Gloeophyllum trabeum* and *Trametes versicolor* (Aguma 2024), and it also inhibits *Sclerotinia sclerotiorum* and *Fusarium oxysporum* (Hilgers *et al.* 2021). Similarly, labdane-type diterpenes are effective in inhibiting the enzymatic degradation of structural polysaccharides, including cellulose and lignin. Another notable compound, eugenol, demonstrates strong fungicidal activity by compromising membrane integrity and disrupting essential cellular processes (Aguma 2024).

Insecticidal and termiticidal action

Terpenoids play a crucial role in plant–insect interactions, functioning both as feeding deterrents and as disruptors of insect behavior (Klocke and Kubo 1991; Messchendorp 1998). These compounds interfere with insect nervous systems by inhibiting acetylcholinesterase, modulating GABA receptors, and affecting the octopaminergic system (Jankowska *et al.* 2017). In addition, some terpenoids act as pheromones, influencing insect behavior across multiple orders (Yang *et al.* 2025). Among these, β-guaiene and cumanin have been shown to exhibit repellency as well as lethal effects against *Coptotermes formosanus* (Aguma 2024). Likewise, phorbol esters derived from *Euphorbia* display toxicity toward wood-feeding beetles and subterranean termites, with their content varying among *Jatropha* cultivars and thereby influencing biological activity (Ratnadass and Wink 2012). Physic nut oil phorbol esters have demonstrated insecticidal activity against cockroaches and termites (Ratnadass and Wink 2012; Lateef *et al.* 2014).

Hydrophobicity and water exclusion

High-molecular-weight terpenoids and resin acids impart water-repellent properties to wood by reducing moisture absorption, which in turn limits fungal colonization. In addition, diterpene coatings have been shown to perform comparably to synthetic hydrophobes such as silicones and wax emulsions.

Photostability and UV protection

Many terpenoids, such as NDGA analogs and labdanes, scavenge reactive oxygen species and stabilize wood surfaces under UV exposure (Lü *et al.* 2010; González-Burgos and Gómez-Serranillos 2012; Manda *et al.* 2020). They are especially useful for exterior applications in tropical and arid environments (González-Burgos and Gómez-Serranillos, 2012).

Synergism and Volatility Considerations

Volatile monoterpenes may have short-term repellent effects but are rapidly lost through evaporation from exposed surfaces. While monoterpenes offer initial repellency, their efficacy can be improved by combining them with less volatile sesquiterpenes or by embedding them in hydrophobic matrices (Isman and Seffrin 2018; Mofikoya *et al.* 2019). Synergistic interactions with fatty acids can further enhance both the efficacy and persistence of terpene-based formulations (Hieu *et al.* 2015).

Structure-Function Insights

As summarized in Table 3, terpenoid biosynthesis through the MVA and MEP pathways yields a common isopentenyl pyrophosphate (IPP)/ dimethylallyl pyrophosphate (DMAPP) pool that is converted to geranyl pyrophosphate (GPP) (C10), farnesyl pyrophosphate (FPP) (C15), and geranylgeranyl pyrophosphate (GGPP) (C20), yielding mono-, sesqui-, and diterpenes. Cheminformatics/QSAR studies link epoxide rings and conjugated double bonds to higher insecticidal potency, whereas hydroxyl groups enhance binding to lignocellulosic substrates and may improve durability (Selassie *et al.* 2002; Pasha *et al.* 2008; Zeng *et al.* 2019). These reported structure-function links should be interpreted as hypothesis-guiding trends rather than universal rules, because the supporting evidence is drawn largely from QSAR/cheminformatics associations and a limited number of empirical datasets, often outside standardized wood-protection exposure contexts. In wood preservation more broadly, performance depends not only on intrinsic bioactivity but also on exposure history and mass-transfer losses from treated wood. In treated wood systems, apparent efficacy also depends strongly on formulation (carrier/matrix), retention, and the extent to which active compounds are lost *via* leaching, volatility, or degradation. Accordingly, further validation using standardized wood durability and termite/decay testing methods across multiple target organisms is needed to strengthen and refine the relationships summarized in Table 3. These structure-function relationships provide the mechanistic basis for the delivery and formulation systems discussed next.

Table 3. Structure-Function Relationships of Terpenoids Relevant to Wood Protection

Structural Motif	Expected Effect	Notes / Evidence
Epoxide ring	↑ insecticidal potency	QSAR/cheminformatics association (Selassie 2002)
Conjugated C=C	↑ insecticidal potency	Electron-rich scaffolds correlate with potency (Selassie 2002)
Hydroxyl (–OH)	↑ binding to lignocellulose → potential ↑ durability	Hydroxylated terpenoids show greater substrate interactions (Pasha 2008)
Class context (GPP/FPP/GGPP)	Mono- (C10), sesqui- (C15), diterpenes (C20)	Pathway overview (Zeng 2019)

Note: Relationships summarized here are based on limited QSAR/cheminformatics and selected empirical studies; translation to treated-wood performance depends on formulation, retention, and exposure (leaching/volatility/weathering). Further standardized validation is needed. Adapted from Selassie *et al.* (2002). Pasha *et al.* (2008), and Zeng *et al.* (2019)

MODE OF ACTION IN WOOD PROTECTION AND PEST MANAGEMENT

Bioactive terpenoids are crucial for plant defense and adaptation, exhibiting diverse biochemical and physical mechanisms that protect against microbial threats and insect pests (Câmara *et al.* 2024; Turatbekova *et al.* 2024). Terpenoids are not merely passive barriers; they actively disrupt microbial metabolism and insect physiology, enhancing plant resilience in challenging environments (Tholl 2015; Huang and Osbourn 2019). Hence, understanding the biosynthesis and ecological roles of terpenoids is essential for optimizing their use in wood protection and termite deterrence (Bohlmann and Keeling 2008; Tahri *et al.* 2022).

Antifungal Mechanisms

Terpenoids such as sesquiterpenes and diterpenes inhibit fungal growth through several converging pathways (Quin *et al.* 2014; González-Hernández *et al.* 2023). One important mechanism is membrane disruption, in which lipophilic compounds integrate into fungal cell membranes, increase permeability, and cause leakage of cellular components (Zore *et al.* 2011; Aderiye and Oluwole 2015; Mendanha and Alonso 2015) (Fig. 2). Compounds such as β-caryophyllene and labdanes exemplify this process by destabilizing phospholipid membranes and compromising their barrier function (Stasiuk and Kozubek 2008; Sadgrove *et al.* 2021).

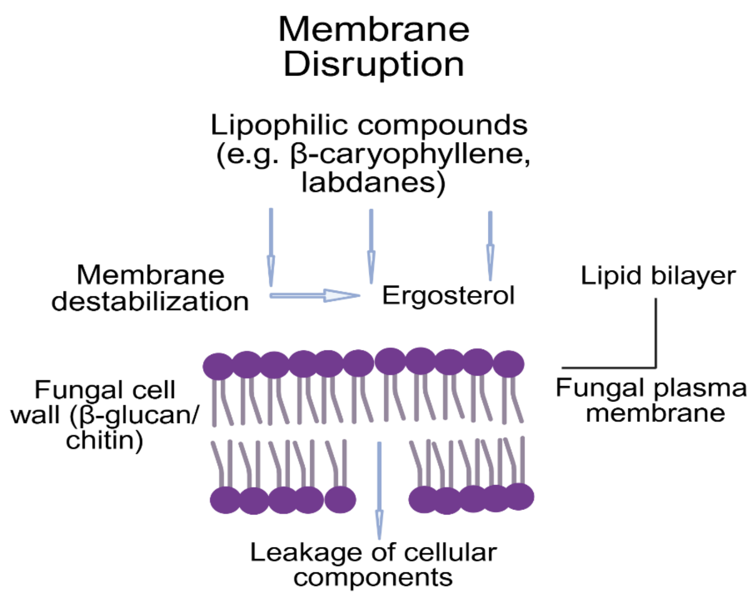


Fig. 2. Schematic representation of membrane disruption in fungal cells by lipophilic compounds. Figure adapted from Stasiuk and Kozubek (2008); Aderiye and Oluwole (2015); Mendanha and Alonso (2015); Sadgrove *et al.* (2021)

Another antifungal mechanism involves enzyme inhibition. While some terpenoids stimulate growth in particular fungal species (Fries 1973), many others inhibit fungal development and enzyme production (De Groot 1972; Váradi 1972). Recent work further supports that fungal responses to terpenoid-rich fractions can vary with both compound chemistry/structure and fungal identity (Li *et al.* 2023). This divergence highlights that outcomes can reverse depending on concentration, solvent/carrier, fungal species, and exposure duration; therefore, single-study conclusions should not be generalized across organisms or use environments. Where possible, comprehensive comparative studies using consistent methodological conditions (substrates, retentions, and test conditions) are needed to determine whether observed differences reflect true biological selectivity or methodological variability. This inhibitory effect is generally more pronounced in fungi associated with deciduous trees than in those inhabiting conifers (Hintikka 1970). Specifically, terpenoids interfere with the production of cellulases and xylanases (Váradi 1972), thereby impairing fungal degradation of key structural wood components such as cellulose and lignin (Leonowicz *et al.* 1999; Martínez *et al.* 2005) (Fig. 3). Terpenoid-rich extracts can also modulate the expression of lignin-degrading genes, with certain laccases showing increased expression in response to phenolic compounds (Yakovlev *et al.* 2013).

Conversely, other ligninolytic genes may be downregulated, resulting in diminished enzyme activity.

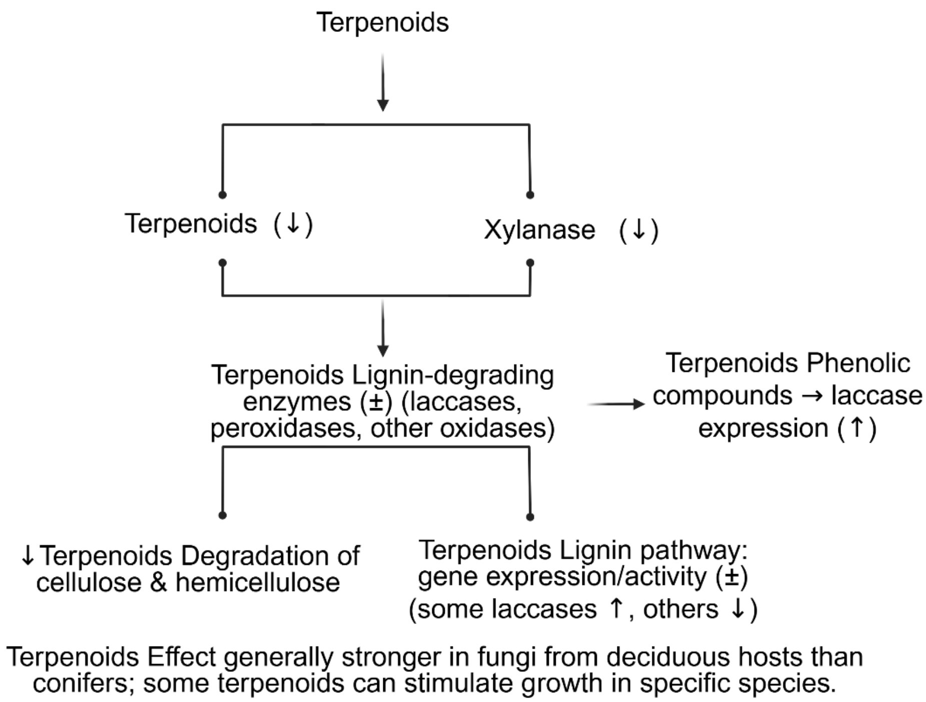


Fig. 3. Schematic representation of enzyme inhibition in fungi by terpenoids. Figure adapted from Hintikka (1970); De Groot (1972); Váradi (1972); Fries (1973); Leonowicz *et al.* (1999); Martínez *et al.* (2005); Yakovlev *et al.* (2013)

A further pathway involves oxidative stress, as certain terpenoids induce the generation of reactive oxygen species (ROS) within fungal cells, leading to oxidative degradation of DNA, proteins, and membranes (Gonzalez-Jimenez *et al.* 2023) (Fig. 4).

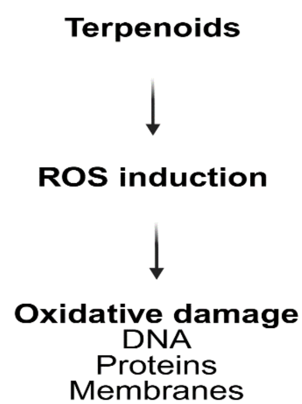


Fig. 4. Schematic representation of oxidative stress induced by terpenoids in fungal cells. Figure adapted from Gonzalez-Jimenez *et al.* (2023)

Termiticidal and Insect-Repelling Effects

Terpenoids exhibit multiple modes of action against wood-destroying insects such as *Coptotermes formosanus* and *Reticulitermes flavipes*. For clarity, these effects can be grouped into direct toxicity *versus* behavioral deterrence. Direct toxic effects include contact and fumigant toxicity and neurophysiological disruption (*e.g*., AChE inhibition and ion-channel modulation) that reduce survival or impair function. Behavioral deterrence mechanisms include repellency, reduced feeding, altered tunneling/foraging, and disruption of chemical signaling. These mechanisms collectively reduce wood consumption even when outright mortality is not the dominant endpoint. Compounds such as nootkatone and its derivatives demonstrate both contact toxicity and fumigant effects, significantly reducing termite survival, tunneling, and feeding activities (Ibrahim *et al.* 2004). One key mechanism is neurotoxicity: terpenoids, particularly monoterpenes, have shown potential as bioinsecticides and anthelmintics because of their capacity to modulate ion channels and inhibit acetylcholinesterase (AChE) in insects and nematodes. By disrupting AChE activity, they act as neurotoxins that interfere with neural transmission and can even induce exoskeletal changes (Zhu *et al.* 2003; Siramon *et al.* 2009).

Another important pathway involves feeding deterrence. Terpenoids reduce wood consumption and alter termite foraging behavior, thereby limiting structural damage (Maistrello *et al.* 2003; Ibrahim *et al.* 2004). A further mechanism of action is signal disruption. Monoterpenoids, particularly alcohols such as eugenol, exhibit strong termiticidal activity and can serve as chemical barriers against termite intrusion (Cornelius *et al.* 1997). In addition, terpenoids act as repellents that drive termites away from treated zones (Bläske and Hertel, 2001).

Evidence from guayule-based studies further supports these findings. Aguma (2024) demonstrated that exposure to resin fractions containing β-caryophyllene led to almost complete deterrence behavior in termites, with negligible wood mass loss, outperforming petroleum-based preservatives.

Water Exclusion and Physical Barrier Formation

Terpenoids, particularly those derived from resin acids or high-molecular-weight diterpenes, contribute to water exclusion by forming a hydrophobic layer on wood surfaces (see Fig. 5). This barrier reduces moisture ingress and consequently limits the window for microbial colonization (Rowell, 2014; Zhu *et al.* 2014). To avoid confusion with living-tree physiology, it is important to note that the "hydrophobic layer" described here refers to treated wood (surface or near-surface barrier effects). In living trees and shrubs, water transport must remain functional in the sapwood; living parenchyma is an integral component of sapwood function, and living cells can constitute a substantial fraction of sapwood volume across taxa (Schenk 2018). Hydrophobization and durability-related impregnation occur predominantly in bark (external barrier) and during heartwood formation, where parenchyma cells contribute to material transport and the conversion of reserve materials into protective substances while the sapwood remains water-conductive (Kuroda 2015). Micron-scale studies also show targeted deposition of protective extractives (*e.g.*, stilbenes and lipids) during the sapwood-heartwood transition (Felhofer *et al.* 2018). Heartwood extractives are also described as arising through parenchyma cell death-linked processes or in response to external stimuli, providing a natural defense mechanism while maintaining vascular integrity (Kirker *et al.* 2024). This distinction underscores that wood-preservation systems aim to mimic durable-tissue chemistry in a non-living substrate rather than impose "water exclusion" on the living vascular system. In addition to enhancing resistance against biological attack, terpenoids improve the dimensional stability of wood, a property that is essential for maintaining structural integrity under fluctuating climatic conditions (Zhu *et al.* 2014; Chen *et al.* 2020; He *et al.* 2023). Their effectiveness can be further increased through synergistic blending with carrier oils such as hempseed or soybean oil, as demonstrated in experimental treatments by Aguma (2024).

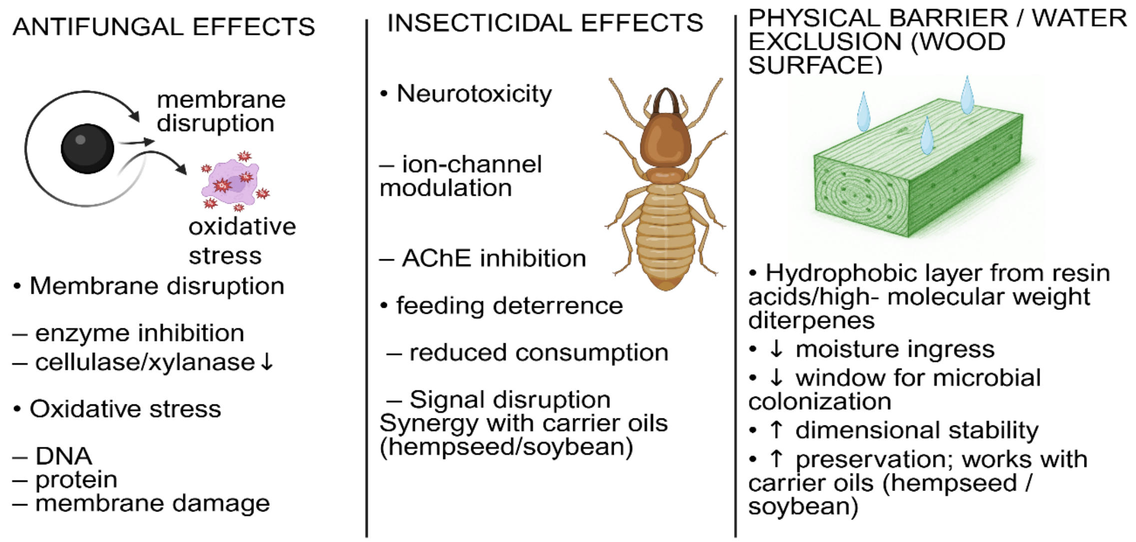


Fig. 5. Mechanisms of action of terpenoids in wood protection. This schematic depicts mechanisms in treated wood; in living plants, external hydrophobicity is primarily associated with bark, while internal extractive impregnation is associated with heartwood formation rather than the water-conducting sapwood. Figure adapted from multiple sources including Siramon *et al.* (2009), Aderiye and Oluwole (2015), Sadgrove *et al.* (2021), and Gonzalez-Jimenez *et al.* (2023)

Terpenoids exert their protective effects through multiple pathways, including fungal membrane disruption, enzyme inhibition, oxidative stress induction, and insect neurotoxicity (Fig. 5). These bioactivities contribute to their antifungal, insecticidal, and preservative functions in lignocellulosic substrates (Fig. 5).

UV and Oxidative Stabilization

Terpenoids found in desert plants play crucial roles in both UV protection and antioxidant defense (Tahri *et al.* 2022). These compounds are capable of absorbing ultraviolet radiation and scavenging free radicals, thereby preventing the photodegradation of lignin and cellulose (Baker and Allison, 2015; Austin *et al.* 2016). In addition, specific molecules such as nordihydroguaiaretic acid analogs from *Larrea tridentata* have been shown to reduce surface weathering and to help preserve wood color and structural integrity during prolonged exposure to sunlight (Manda *et al.* 2020). Here, "analogs/derivatives" refers to structurally related compounds inspired by plant metabolites; however, structural modification can alter environmental fate**,** potentially reducing biodegradability or increasing persistence despite apparent similarity to natural metabolites. While many terpenoid-like scaffolds may still degrade readily, modifications introduced to improve stability or performance may change degradation behavior; therefore, environmental advantage should not be assumed solely from structural similarity (Thakkar 2025). Accordingly, compound-specific biodegradability and ecotoxicity screening is recommended when developing synthetic or semi-synthetic analogs, particularly for applications involving long-term exterior exposure (Woźniak 2022). These analogs act as photoprotectants by screening UV-B radiation and quenching reactive oxygen species (Takshak and Agrawal 2019).

UV screening by extractives can also be partly sacrificial, in the sense that repeated photon absorption can contribute to chemical transformation or breakdown of the UV-absorbing compounds themselves over long exposure periods. Consequently, durable exterior performance may require stabilization strategies such as encapsulation, UV-stable matrices/topcoats, co-formulated antioxidants, or maintenance/replenishment cycles, in addition to initial UV absorption capacity.

Spectrum of Activity: Broad and Selective Modes

Broad-spectrum terpenoids, such as phorbol esters, a diverse class of plant-derived compounds with wide-ranging biological activities, exhibit general cytotoxic, antimicrobial, and insecticidal properties, allowing them to target a broad array of insects and microbes. These characteristics make them promising candidates for crop protection and pest control (Goel *et al.* 2007; Ratnadass and Wink 2012) (Fig. 6). By contrast, some terpenoids may exhibit relative selectivity (*i.e.*, stronger effects on certain taxa or behaviors than others) depending on dose and exposure route; however, the evidence base remains limited and context-dependent. Partial support comes from laboratory ecotoxicology studies showing differential responses across target and non-target organisms. For example, Castilhos *et al.* (2017) reported that several terpenoids/essential-oil constituents showed *relative selectivity* when assessed against a beneficial predator insect, with toxicity varying among compounds. Duarte *et al.* (2024) likewise found terpenoid-based nanoemulsions with larvicidal activity against mosquitoes, while also reporting behavioral changes in zebrafish at high doses; highlighting that non-target effects can occur and should be evaluated across relevant exposure ranges. Toledo *et al.* (2020) further illustrated ecotoxicological selectivity by comparing effects of an essential-oil treatment on a target pest versus a non-target beneficial insect. Accordingly, "selectivity" should be treated as a working hypothesis requiring broader comparative testing across target and non-target organisms and standardized exposure conditions to establish robust conclusions (Hashiesh *et al.* 2021) (Fig. 6).

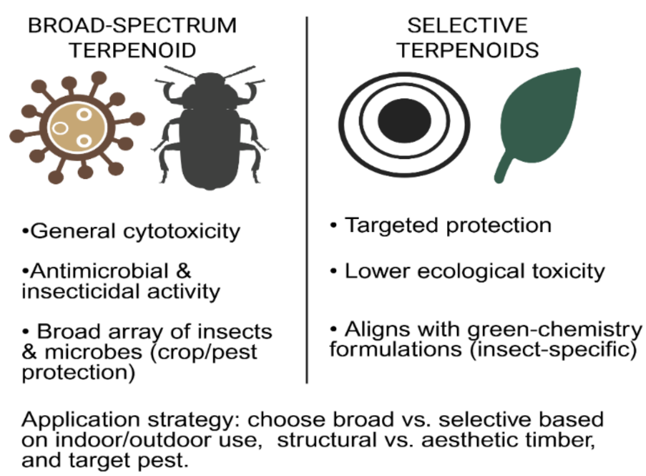


Fig. 6. Spectrum of activity of terpenoids. Figure *adapted from* Goel *et al.* (2007); Ratnadass and Wink (2012); Hashiesh *et al.* (2021)

As summarized in Fig. 6, these distinctions allow for the development of tailored formulation strategies depending on application needs, whether for indoor versus outdoor use, structural versus aesthetic timber, or insect-specific protection. The multifunctional modes of action of terpenoids, illustrated in Fig. 6, not only ensure protection against biological agents but also enhance the physical resilience of wood. This dual function: combining bioactivity with physicochemical reinforcement, underscores the unique value of desert shrubs in sustainable wood preservation systems (Tholl 2015; Tahri *et al.* 2022).

DELIVERY SYSTEMS AND FORMULATION STRATEGIES

While the bioactivity of terpenoids from desert shrubs is well-established, their efficacy in real-world wood applications depends significantly on delivery mechanisms, formulation stability, and substrate compatibility. Terpenoids and essential oils from plants show promise for wood preservation and pest control, but their effectiveness is limited by poor solubility, high volatility, and susceptibility to environmental degradation, which can reduce field performance if not properly formulated (Broda 2020; Ninkuu *et al.* 2021). In exterior service conditions, loss of efficacy is driven mainly by (i) volatilization of lighter terpenes, (ii) leaching during rain and wet-dry cycling, and (iii) photochemical degradation under UV exposure. Bueno *et al.* (2020) demonstrated that terpenes are inherently volatile, supporting volatilization as a realistic loss pathway as treated materials age. *Pospisilova et al.* (2021) provided molecular-level evidence that terpenes can undergo substantial photodegradation under UV radiation, with oxygenated terpene structures showing elevated photoactivity. Leaching dynamics are well documented for coating-associated biocides under natural weathering, illustrating how early exposure periods can dominate runoff losses in some systems (Bollmann *et al.* 2016). UV-driven changes in wood substrates further complicate persistence: wood is highly sensitive to UV radiation (300-400 nm), which induces major chemical changes (particularly in lignin) and can generate reactive radicals and colored oxidation products (Teacă and Bodîrlău 2016). Accordingly, durable formulations emphasize less-volatile fractions *(e.g.*, sesquiterpene/diterpene-rich resins), slow-release carrier systems, and physical/chemical fixation *via* encapsulation or polymer/biopolymer matrices that reduce mass-transfer to the environment. Multiple studies have demonstrated stabilization approaches using slow-release carriers and fixation concepts (Deng 2025). In particular, encapsulation strategies using polymers/biopolymers and specialized matrices have been developed to protect volatile bioactives and enable controlled release (Dajić Stevanovic *et al.* 2020). Mamusa *et al.* (2021) report that such approaches can enhance efficacy, safety, and stability while allowing tuning of release profiles. For stronger comparability across studies, future evaluations should report retention/loading, include standardized leaching/weathering conditioning, and quantify mass-balance loss (leaching and volatility) alongside biological performance endpoints.

Carrier Oils: Natural Solvents and Enhancers

Plant-based oils serve as effective carriers and functional additives in terpenoid delivery systems, offering multiple benefits. They enhance resin penetration into lignocellulosic matrices while improving the stability and bioavailability of terpenes (Kaspute *et al.* 2025). In addition, they act synergistically with terpenoids to deter termites, as demonstrated in several studies (Fatima and Morrell 2015; Ahmed *et al.* 2020; Aguma 2024). Another important contribution is their ability to reduce volatility and promote the slow release of active compounds, which makes them suitable for semichemical formulations (Muskat *et al.* 2022). The combination of plant oils and terpenoids thus provides a biodegradable and environmentally friendly alternative to conventional pesticides (Garay 2020). Research on the use of plant-derived oils in wood preservation and pest control applications shows promising results, with some oils outperforming others in efficacy (Patil *et al.* 1998; Ahmed *et al.* 2020; Aguma 2024).

Among the most studied oils, hemp seed oil is notable for its high polyunsaturated fat content, which enhances dispersion and moisture exclusion (Aguma 2024; Mygdalia *et al.* 2025). It has also exhibited the highest larvicidal activity against *Aedes aegypti* mosquitoes, with an LC50 of 348 ppm, where effectiveness correlated with linoleic acid content (Njoroge and Berenbaum 2019). Soybean oil has likewise demonstrated considerable potential for pest control applications, particularly against arthropods and termites. Research has shown that soybean oil exhibits strong acaricidal effects against spider mites, with LC50 values as low as 0.05 to 0.07% (Qayyoum *et al.* 2025). For termite control, it has proven highly effective when combined with other compounds. For instance, epoxidized soybean oil-based hybrid resins demonstrate anti-termite activity (Kusumkar *et al.* 2022), while epoxidized soybean oil treatments achieve 100% termite mortality (Kose Demirel *et al.* 2020). Plant-derived oils, including soybean oil, rapidly disrupt termite gut protozoa, leading to worker mortality within seven days (Fatima and Morrell 2015). Additionally, soybean oil improves boron retention in wood treatments, thereby enhancing protection against both termites and fungi (Lyon *et al.* 2007). The oil's fatty acid composition, rich in linoleic acid, can also be modified through genetic engineering to achieve high oleic acid content (>80%) while reducing linoleic and linolenic acids to below 3% (Demorest *et al.* 2016; Bilyeu *et al.* 2018). Notably, soybean oil enhanced termite deterrence when combined with guayule resin (Aguma 2024).

Neem oil represents another important carrier. It contains azadirachtin, which may synergize with terpenoids to provide broad-spectrum insect repellency. Studies have documented its strong repellent effects against insect pests such as *Sitophilus granarius* and *Aedes aegypti* (Darwish *et al.* 2013; Mukesh *et al.* 2014). Consistently, neem oil has demonstrated broad-spectrum repellency and deterrent effects, effectively repelling lesser grain borers and red flour beetles with persistent activity lasting several weeks (Jilani *et al.* 1988; Jilani and Saxena 1990). Against termites, neem oil disrupts hindgut protozoa and leads to worker mortality within seven days (Fatima and Morrell 2015). Its active compound azadirachtin further provides target-specific mosquitocidal effects without environmental toxicity (Chatterjee *et al.* 2023). Wood treatment studies confirmed neem oil's protective role, with maximum termite protection achieved at 100% concentration, reducing weight loss to 23.2% compared to 51.7% in untreated controls (Adebawo and Adekanbi 2011).

Desert-derived carrier oils (arid-zone options)

Research demonstrates that plants in arid environments produce terpenoids and oils that serve multiple functions. Desert plants develop specialized lipophilic metabolites, including terpenoids, as adaptation mechanisms for drought tolerance and pathogen protection (Tahri *et al.* 2022). Several oils from desert and semi-desert plants function as low-toxicity solvents and penetration enhancers for terpenoids, while also contributing hydrophobicity and oxidative/UV stability.

Physic nut oil (*Jatropha curcas*) contains toxic phorbol esters that currently limit its industrial applications; however, various detoxification methods show promise for safe utilization. Phorbol ester concentrations vary significantly among provenances, ranging from 0.23% to 1.58% (Ahmed and Salimon 2009). Despite these toxicity concerns, phorbol esters have potential pharmaceutical applications, including the synthesis of prostratin (Devappa *et al.* 2013). As an industrial dryland oil, physic nut oil remains promising as a carrier for non-contact structural uses, provided that phorbol esters are removed or deactivated during refining.

Jojoba oil (*Simmondsia chinensis*) is a unique liquid wax ester composed of long-chain fatty acids and alcohols, with virtually no glycerine content, which distinguishes it from conventional seed oils (Wisniak 1977; Arya and Khan 2016; Bala 2022). This drought-resistant desert shrub produces seeds containing up to 54% wax content and demonstrates exceptional oxidative stability (Wisniak 1977; Sturtevant *et al.* 2020). It can also slow release sesquiterpenes and diterpenoids in exterior exposures. As a carrier oil, jojoba stabilizes sensitive compounds against air oxidation and UV degradation (Belostozky *et al.* 2019).

Argan oil (*Argania spinosa*), extracted from the kernels of the argan tree, is rich in unsaturated fatty acids, with oleic acid comprising 45 to 53% and linoleic acid 25 to 37%, so that unsaturated fatty acids account for approximately 79 to 83% of the total fatty acids (Yousfi *et al.* 2009; Kouidri *et al.* 2015; Sabiri *et al.* 2023). It also contains significant levels of natural antioxidants, particularly tocopherols (657 to 1028 mg/kg), with γ-tocopherol as the predominant isomer (Yousfi *et al.* 2009; Kouidri *et al.* 2015). Its major triacylglycerols include "dilinoleoyl-oleoyl-glycerol, dioleoyl-linoleoyl-glycerol, and palmitoyl-dioleoyl-glycerol" (Kouidri *et al.* 2015; Zaaboul *et al.* 2019). These compounds contribute to argan oil's antioxidant, anti-inflammatory, and protective effects against toxicities (Mechqoq *et al.* 2021; Amssayef *et al.* 2025). The combination of oleic- and linoleic-rich composition with natural antioxidants supports its use in wood protection, improving the dispersion of terpenoid actives and enhancing photoprotection in decorative timbers.

Prickly pear seed oil (*Opuntia ficus-indica*) is characterized by high linoleic acid content, typically ranging from 56 to 79%, depending on variety and extraction method (Sawaya and Khan 1982; de Wit *et al.* 2018; Al-Naqeb *et al.* 2021). Its high degree of unsaturation (82%) results in a light, fast-wetting oil with low viscosity (Sawaya and Khan 1982). Oil content varies between cultivars, ranging from 4.09 to 12.5% of seed mass (de Wit *et al.* 2018; Kadda *et al.* 2021). The fatty acid profile consistently shows linoleic acid as the dominant component (58.8 to 79.8%), followed by oleic acid (16.4 to 25.5%) and palmitic acid (11.2 to 26.6%) (Ghazi *et al.* 2013; Ettalibi *et al.* 2021;). Physical properties include relatively low oxidative stability (2.16 to 4.15 hours) and iodine values of 111 to 126, reflecting high unsaturation suitable for penetration applications (De Wit *et al.* 2018). Its light and fast-wetting qualities make it particularly useful for penetration into porous woods and engineered panels, where low viscosity is desirable.

Desert date oil (*Balanites aegyptiaca*) represents another arid-adapted oil source, with kernels containing up to 46.7% oil rich in oleic and linoleic acids. This composition makes it well-suited to pair with terpenoids for antifeedant systems, while also providing moisture exclusion in hot, seasonally dry climates (Chapagain *et al.* 2009).

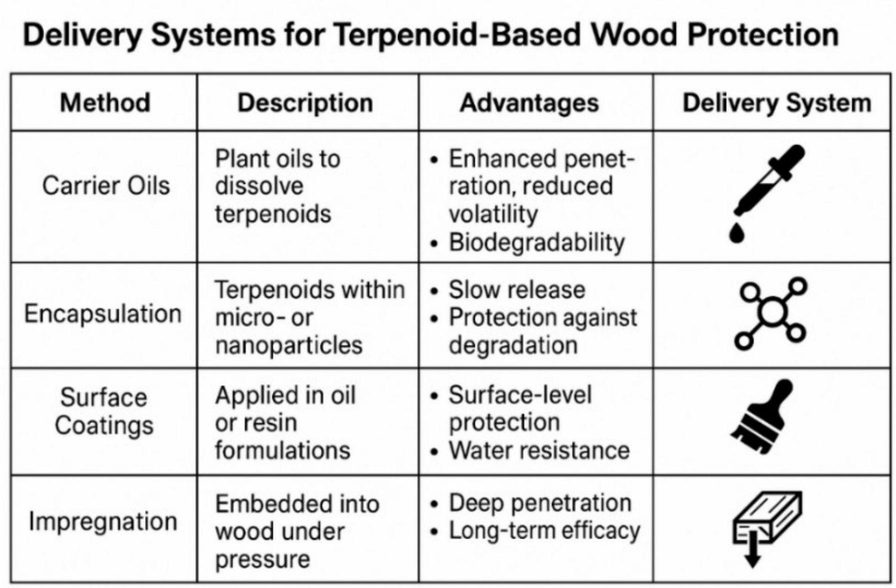
From a practical standpoint, more oxidation-stable oils such as jojoba are preferable for high-UV, exterior applications, while lighter oils such as prickly pear are better suited where deeper penetration is prioritized. Blending different oils allows for balancing penetration with longevity, enabling tailored applications in wood preservation.

Resin-Oil Blends: Simple, Scalable Formulations

Research by Aguma (2024) demonstrated that directly blending guayule resin with plant-based oils, without the use of solvents or synthetic additives, produced high-performance and eco-friendly wood protectants. Hemp-resin-treated samples exhibited complete visual termite resistance, while treated wood showed only 2.87 to 4.76% weight loss compared to 40 to 47% in untreated controls. In addition, stability and adhesion to wood surfaces were enhanced through resin-oil interactions. These resin-oil systems therefore represent low-tech, scalable, and circular economy-compatible solutions, making them particularly well suited to decentralized or rural wood processing industries.

Encapsulation and Controlled Release Technologies

Delivery options for terpenoid-based wood protection span carrier oils, encapsulation, surface coatings, and impregnation; this subsection focuses on encapsulation and controlled release. Recent research has investigated encapsulation strategies to reduce volatility and enable controlled release of essential oils and terpenes in wood protection and pest control applications (Sousa *et al.* 2022). Although encapsulation can delay exposure by limiting mass transfer, it does not by itself prevent UV-driven degradation once actives are released and reach (or are exposed at) the wood surface; durable UV performance therefore typically requires UV-stable matrices/topcoats and/or co-formulated photostabilizers (*e.g.*, UV absorbers and antioxidants) (Jirouš-Rajković and Miklečić 2021). However, if capsules are located sufficiently below the surface (*e.g.*, several millimeters), incident UV radiation will be attenuated primarily within the wood surface layers (including lignin-rich regions), reducing UV exposure of encapsulated actives while they remain embedded. As release and migration progress toward the surface, susceptibility to photodegradation increases, reinforcing the need for surface-level UV stabilization rather than reliance on encapsulation alone. A comparative overview of the key delivery platforms considered in this section is presented in Fig. 7.


Delivery Systems for Terpenoid-Based Wood Protection

Method	Description	Advantages	Delivery System
Carrier Oils	Plant oils to dissolve terpenoids	• Enhanced penet-ration, reduced volatility • Biodegradability	
Encapsulation	Terpenoids within micro- or nanoparticles	• Slow release • Protection against degradation	
Surface Coatings	Applied in oil or resin formulations	• Surface-level protection • Water resistance	
Impregnation	Embedded into wood under pressure	• Deep penetration • Long-term efficacy	

Fig. 7. Comparative overview of terpenoid delivery systems for wood protection**.** Figure adapted from De Oliveira *et al.* (2018); Broda (2020); Muskat *et al.* (2022), and Aguma (2024)

Microencapsulation using chitosan, cyclodextrins, and polysaccharides enables slow-release behavior (Marques 2010; Campos *et al.* 2015; De Oliveira *et al.* 2018; Karlsen 2020). Similarly, nanoemulsions have been shown to increase surface area and penetration into dense wood structures (Ayllón-Gutiérrez *et al.* 2024). Polysaccharide-based hydrogels provide another effective option by retaining terpenoids and releasing them in response to humidity or termite activity (Soto *et al.* 2021). Collectively, these methods demonstrate significant promise for improving stability, reducing environmental impact, and enhancing efficacy against pests and UV degradation (Cai and Niska 2012; Clausen 2012).

Encapsulation techniques have proven to be highly efficient, with certain formulations maintaining stability for up to 120 days and providing environmentally responsive controlled release (De Oliveira *et al.* 2018; Soto *et al.* 2021). Encapsulation approaches trade greater control and longevity for increased processing requirements. Although these strategies hold strong potential for large-scale wood treatment systems, further validation is required, particularly under tropical and subtropical exposure conditions (Ayllón-Gutiérrez *et al.* 2024).

Different delivery strategies offer varying degrees of bioavailability, longevity, and scalability. Resin-oil blends provide low-tech, eco-friendly options, while nanoemulsions and encapsulation offer enhanced control but require more advanced processing. This comparison highlights trade-offs between simplicity, stability, and field efficacy.

Comparative Considerations: Penetration Depth and Leaching Resistance

Oil-based systems (including resin-oil blends) can achieve effective wood penetration, especially when paired with low-viscosity carriers and vacuum-pressure impregnation (Robinson *et al.* 2013). However, unless actives are fixed, these systems can be more vulnerable to loss by leaching and volatilization during exterior wet-dry cycling. Robinson *et al.* (2013) showed that pyrolysis-oil penetrants (≥10%) can reduce moisture sorption and swelling, supporting their practical role in moisture management, while leaching resistance depends strongly on emulsion design and fixation. For example, Tomak *et al.* (2010) reported that water-in-oil emulsion systems can reduce leaching (up to 35%), and Mourant *et al.* (2009) emphasized that formulation choice is critical for minimizing active loss under environmental stress. Encapsulation platforms (microcapsules, nanoemulsions, and responsive hydrogels) offer improved retention and controlled release, with potential gains in persistence under UV and variable environments (Ayyaril *et al.* 2023; Yu *et al.* 2024). In addition, nanoemulsions can enhance access to wood capillary/microstructure pathways; Carrillo *et al.* (2013) reported substantially improved penetration efficiency relative to water-based delivery. Polymer/biopolymer-matrix systems (including adhesive/coating-type matrices) can provide high leaching resistance by immobilizing actives within a solid network, often with controlled-release behavior (Cai and Niska 2012; Clausen 2014). Lin *et al.* (2021) further demonstrated that resin incorporation can significantly reduce leaching of incorporated chemicals, supporting matrix fixation as a persistence strategy. However, these matrix systems are most commonly deployed as surface coatings or engineered-wood additives rather than deep-impregnation treatments, and therefore may require design optimization where through-thickness protection is needed.

Surface Coatings and Impregnation Techniques

Brush or dip coatings that employ terpenoid-rich oils or resins provide rapid, surface-level protection against biological and environmental deterioration. For applications requiring greater durability, vacuum-pressure impregnation allows deeper penetration of protective substances such as resin-oil blends into structural timbers, with viscosity adjustments made as needed to optimize performance (Morrell *et al.* 1996; Aguma 2024). In addition, thermal treatment can be integrated into these approaches to enhance performance and application characteristics. Preheating terpenoid-resin composites reduce viscosity, improves physical properties, and facilitates either easier application or stronger bonding to wood substrates (Woolum *et al.* 2008; Lucey *et al.* 2010).

Compatibility with Existing Wood-Treatment Infrastructure

From an implementation perspective, terpenoid-based wood protection systems are most readily deployable when they align with existing wood-protection unit operations, particularly surface coating and vacuum-pressure impregnation, which can be selected according to product type and exposure class. For appearance-grade or non-ground-contact products, conventional surface coating methods (brush, dip, or spray) provide a practical route for applying terpenoid-rich oils and resin-oil blends (Calovi *et al.* 2024). For structural timbers where deeper protection is required and treatability allows, vacuum-pressure impregnation can provide improved penetration and durability (Teacă *et al.* 2019; Messaoudi *et al.* 2020). In both cases, performance depends on maintaining process-compatible viscosity (potentially aided by modest thermal conditioning) and on formulation choices that reduce losses by leaching and volatilization during service; coating composition and flexibility are also important contributors to durability (Nejad and Cooper 2017). Treatment outcomes further depend on wood anatomy and permeability, which vary across species and influence fluid flow and preservative distribution (Messaoudi *et al.* 2020). Where engineered wood products are targeted, incorporation into adhesives or coating matrices can enable integration into existing panel and finishing workflows, but such treatments should be paired with bonding/adhesion validation (see Future Directions).

Hybrid Systems with Biopolymers and Natural Adhesives

There is increasing interest in integrating terpenoids into biopolymer matrices to expand their applications in engineered wood products. For instance, lignin-resin copolymers are being developed as structural adhesives with inherent antifungal properties. Similarly, soy-based adhesives fortified with terpenoids offer promising pathways for producing formaldehyde-free panel boards. Other approaches employ shellac or rosin as carriers, producing high-gloss, UV-resistant protective coatings. Collectively, these hybrid formulations extend the role of terpenoids beyond simple biocides, positioning them as multifunctional material enhancers.

Effective delivery of desert-shrub terpenoids is not merely a formulation challenge but a strategic design problem that intersects chemistry, material science, and environmental engineering. By leveraging low-toxicity carriers, scalable blending methods, and controlled-release systems, these compounds can be integrated into the wood protection value chain with minimal ecological cost and maximal functional payoff.

ENVIRONMENTAL AND COMMERCIAL PERSPECTIVES

As global industries transition toward greener materials and carbon-conscious processes, terpenoid-based wood protectants offer a timely and strategic solution. Their biodegradability**,** renewable biomass origin, and low toxicity profiles align closely with international environmental mandates. However, successful adoption also depends on economic viability, supportive regulatory frameworks, and robust performance validation under real-world conditions**.**

Environmental Safety and Sustainability

Conventional wood preservatives, particularly chromated copper arsenate (CCA), pentachlorophenol (PCP), and creosote, have faced growing regulatory restrictions because of their environmental and health risks (Schultz and Nicholas 2003; Morais *et al.* 2021; Emenike *et al.* 2024). These preservatives persist in the environment, leach toxic compounds, and pose risks to aquatic ecosystems as well as to human health (Stook *et al.* 2005; Townsend and Solo-Gabriele 2006).

In contrast, terpenoids; a diverse class of plant secondary metabolites, offer numerous advantages as natural preservatives and bioactive compounds. They exhibit low bioaccumulation potential and undergo rapid environmental degradation (Tahri *et al.* 2022). Compared to heavy-metal-based preservatives, terpenoids present minimal ecotoxicological impact on aquatic organisms. Furthermore, when delivered *via* plant oils or biopolymer matrices, they reduce volatile organic compound (VOC) emissions. Many terpenoids are classified as Generally Recognized as Safe (GRAS), underscoring their favorable toxicological profiles across multiple applications (Neerja Gupta *et al.* 2011; Lyu *et al.* 2019). Beyond wood protection, these compounds also demonstrate antimicrobial, antioxidant, and anti-inflammatory properties, supporting their use in the food, pharmaceutical, and cosmetic sectors (Masyita *et al.* 2022; Câmara *et al.* 2024).

Life Cycle and Circular Economy Considerations

Guayule, a desert shrub cultivated primarily for natural rubber production, generates significant biomass waste in the form of resin and bagasse. A systems view of this valorization pathway is presented in Fig. 8. Transforming these by-products into wood preservatives enables the closing of material loops and the promotion of circular bioeconomy principles, while simultaneously lowering net greenhouse gas (GHG) emissions through waste minimization and the substitution of fossil-based chemicals (Bougherra *et al.* 2023; Silagy *et al.* 2024). In addition, valorization strategies encourage regionally self-sufficient industries, particularly in arid zones where hardy shrubs are accessible (Bougherra *et al.* 2023; Silagy *et al.* 2024).

Research by Aguma (2024) demonstrated that resin fractions can be extracted without the use of solvents, further reducing environmental burden, and making field-scale applications safer and more sustainable. As shown in Fig. 8, bagasse and other agricultural residues can be routed to bioenergy, fiberboard, or compost streams, while resin is directed toward preservative formulations, effectively linking guayule cultivation to circular bioeconomy outcomes.

Integrating these coproducts into a circular bioeconomy framework maximizes resource efficiency while minimizing waste. This framework, which is outlined in Fig. 8, encompasses several interlinked pathways. First, resin valorization into wood preservatives can be achieved through environmentally friendly or solvent-free extraction methods (Aguma 2024), producing bioactive preservatives that substitute for fossil-derived chemicals and reduce the burden of solvent-intensive processes. Second, bagasse and lignocellulosic residues may be utilized for bioenergy production, incorporated into fiberboard manufacture, or composted to recycle nutrients back into the soil. Such applications close material loops by converting processing waste into valuable coproducts. Third, these practices generate environmental benefits by lowering GHG emissions through both waste minimization and the replacement of fossil-based inputs (Bougherra *et al.* 2023; Silagy *et al.* 2024). Finally, guayule cultivation supports regional self-sufficiency and socio-economic resilience in arid zones, where valorization pathways create added value in rural communities and strengthen local economies.

Taken together, these strategies demonstrate how guayule-derived wood protection systems advance circular bioeconomy objectives by combining material circularity, reduced carbon intensity, and regional value addition (Bougherra *et al.* 2023; Aguma 2024; Silagy *et al.* 2024).

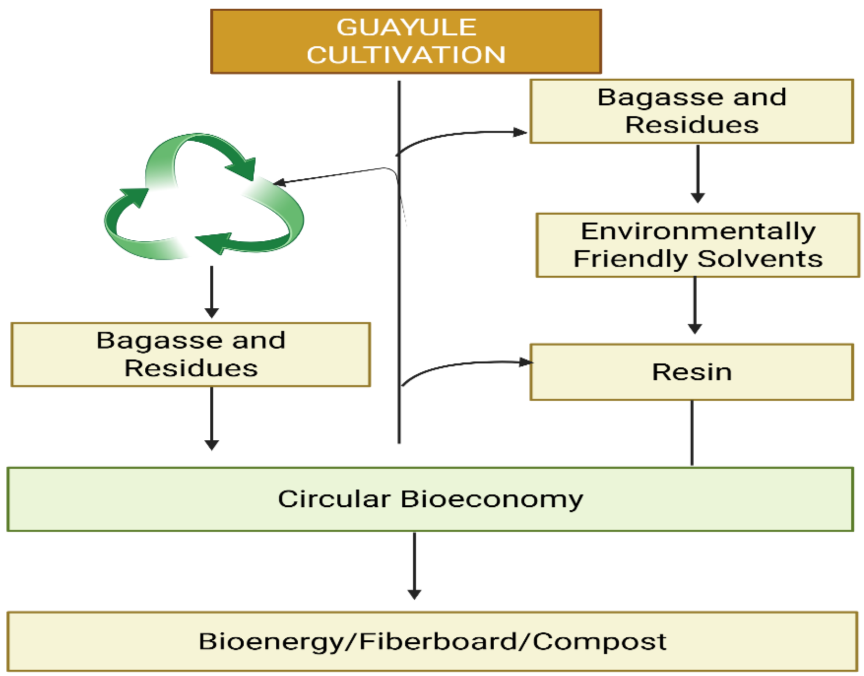


Fig. 8. Circular bioeconomy pathway for guayule-derived wood protection systems**.** Figure adapted from Bougherra *et al.* (2023).; Aguma (2024), and Silagy *et al.* (2024)

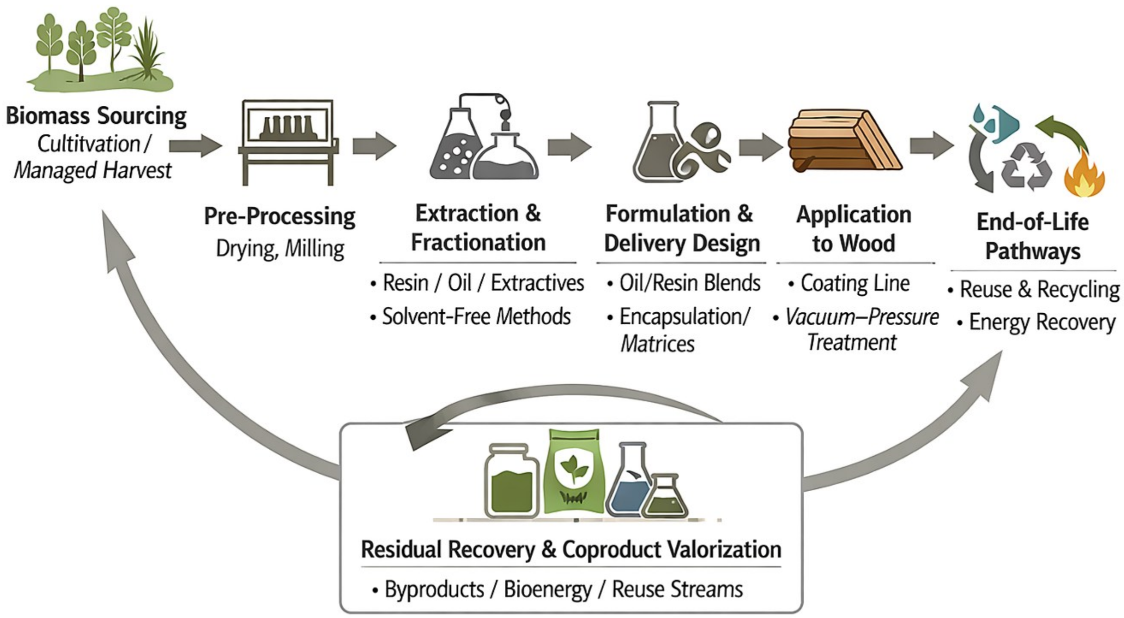


Fig. 9. Circular-bioresource integration pathway for desert-shrub terpenoids in wood protection, from sourcing and extraction/fractionation through formulation/application, service-life loss pathways (volatility, leaching, UV degradation), and end-of-life recovery (reuse, recycling, energy recovery) with coproduct valorization (Conceptual schematic developed by the authors).

Guayule cultivation generates multiple biomass streams. Resin by-products from rubber processing can be valorized into bioactive wood protectants using low-tech, solvent-free methods. This integrated model promotes material circularity, rural value addition, and reduced environmental impact (Fig. 8). A generalized circular-bioresource integration pathway for desert-shrub terpenoids in wood protection is summarized in Fig. 9**.**

Forest Ecosystem Integration and Carbon Implications

Research has demonstrated that extending the service life of harvested wood products (HWPs) significantly lengthens carbon storage and strengthens climate-mitigation outcomes. Lifetime extension works in tandem with circular-bioeconomy strategies, with combined measures achieving up to 32% emission reductions (Király *et al.* 2023). Circular design that increases building lifespans from 50 to 80 years can even yield negative whole-life carbon emissions (−0.09 kg CO_2-eq./m^2/year), highlighting the value of prolonged biogenic carbon storage (Schwarzschachner and Hernandez, 2024). Shifting wood use toward long-life construction materials likewise increases carbon residence time within HWP pools (Parobek *et al.* 2019; Kallio *et al.* 2023). In this context, extending service life with terpenoid-based preservation increases the time biogenic carbon remains stored in harvested wood products (HWP), complementing the circular-bioeconomy pathway outlined for guayule and other arid-zone inputs and enhancing climate-mitigation potential (Li *et al.* 2022; Király *et al.* 2023; Kouame and Ghannadzadeh 2023; Spear and Hart 2025). By reducing replacement demand, greater durability can ease pressure on standing forests and align with co-benefits such as watershed quality and biodiversity (Khademibami and Bobadilha 2022; Calovi *et al.* 2024). Transitioning away from persistent synthetic preservatives toward plant-derived systems also lowers the broader environmental chemical burden.

Commercial Viability and Market Positioning

Recent trends favor the market introduction of bioactive, terpenoid-based products in the construction industry. This momentum is driven by the rising global demand for eco-certified or eco-friendly building materials that serve as alternatives to pressure-treated wood (Schiopu and Tiruta-Barna 2012; Yildirim *et al.* 2020). Growth in green building certifications such as LEED, WELL, and BREEAM further accelerates adoption by prioritizing the use of non-toxic materials (Blanchet and Pépin 2021). At the same time, increasing regulatory scrutiny and the gradual phase-out of fossil-derived wood preservatives are creating a favorable policy environment for the commercialization of terpenoid-based systems.

Nevertheless, several challenges remain. Resin yields and chemical profiles can vary significantly across growing seasons and geographic locations, complicating standardization efforts (Broda 2020; Seyfullah *et al.* 2021). In addition, the higher up-front costs of these products, relative to synthetic preservatives, pose barriers to adoption unless economies of scale are achieved (Broda 2020). A further limitation lies in the lack of standardized protocols for field-based efficacy testing of plant-derived wood treatments, which continues to hinder widespread acceptance (De Groot *et al.* 1996; Lebow *et al.* 2004).

Cross-study comparability is further constrained because published evaluations vary widely in wood species, treatment method (surface coating *vs.* impregnation), retention/loading, formulation (neat oils *vs.* blends *vs.* encapsulated systems), conditioning/leaching steps, target organisms, and exposure duration. As a result, strong laboratory bioactivity does not always translate into durable protection under outdoor or ground-contact scenarios. Schultz and Nicholas (2009) showed that laboratory efficacy does not necessarily predict field performance, with substantial variability in decay outcomes even within nominally similar treatment groups. Differences in wood species, treatment methods, preservative formulations, and exposure conditions further contribute to inconsistent outcomes across studies (Lebow *et al.* 2014). These limitations reinforce the need for harmonized reporting protocols (retention, mass-balance loss, leaching/volatility metrics, and standardized performance endpoints) alongside multi-site field validation. Schoknecht *et al.* (2014) specifically recommends standardizing leaching test procedures to improve comparability, and De Vetter *et al.* (2008) emphasize integrating efficacy assessment with environmental-impact considerations to support comprehensive evaluation of wood preservation technologies. Despite these constraints, niche markets such as playground equipment, organic-certified farms, and heritage buildings present promising early entry points for commercialization, where the premium placed on safety, sustainability, and authenticity can offset higher costs and variability.

Policy Alignment and Certification Potential

International and national policy frameworks are increasingly supportive of biobased preservatives. Within the European Union, the Green Deal and REACH regulations encourage the use of non-toxic, biodegradable biocides (Fritz and Garay 2025). In the United States, agencies such as the Environmental Protection Agency (EPA) and United States Department of Agriculture (USDA) provide certification pathways for biobased products through the Safer Choice Program and the BioPreferred Program, respectively (Fritz and Garay 2025). Furthermore, terpenoid-derived protectants may qualify as low-risk biopesticides under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), provided that their toxicological and environmental profiles are sufficiently substantiated.

Regulatory Readiness and Approval Pathways.

The European Union regulates wood preservative formulations through the Biocidal Products Regulation (BPR) (EU) No 528/2012, including Product Type 8 (wood preservatives)**,** with requirements for active-substance approval and product authorization for defined use patterns; the framework also includes labeling and information obligations for treated articles when biocidal claims are made. Regulatory control of biocidal products in Europe also has a longer history of risk-management thinking and harmonization efforts (Kähkönen and Nordström 2008). Earlier work likewise reflects that biocide-related regulatory efforts and evaluation approaches were already active prior to BPR-era consolidation (Rasmussen *et al.* 1999). Ongoing implementation discussions (*e.g.*, "Current uses of nanomaterials in biocidal products and treated articles in the EU") further indicate that practical challenges such as consistent product labeling and communication obligations remain important to address as technologies evolve.

In the United States, wood preservatives are regulated as pesticides under FIFRA, requiring EPA registration supported by data on efficacy, human-health risk, and environmental fate/exposure that reflect realistic treated-wood use scenarios. From an industrial development perspective, substantiating a new wood preservative system for residential exterior applications can require multi-year evidence generation, commonly cited as on the order of 5 to 10 years (Helmer 2008). EPA-oriented performance packages typically emphasize reporting of retention/loading, standardized conditioning (including leaching/weathering where relevant), and durability endpoints to support evaluation of long-term exposure and real-world effectiveness (Jacoby and Freeman 2008). Leaching/ fate considerations have also been emphasized in the treated-wood literature as central to environmental exposure characterization (Lebow *et al.* 2004).

Certification and procurement signals

Beyond regulatory authorization, voluntary labeling and procurement programs can accelerate adoption. For example, the USDA Certified Biobased Product (BioPreferred) label provides third-party verification of biobased content for eligible categories, which may strengthen ESG and sustainable procurement positioning; however, such labels complement rather than replace biocidal/pesticide approval requirements. Devlin *et al.* (2011) further notes that the BioPreferred Program includes federal procurement preference mechanisms intended to increase biobased product uptake. Peuckert and Quitzow (2017) similarly report expert support for product labeling approaches, particularly when combined with environmental performance criteria. Taken together, regulatory authorization and voluntary certification/procurement signals shape the practical adoption landscape for terpenoid-based wood protection systems.

Incorporating these compounds into biobased wood treatments can help manufacturers meet ESG benchmarks, climate reporting mandates, and sustainable procurement criteria while addressing long-standing environmental and health concerns. The environmental and commercial case for terpenoid-based wood protectants is strong, but realizing this potential will require strategic investment, effective regulatory navigation, and robust industrial partnerships to overcome current limitations in standardization and field performance. By aligning with global sustainability goals and responding to the health and safety risks associated with traditional preservatives, these compounds have the potential to define the next generation of high-performance, low-impact wood protection technologies.

FUTURE DIRECTIONS AND RESEARCH GAPS

Despite the growing promise of terpenoids from desert-adapted shrubs, their commercial and scientific potential remains largely untapped. The research frontier now lies in expanding from laboratory-scale insights to field-ready applications, through deeper mechanistic understanding, advanced formulation development, and strategic alignment with regulatory and market ecosystems.

This section outlines the critical research priorities and innovation pathways needed to mainstream terpenoid-based wood protectants and pest management tools.

Most published studies, including Aguma (2024), have demonstrated success under controlled laboratory environments. However, field trials are essential to evaluate the durability of wood treatments and composites under realistic exposure scenarios. Laboratory tests may not reliably predict long-term performance (Alfredsen and Westin 2009; Schultz and Nicholas 2009). Environmental factors such as UV exposure, rainfall, microbial diversity, and termite pressures significantly influence outcomes (Chang *et al.* 2020).

To address these challenges, standardized test protocols, such as modified American Wood-Protection Association AWPA E1**:** *Standard Method for Laboratory Evaluation to Determine Resistance to Subterranean Termites* or ASTM International ASTM D3345: *Standard Test Method for Laboratory Evaluation of Wood for Resistance to Subterranean Termites*, must be adapted for biobased, slow-release systems. These adaptations should account not only for average efficacy ratings but also for the proportion of samples that fall below performance thresholds (Schultz and Nicholas 2009). Furthermore, realistic dose-response data and long-term degradation studies will be critical for regulatory approval and commercial acceptance. Short-term data may not adequately correlate with real-world durability, underscoring the urgent need for longitudinal research in this area (Schultz and Nicholas 2009).

Compatibility with Coatings, Adhesives, and Engineered Wood Manufacturing

Compatibility with downstream manufacturing steps is an important practical constraint for terpenoid-based systems. Hydrophobic extractives and preservative additives can change wood wettability and surface energy, which may affect adhesive bond formation (*e.g.*, shear strength and delamination resistance) and the adhesion/cure behavior of coatings or finishes. Prior work also indicates that wood extractives can influence bonding performance through their effects on surface wetting and interfacial interactions (Taşçıoğlu 2007). Accordingly, future studies should report (i) basic surface/wetting metrics (*e.g*., contact angle or surface free energy), (ii) representative bonding performance (*e.g*., lap-shear strength and delamination cycling), and (iii) coating adhesion and appearance after weathering, alongside biological durability endpoints. Where incompatibilities arise, mitigation strategies include post-treatment conditioning, light planing/sanding, use of compatible primers/coupling agents, and formulation approaches that immobilize terpenoids (*e.g*., encapsulation or polymer-matrix incorporation) to reduce surface migration and maintain bondline/coating integrity (Lu *et al.* 2000). Coupling-agent concepts have long been used to improve compatibility between dissimilar materials, including approaches based on reactive organic chemistries such as isocyanates/ anhydrides/silanes (Kim 1991; Lu *et al.* 2000).

A further sustainability requirement is longevity: a preservative system that performs well initially but loses actives rapidly may increase environmental burdens through more frequent re-treatment or premature replacement. For terpenoid-based systems, long-term performance is most commonly limited by (i) volatilization of lighter components, (ii) leaching during rainfall and wet-dry cycling, and (iii) photochemical degradation under UV exposure. Such processes can reduce field durability even when short-term laboratory bioactivity appears strong. Consistent with this, future studies should pair standardized biological performance testing with reporting of retention/loading and mass-balance losses (volatility and leaching) over time, so that sustainability claims are anchored to demonstrated service-life extension rather than short-term efficacy.

High-Throughput Screening and Compound Synergy Mapping

The terpenoid family is vast and chemically diverse (Zeng *et al.* 2019; Hosseini and Pereira 2023). To harness this diversity effectively, a scalable pipeline is needed that can rapidly screen structurally varied terpenoids for bioactivity against target fungi and insects through AI-assisted bioassays. Cheminformatics and machine learning tools should be applied to correlate molecular structures with performance metrics such as termite repellency, water exclusion, or oxidative resistance. In parallel, mapping synergistic interactions among terpenoids, fatty acids, and other natural compounds will be essential for optimizing low-dose efficacy while simultaneously minimizing toxicity and cost.

Fractionation and Refinement Technologies

Guayule resin, like other natural resins, is chemically complex and variable. To advance its commercial readiness, investment in modular thermal or membrane-based separation systems is needed to improve yield consistency and scale-up viability. At the same time, exploring non-thermal fractionation methods, such as supercritical CO_2 extraction or cryofractionation, may help preserve thermolabile bioactive compounds. In addition, the development of on-site or mobile extraction technologies could enable rural producers to sustainably valorize local shrub biomass, thereby linking resin refinement directly to decentralized production systems.

Sustainable Sourcing and Agronomic Development

Desert shrubs such as guayule and creosote bush are not yet widely cultivated on a global scale. For large-scale deployment of terpenoid-based protectants, it will be essential to develop sustainable agronomic systems that avoid overharvesting and prevent the degradation of fragile desert ecosystems. In this context, it is important to recognize that large-scale wild harvesting of slow-growing desert shrubs, if not managed; could reduce vegetative cover and exacerbate land degradation, potentially accelerating desertification in already fragile environments. Schlesinger *et al.* (1990) showed that long-term resource extraction can increase spatial heterogeneity of soil resources and contribute to soil fertility loss, while Okin *et al.* (2001) emphasized that arid shrublands with wind-erodible soils are highly susceptible to degradation, with aeolian removal and transport contributing to plant mortality and disruption of nutrient accumulation. Kraudzun *et al.* (2014) further notes that although dwarf shrub harvesting can be important for local livelihoods, uncontrolled extraction can pose ecological risks. Therefore, supply strategies should prioritize cultivation and managed agronomic systems, use of byproducts/coproduct streams (rather than whole-plant removal), and governance measures (*e.g.*, harvest limits, restoration/ replanting, and ecological monitoring) to ensure that biomass sourcing improves rural value chains without compromising ecosystem stability. Domestication, selective breeding, and biotechnological enhancement of terpenoid-rich genotypes could further ensure higher and more consistent yields (Lemenih *et al.* 2014). In addition, dual-use strategies, such as combining rubber and resin production or integrating seed oil extraction with bioactive extractives; can significantly improve the economic viability of whole-plant utilization models, thereby aligning ecological sustainability with market competitiveness.

Policy Innovation and Risk Communication

As Fig. 10 indicates, policy innovation and risk communication are enabling pillars that must advance in step with technical priorities. To ease the adoption of terpenoid-based wood protectants, regulatory harmonization is needed to streamline approval pathways for low-toxicity natural compounds used in biocidal applications. At the same time, clear, science-based risk communication can help overcome industry resistance by emphasizing the health and ecological benefits of these alternatives over synthetic preservatives. Supportive public policy, including subsidies for green innovation and bioeconomy tax credits, can further accelerate industrial uptake.

Taken together, and as visualized in Fig. 10, these measures target cross-cutting barriers that sit alongside technical gaps. Future progress requires a transdisciplinary, collaborative approach that brings together natural product chemists, wood scientists, ecologists, and regulatory policymakers (Ngo *et al.* 2013). If the challenges outlined here are addressed, bioactive terpenoids from desert shrubs have the potential to redefine how we preserve, protect, and value wood in the 21st century.

Figure 10 summarizes current challenges spanning multiple domains; standardized efficacy testing, high-throughput screening, fractionation technologies, sustainable sourcing, and policy innovation - highlighting relative progress and priority needs for advancing terpenoid innovation.

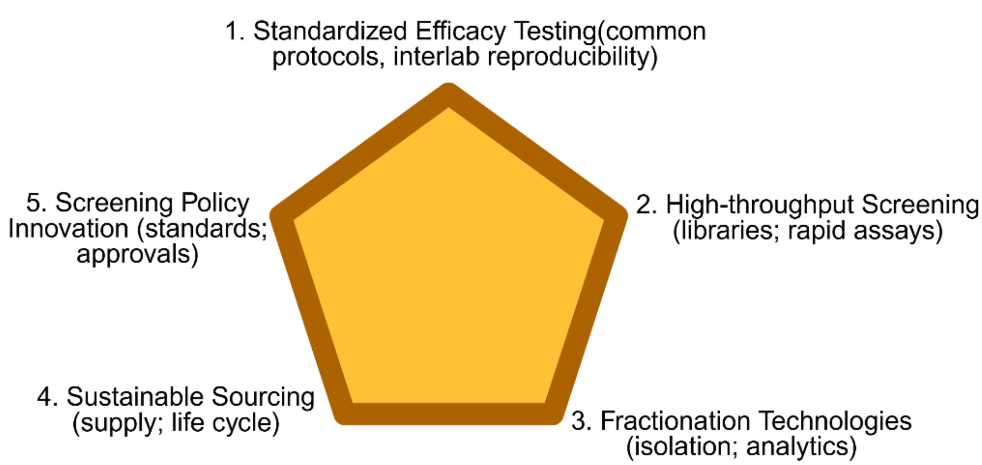


Fig. 10. Radar chart summarizing five priority research gaps in terpenoid-based wood protection**:** (1) standardized efficacy testing, (2) high-throughput screening, (3) fractionation technologies, (4) sustainable sourcing, and (5) policy innovation. Figure adapted from Schultz and Nicholas (2009); Hosseini and Pereira (2023), and Aguma (2024)

CONCLUSIONS

In response to growing environmental scrutiny and the need for sustainable alternatives to synthetic wood preservatives and pesticides, bioactive terpenoids from underutilized desert shrubs represent a compelling frontier. These naturally evolved molecules, which are produced by hardy species such as *Parthenium argentatum*, *Larrea tridentata*, *Jatropha curcas*, and *Euphorbia* spp., combine biological efficacy, ecological resilience, and material compatibility.

This review has shown that terpenoids, spanning mono-, sesqui-, and diterpenoid classes, possess multifunctional properties. These include antifungal, insecticidal, hydrophobic, and UV-stabilizing, that collectively address both biological and physical modes of wood degradation. Resin-based and solvent-free formulations, such as those derived from guayule resin, demonstrate significant potential for safe, scalable protection across diverse environments. Emerging delivery systems, including oil-resin blends, nanoemulsions, and biopolymer matrices, offer versatile pathways for integrating these compounds into industrial wood products. Moreover, the environmental benefits and alignment with circular-bioeconomy principles position terpenoid-based systems as tools for reducing ecological impact while valorizing agricultural and industrial by-products. Specific research priorities emerging from this review include: (i) improving formulation stability and retention by quantifying and mitigating loss pathways (volatility, leaching during wet-dry cycling, and UV-driven degradation); (ii) expanding standardized, field-relevant validation**,** including reporting of retention/loading and mass-balance loss alongside biological durability endpoints; (iii) advancing scalable extraction and fractionation strategies that improve yield consistency while minimizing environmental burden; (iv) optimizing cost-performance trade-offs to support competitive deployment; and (v) verifying compatibility with wood-treatment infrastructure and downstream manufacturing (pressure treatment, coating lines, and engineered-wood bonding/finishing) to accelerate industrial uptake.

Realizing this potential will require bridging current gaps in field validation, standardization, compound refinement, and agronomic scalability. Continued progress depends on interdisciplinary collaboration among chemists, materials scientists, and forestry engineers, supported by enabling policy frameworks. Ultimately, the strategic use of desert-shrub terpenoids signals a paradigm shift in the design and regulation of bio-based materials for structural protection; one capable of generating rural value chains, displacing hazardous chemicals, and aligning wood preservation with global sustainability goals.

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Conflict of Interest

The authors declares that there are no financial or personal relationships that could have inappropriately influenced the work reported in this paper.

Use of Generative AI

No generative artificial intelligence tools were used in the preparation of this manuscript.

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