

Review

Green Extraction and Functional Polymer Applications of Urushiol for Advanced Coatings: Progress and Perspectives

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Abstract

Urushiol, the main active compound in raw lacquer, is a catechol derivative with long alkyl side chains. Its use in traditional coatings has long been held back by slow enzymatic curing, UV sensitivity, and its own allergenicity. Over the past decade, greener ways to extract it have emerged—ultrasound- and microwave-assisted methods, plus vortex-assisted matrix solid-phase dispersion and ball-milling-enhanced microextraction. These approaches have been shown to recover urushiol efficiently, using less solvent and lowering operator risk. The catechol structure explains its many uses: fast-curing UV coatings that resist corrosion, antibacterial materials (both plain and metal-coordinated), super-wetting surfaces for oil–water separation, and selective uptake of heavy metals and rare-earth ions. Early biomedical work also hints at its potential as a bioactive scaffold, drug carrier, or low-toxicity starting point. To balance performance and safety, multiple strategies have been proposed to reduce allergenicity: protecting the hydroxyl groups, modifying specific sites on the ring, and designing synthetic mimics. Still, a few bottlenecks are holding back industrial scale-up. These include large-scale green extraction, long-term material stability, and the lack of solid biocompatibility data. Future work needs to integrate three core research directions: high-throughput structure–activity–toxicity screening, cross-disciplinary molecular design, and life-cycle assessment. The integrated development of these three directions will facilitate the industrial transformation of urushiol-based materials from laboratory prototypes to high-value commercial products. This review summarizes and outlines a roadmap for green extraction, functional polymer applications, and the safe use of urushiol.

Keywords: urushiol; green extraction; polymer-based functional materials; antibacterial coatings; allergenicity mitigation

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1. Introduction

Urushiol is the main active component in raw lacquer. It has been utilized as a durable, high-gloss coating across East Asia for thousands of years. It usually makes up 60–65% of lacquer sap, along with polysaccharides (5%–7%), enzymes (<1%), glycoproteins (2%–5%), and water (20%–30%). Together, these give the material strong adhesion and good film-forming ability [1]. Structurally, urushiol is a catechol derivative with a C15 alkyl side chain that carries 0–3 double bonds. Among them, triene urushiols make up

about 65% of the total [2]. These unsaturated long-chain catechols are prone to rapid oxidation and subsequent polymerization when exposed to air, light, or heat. Polymerization markedly reduces the extraction yield. Urushiol is conventionally regarded as a typical coating material. Its catechol group and hydrophobic side chain render it a versatile chemical platform. Researchers have turned urushiol into antibacterial materials, built functional surfaces with it, and even started looking at it for new biomedical uses [3,4].

Urushiol possesses broad application potential, but using it safely and efficiently is still challenging. Take conventional extraction methods like solvent extraction or column chromatography. Conventional techniques like solvent extraction and column chromatography are solvent-intensive, time-consuming, and associated with considerable operator exposure, in addition to causing environmental damage [4]. On top of that, urushiol is a strong contact allergen. Even a small exposure can cause local or even serious dermatitis, which poses a major obstacle to large-scale operation [4]. Historically, its application was mainly restricted to traditional coatings. These coatings are highly sensitive to temperature and humidity, and they also crack and fade under UV light [5]. Recent studies have further extended these efforts to more specific applications, including UV-curable coatings, antibacterial polymers, superwetting surfaces, ion-selective adsorbents, and early biomedical explorations [6]. However, the relationships between its chemical structure (e.g., the number of double bonds on the side chain and substituents attached to the catechol ring) and its performance as well as allergenicity remain largely unclear. Furthermore, the translation from lab-scale results to real industrial or clinical settings also presents a series of technical challenges, including the reliable scale-up of green extraction methods, how long the materials will last, and whether they can meet strict biocompatibility requirements [7,8].

This review has two main objectives. First, it summarizes recent progress in green extraction methods and polymer-based functional applications of urushiol, with an emphasis on how molecular structure governs material functionality. On the extraction side, we examine the transition from traditional solvent and column techniques to modern assisted methods (ultrasound, microwave) and emerging microextraction strategies such as vortex-assisted MSPD and ball-mill-enhanced vortex extraction, focusing on efficiency, safety, and environmental compatibility [9,10]. Second, it reviews the current state of urushiol-based functional materials—including UV-curable coatings, antibacterial systems, superwetting surfaces, ion-selective adsorbents, and early biomedical studies—and illustrates how structural features enable multifunctional performance. The review also discusses the molecular mechanisms underlying urushiol allergenicity and bioactivity, along with strategies for reducing sensitization while preserving functional properties, and identifies key challenges in scale-up and long-term stability, with the goal of offering a perspective on sustainable, safe, and high-value development of urushiol-based materials [4,11].

2. Green Extraction Methods of Urushiol

2.1. Limitations of Traditional Extraction Methods

Raw lacquer is an important forestry product in China. Urushiol accounts for approximately 60%–65% of lacquer sap. The rest is polysaccharides (5%–7%), laccase (<1%), glycoproteins (2%–5%), and water (20%–30%) [1]. It is necessary to selectively extract and purify urushiol for multiple purposes: acquiring high-purity active components, eliminating impurities, mitigating its allergenicity, and enabling further modification and application. As a chemical compound, urushiol belongs to alkylcatechols, which feature a catechol skeleton and a C15 side chain containing zero to three double bonds. The unsaturated forms make up approximately 95% of total urushiol, and among those, trienes account for 65% [12]. This structure is highly labile. When exposed to air, light, or heat, it

readily oxidizes, which triggers polymerization and the formation of complex oligomers, leading to a marked drop in extraction yield. This chemical instability poses significant challenges to conventional extraction methods.

Conventional techniques usually include mechanical stirring, solvent extraction, and column chromatography. Although these methods can achieve high purity, they are limited by low throughput, excessive solvent consumption, and high occupational exposure risks. A typical study conducted by He et al. adopted methanol to extract urushiol from Maoba lacquer, before storing the extract at low temperature for 24 h to remove gums and waxes. This procedure improves product purity but significantly prolongs the extraction cycle. Subsequently, medium- to low-pressure normal-phase silica gel column chromatography was carried out with a petroleum ether–ethyl acetate elution gradient. This approach increased the purity of C15 triene urushiol to 92.3%, and the total purity of urushiol exceeded 90% [13]. Nevertheless, this exemplifies the trading off of high purity for low efficiency. A 24 h static treatment is required, followed by slow gradient elution at a flow rate of 4 mL/min. Furthermore, partial dimerization of urushiol monomers occurs during separation. Accordingly, partial loss of the target compound takes place. The authors described it as ‘rapid,’ yet the process remains labor-intensive, multi-step and low in throughput.

Such separation difficulties are not unique to China. ElSohly et al. pointed out years ago that urushiol from poison ivy is “highly sensitive to air oxidation and polymerization, and exhibits irreversible binding to conventional chromatographic adsorbents.” This statement illustrates the inherent challenges of urushiol purification [3].

Apart from the trade-off between purity and extraction efficiency, operational safety and solvent use are also key issues. As a potent contact allergen, urushiol exhibits higher sensitization with increasing side-chain unsaturation. Human exposure may cause local erythema, papules, blisters or systemic dermatitis, disrupting regular production. Some long-term workers develop desensitization, whereas others suffer worsening symptoms after repeated contact. Even with full protective measures, occupational risks cannot be fully eliminated, raising safety standards and operational costs (Figure 1) [4].

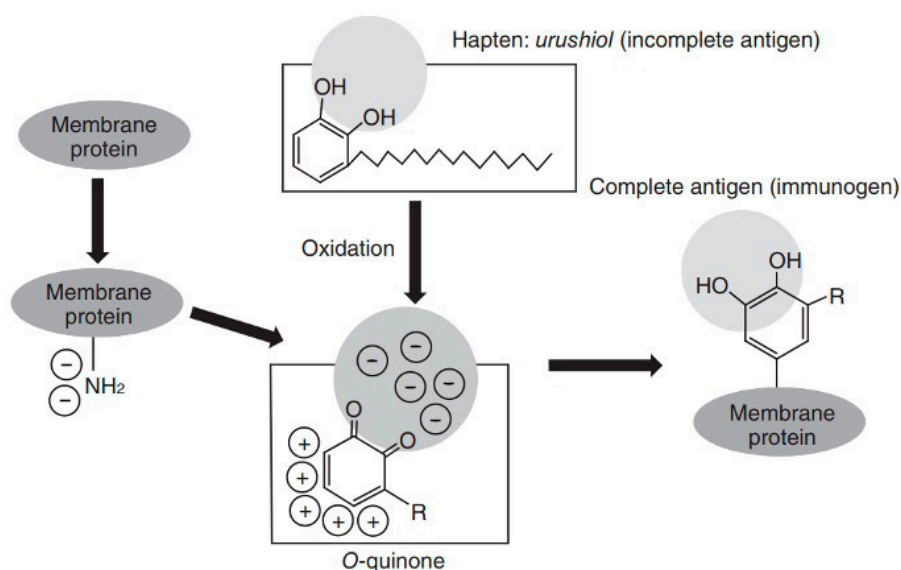


Figure 1. Mechanism of urushiol-induced contact dermatitis [4].

Conventional solvent extraction and column chromatography consume massive amounts of organic solvents. These solvents are volatile and flammable, and pose severe environmental hazards. Large volumes of eluent are consumed during gradient elution,

and solvent recovery remains difficult. While pursuing high-purity urushiol, it is equally important to reduce solvent consumption, mitigate environmental impacts, and ensure operator safety.

2.2. Modern Assisted Extraction Techniques

To address these drawbacks, researchers have introduced physical-field-assisted extraction techniques for urushiol. For this reason, researchers have introduced physical-field-assisted extraction techniques for urushiol. The objective is to maintain satisfactory extraction yields while shortening processing time, reducing solvent dosage and lowering allergen exposure risks for operators. Two mainstream green methods are ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE). Both techniques enhance solvent penetration into plant tissues and facilitate the release of target compounds, relying on cavitation and dielectric heating respectively to improve overall extraction efficiency.

UAE is recognized as an eco-friendly and efficient approach. It combines mechanical, thermal, and cavitation effects to promote mass transfer during extraction. This technology has been increasingly adopted to isolate bioactive constituents from natural products, featuring shorter processing duration, lower energy consumption and reduced organic solvent usage. Shen et al. reviewed the principles, advantages, equipment and combined applications of UAE, and verified its capability to achieve high efficiency with limited solvent consumption [9]. Xia et al. conducted single-factor experiments to explore the influences of extraction cycle, duration, temperature and solid–liquid ratio on the yield of diene urushiol using lacquer tree leaves as raw materials. Three key parameters were further optimized via Box–Behnken response surface methodology. The results indicated that extraction temperature exerted the most significant effect, followed by solid–liquid ratio and extraction time. A significant interaction was observed between extraction time and temperature ($p < 0.01$). The quadratic regression model showed good fitting performance ($R^2 = 0.9876$). The optimal conditions were three extraction cycles, 55 min per cycle and an extraction temperature of 50 °C with a solid–liquid ratio of 10:1 mL/g. Under these conditions, the practical yield of diene urushiol reached 4.56 mg/g fresh weight, which was close to the predicted value of 4.69 mg/g (RSD = 2.26%) [14]. Table 1 summarizes the single-factor ranges and response surface optimization results.

Table 1. Single-factor experimental ranges and response surface optimization results for ultrasound-assisted extraction of diene urushiol from lacquer tree leaves.

Factor	Single-Factor Range	Response Surface Optimization Levels	Optimal Condition
Extraction time (min)	15, 30, 60, 90, 120	30, 60, 90	55
Solvent-to-material ratio (mL/g)	3:1, 5:1, 10:1, 15:1	5:1, 10:1, 15:1	10:1
Extraction temperature (°C)	30, 40, 50, 60	40, 50, 60	50
Number of extractions	1, 2, 3, 4	— (discrete variable, not included in RSM)	3

Microwave-assisted extraction (MAE) enables microwaves to penetrate plant cell walls and interact with intracellular water and polar molecules. This process induces dipole rotation and ionic conduction, leading to a rapid rise in intracellular temperature and pressure. When the internal pressure exceeds the mechanical strength of cell walls, cells rupture and bioactive compounds are released into the solvent [15]. Compared with con-

ventional reflux extraction, MAE provides more uniform heating, shorter extraction time, lower solvent consumption and higher product yields.

MAE has been widely applied for the efficient recovery of phenolic compounds. Wong et al. systematically reviewed relevant studies and confirmed that MAE can acquire high yields within a short period while reducing solvent consumption, which conforms to the principles of green chemistry [16]. Laina et al. proved that the integrated ultrasound–microwave extraction performs well for four medicinal plants: oregano, rosemary, Hypericum and chamomile. The research team optimized microwave power, ultrasound intensity, and extraction time. Under optimal parameters, the total phenolic content increased remarkably. For Hypericum, as an example, the total phenolic content reached 53.7 mg GAE/g at a microwave power of 200 W. This finding fully demonstrates the high efficiency of MAE in extracting phenolic substances [17].

It should be noted, however, that these assisted extraction techniques are not without drawbacks. Both ultrasound and microwave irradiation can generate significant localized heating during operation. Given that urushiol is inherently prone to oxidation and polymerization upon heating (as discussed in Section 2.1), such temperature elevation may inadvertently trigger premature oligomerization of urushiol monomers, thereby reducing extraction yield and complicating subsequent purification. This is precisely why temperature control is critical in these assisted extraction processes—a factor that has been systematically optimized in response surface studies to balance extraction efficiency and thermal degradation.

A comparative analysis shows that MAE and UAE deliver 32%–36% higher extraction efficiency and approximately 15-fold lower energy consumption, along with better extract quality than conventional Soxhlet and reflux extraction. Nevertheless, dedicated studies on MAE for urushiol extraction are still scarce. Considering its excellent performance in extracting other phenolic substances as well as the structural characteristics of urushiol, MAE is regarded as a promising technology for the green and efficient extraction of urushiol.

2.3. Novel Microextraction Techniques: A Paradigm Shift

Although ultrasound- and microwave-assisted extraction improves efficiency and speed, they still consume large quantities of organic solvents and cannot fully isolate operators from urushiol. Consequently, allergen risks and environmental pressures persist, which drives the development of novel microextraction techniques. These methods use minimal samples and solvents, feature simple operation and high safety, marking a notable shift from traditional bulk extraction to rapid low-risk microanalysis.

It should be emphasized, however, that these microextraction techniques are primarily designed for analytical-scale applications rather than industrial-scale production. When scaled up to larger volumes, the solvent-to-sample ratio inevitably approaches that of conventional extraction methods, and the absolute amounts of material obtained remain too small for bulk manufacturing or commercial coating applications. Their true value lies in rapid screening, trace analysis, and high-throughput sample preparation for quality control and research purposes.

As a promising alternative, vortex-assisted matrix solid-phase dispersion (MSPD) microextraction overcomes the shortcomings of conventional and assisted extraction in sample dosage, solvent use and allergen exposure. Derived from standard MSPD, it integrates homogenization, cell disruption, and extraction into one step to simplify workflows. Zgola-Grześkowiak et al. reviewed the progress of MSPD for plant and food samples, confirming the superior performance of its vortex-, ultrasound- and magnetic-adsorbent-assisted modes (Figure 2) [18].

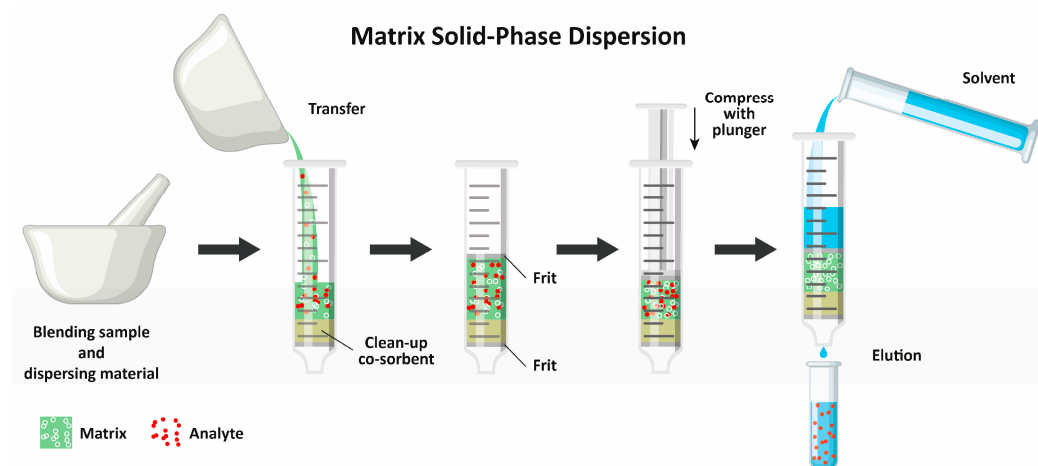


Figure 2. Scheme of the MSPD procedure [18].

In this integrated approach, magnetic or magnetizable materials are mixed directly with the sample matrix as dispersing adsorbents. Vortex agitation ensures rapid and uniform contact between the adsorbent and the target analytes. After the target compounds become attached to the magnetic adsorbent, an external magnet separates them from the solution, and then a small number of solvent washes them off. Conventional solid-phase extraction requires packing a column and going through multiple loading and elution steps, which is time-consuming. The new method greatly shortens sample pretreatment and is well suited for trace analysis. For urushiol, Chen et al. developed a vortex-blending MSPD method combined with UPLC-Q-TOF/MS to extract and analyze urushiols from *Toxicodendron vernicifluum* bark [19].

The researchers synthesized the Fe_3O_4 -modified ZSM-5 molecular sieve (ZSM-5/ Fe_3O_4) via in situ coprecipitation as the magnetic adsorbent. Scanning electron microscopy, X-ray diffraction, and infrared spectroscopy were adopted to characterize its morphology and structure. A comparative test among five adsorbents (Florisil, ZSM-5/ Fe_3O_4 , acid-treated alumina, C18 and C8) demonstrated that ZSM-5/ Fe_3O_4 possessed the highest extraction efficiency for four urushiol homologs. This method is simple, sensitive, and reproducible, offering a reliable tool for trace analysis of urushiol and for safer extraction of highly allergenic natural products.

Ball milling coupled with vortex agitation offers another green microextraction option. In this approach, a small quantity of sample, dispersant, and grinding balls are placed inside a sealed centrifuge tube. High-frequency ball milling rapidly pulverizes and mixes the contents. After that, a small volume of solvent is added for vortex-assisted elution, and the extract is obtained by centrifugation. Automating the grinding step with ball milling allows precise control of operational parameters. Meanwhile, the sealed system considerably reduces the operator's contact with highly sensitizing samples. Yan et al. developed a ball mill-assisted vortex-enhanced matrix solid-phase dispersion (BM-VEMSPD) method combined with high-performance liquid chromatography to determine five phenolic compounds in *Rubi Fructus* [20].

The optimized conditions were as follows: Al-SBA-15 served as the dispersant, the sample-to-dispersant ratio was 1:3, ball milling was performed for 2 min at 1300 rpm, elution used 1.4 mL of methanol, and vortex extraction lasted 3 min. Method validation gave excellent linearity ($r^2 > 0.999$), recoveries between 98.7% and 102%, and detection limits of 0.02–0.19 $\mu\text{g/mL}$. In comparison with conventional reflux extraction (1 h, 50 mL solvent) and ultrasound extraction (30 min, 50 mL solvent), the present method consumed only 20 mg of sample and 1.4 mL of solvent, with a total extraction time of about 5 min. These figures indicate noticeably higher efficiency and a greener profile [20]. This concept is con-

sistent with the strategy reported by Chen et al. for urushiol extraction from lacquer bark using vortex-assisted MSPD with magnetic adsorbents. That method required only 0.1 g of sample and 4 mL of solvent, with a total extraction time of 10.5 min and detection limits of 0.20–0.50 µg/mL [19]. Together, these two approaches demonstrate that green microextraction techniques are well suited for the analysis of allergenic natural products such as urushiol.

2.4. Comparative Evaluation and Selection Strategies of Extraction Methods

The previous sections have covered the features of conventional solvent extraction, modern assisted extraction techniques, and novel microextraction methods. In practice, however, choosing an extraction method should not be based on a single performance indicator alone. Rather, it requires balancing several factors: the physicochemical properties of the target compound, the intended application, and the multiple criteria of green chemistry. No single extraction technique works for all cases; each comes with its own strengths and limitations. As summarized in Table 2, Cao et al. compared different extraction technologies across multiple dimensions [10].

Table 2. Comparative evaluation of different urushiol extraction methods.

Comparison Dimension	Conventional Solvent Extraction and Column Chromatography	Ultrasound-Assisted Extraction	Vortex-Assisted MSPD	Ball-Milling-Coupled Vortex Extraction
Sample Amount	5–10 g	1 g	0.1 g	0.02 g
Solvent Consumption	Tens to hundreds mL	Tens mL	4 mL	1.4 mL
Extraction Time	24 h standing + several hours	55 min	10.5 min	~5 min
Purity/Yield	Purity > 90%	4.56 mg/g	0.20–0.50 µg/mL	98.7%–102% recovery
Allergenicity Risk	High	Medium	Low	Low
Application Scenario	High-purity preparation	Rapid extraction	Trace analysis	Trace analysis

When comparing extraction efficiency and purity, conventional column chromatography can reach a purity above 90%, but the process may take anywhere from several hours to days. Ultrasound-assisted extraction takes about 55 min, while vortex-assisted matrix solid-phase dispersion microextraction finishes in just 10.5 min. That makes the latter a perfect fit for rapid trace analysis. On the safety side, traditional methods often handle toxic solvents like n-hexane and acetone out in the open, posing significant toxicity and environmental hazards; operators are also directly exposed to urushiol, which carries a high allergy risk. Green microextraction techniques, on the other hand, use sealed centrifuge tubes and low-toxicity solvents that substantially reduce operator exposure. When it comes to sample and solvent use, conventional methods need grams of sample and tens to hundreds of milliliters of solvent. Microextraction methods need only 0.02–0.1 g of sample and 1.4–4 mL of solvent. Therefore, they offer higher efficiency and better environmental compatibility for analytical-scale applications, though their utility for industrial-scale preparation remains limited.

3. Polymer-Based Functional Applications

3.1. Performance Enhancement of Traditional Lacquer Coatings

Raw lacquer is often referred to as the “king of coatings”, and its excellent film-forming capacity is derived from urushiol. The catechol structure endows the material with strong adhesion and chemical stability, while the long unsaturated side chains impart flexibility and weather resistance. Triene urushiol provides more crosslinking sites and higher hardness, whereas monoene and saturated forms yield softer films. It should be noted that while this section is titled “polymer-based functional applications,” the discussion also covers the direct use of parent urushiol in its native form, as metal complexes, or as salts—as these materials often serve as precursors, functional additives, or composite components within polymer-based systems. Nevertheless, natural lacquer faces two major drawbacks in practical applications. First, its curing process is catalyzed by laccase and highly dependent on temperature and humidity. The drying procedure takes hours or even days under 20–30 °C and 70%–90% relative humidity, which greatly restricts industrial production efficiency [21]. Second, conventional lacquer films are prone to discoloration and cracking under UV radiation, limiting their application in outdoor scenarios and high-transparency fields. To solve these defects, two major strategies have been proposed to modify traditional urushiol-based coatings.

The first approach replaces the laccase-catalyzed curing system with UV-curing technology to shorten reaction time and reduce environmental restrictions. The second one improves thermal stability, transparency and mechanical properties via chemical blending, nanocomposite modification and organic–inorganic hybridization.

UV-curable urushiol-based polyurethane coatings are a major breakthrough in this field. Wu et al. first synthesized urushiol epoxy resin (UE) through the reaction between urushiol phenolic hydroxyl groups and bisphenol A epoxy resin. The product was further esterified with methacrylic anhydride to prepare urushiol epoxy acrylate (UEA), a photopolymer with terminal double bonds. To prevent the migration of small-molecule photoinitiators and maintain coating appearance, cellulose nanofibers were adopted as carriers. Photoinitiator 2959 was grafted onto nanofibers via toluene-2,4-diisocyanate (TDI) bridges to fabricate modified cellulose nanofiber photoinitiators (MCNFI), which acted as both photoinitiators and nano-reinforcements. Under 365 nm UV irradiation, the MCNFI/UEA composite coating gelled within 60 s with a curing rate of 82%. The composite achieved optimal corrosion resistance and mechanical performance at an MCNFI dosage of 8 wt% [6]. Shin et al. subsequently developed a self-initiating UV-curable system based on urushiol and lignin. In this system, urushiol phenolic groups generate free radicals under UV light and trigger crosslinking of side-chain olefins and aromatic rings to form C–O–C ether and carbonyl bonds. Although lignin slightly reduces the curing efficiency due to UV absorption, it participates in crosslinking reactions and improves the material’s hydrophobicity (water contact angle: 112.5°), tensile strength (42.53 MPa) and thermal stability (decomposition temperature: 438 °C) [22].

Natural lacquer films have their strengths, but they clearly fall short in thermal stability, transparency, and mechanical performance. Their thermal decomposition temperature exceeds 300 °C. Nevertheless, prolonged exposure to high temperatures will cause oxidation, discoloration, and embrittlement. Poor transparency is another drawback. Abundant quinones and oxidation products endow the films with a dark brown to black appearance, which limits their application in high-transparency and light-colored coatings. In terms of mechanical properties, the films possess high hardness (4H–6H), strong adhesion (>9 MPa), and excellent wear resistance, but relatively low flexibility and impact resistance. They are prone to cracking under large deformation or external impact [23].

To overcome these limitations, multiple modification strategies have been developed. One is the incorporation of nano-inorganic fillers such as SiO₂, TiO₂, and Mg(OH)₂. Another method is copolymerization with heat-resistant polymers, including polyurethane and organosilicon resins. These approaches increase the decomposition temperature and the residue at high temperatures. For instance, dispersing nano-SiO₂ in urushiol-formaldehyde polymers reduced gloss loss from 52% to 23% after 1000 h of UV aging. Transparency can be improved through chemical modification of the urushiol catechol groups or by blending with transparent resins. Nevertheless, achieving fully transparent films remains difficult because urushiol is prone to oxidation and color formation. Mechanical properties are enhanced by copolymerizing urushiol with flexible polymers like polyurethane or polyamide-amine, or by adding nanomaterials such as carbon nanotubes and graphene. These methods simultaneously increase hardness, adhesion, and impact resistance. Hou et al. showed that repeated Kurome treatment (hydration–dehydration mechanical stirring) could shorten the curing time from 74 h to 3.6 h while preserving high gloss (~90 GU), strong adhesion (9.58–9.75 MPa), and wear resistance. The trade-off is a darker color and reduced transparency [24]. Taken together, these studies underline the trade-offs among thermal, optical, and mechanical properties, and indicate that modification strategies should be chosen according to the specific application requirements.

3.2. Development of High-Efficiency Antibacterial Materials

Urushiol is not only a good coating material but also has intrinsic antibacterial activity. This activity comes from its catechol structure, which allows it to fight a wide range of harmful microbes by disrupting their membranes and causing oxidative stress. The long C15–C17 hydrophobic side chains can insert into bacterial phospholipid bilayers, disturbing membrane integrity, increasing permeability, and causing leakage of intracellular contents, which leads to bacterial death. At the same time, the catechol groups undergo redox cycling and generate reactive oxygen species (ROS). These ROS damage bacterial DNA, proteins, and lipids. The two mechanisms reinforce each other. ROS production first weakens the membrane, and the weakened membrane then allows more ROS to escape, creating a self-amplifying loop often described as “ROS burst → membrane damage → ROS leakage” (Figure 3) [25,26]. In addition, hydrogen bonding interactions with key bacterial metabolic enzymes contribute to a multi-target antibacterial effect. Some urushiol derivatives have shown >99% inhibition against both Gram-positive and Gram-negative bacteria, in some cases even exceeding traditional agents such as silver ions and quaternary ammonium salts [27].

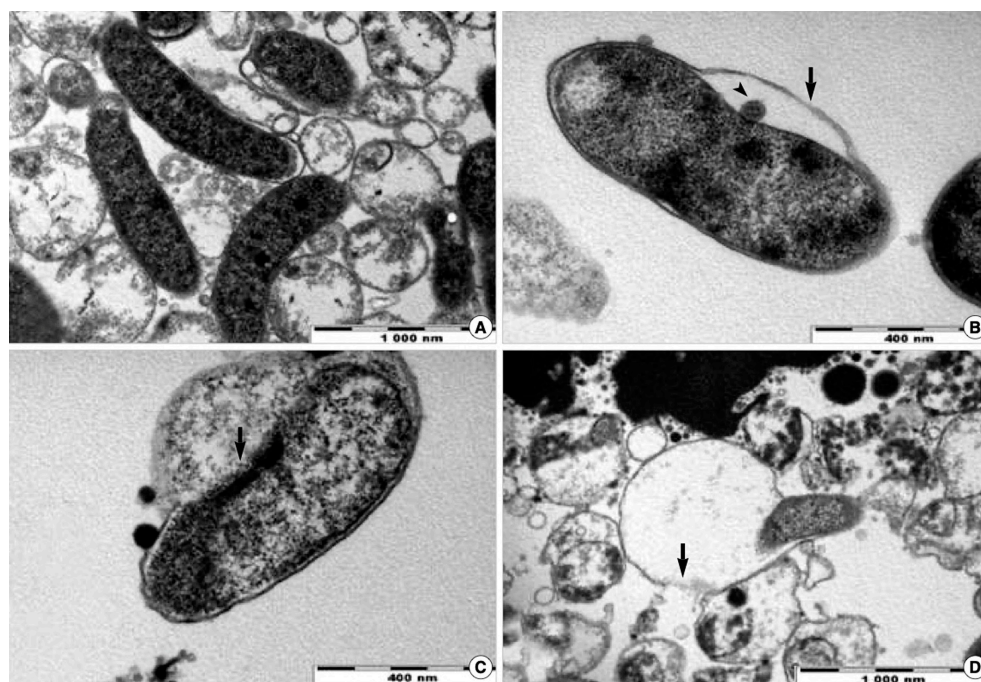


Figure 3. Transmission electron microscopy images showing the time-dependent morphological changes in *Helicobacter pylori* upon exposure to 1× minimal inhibitory concentration of urushiol. (A) Untreated cells with intact morphology; (B) after 3 min, showing cell wall separation and cytoplasmic leakage; (C) after 6 min, showing pronounced membrane disruption; (D) after 10 min, showing complete cell lysis [28].

Urushiol's catechol group can also bind to metal ions such as Ag^+ and Cu^{2+} , creating antibacterial systems in which both components work together. Acting as a bidentate ligand, urushiol forms stable five-membered chelate rings with transition metals. This coordination achieves two things at once: controlled release of metal ions, and a combination of urushiol's own membrane-disrupting ability with the metal's antibacterial effect. Take Wang et al.'s work as an example. They developed urushiol-based polybenzoxazine/AgNPs coatings. In that study, the phenolic hydroxyls of urushiol reduced Ag^+ to silver nanoparticles in situ without any external reducing agent. They obtained effective inhibition of bacteria and marine microalgae at AgNP loadings as low as ≤ 1 wt% [25]. Similarly, Chen et al. synthesized urushiol-based benzoxazine copper polymers (UBCP) via Mannich reactions followed by Cu^{2+} coordination. The resulting coatings had low surface energy, strong substrate adhesion, and controllable Cu^{2+} release. They achieved near-100% antibacterial activity and >99% anti-algal efficacy [29].

Urushiol can also be incorporated into polymer frameworks through covalent bonds or coordination, yielding antibacterial materials that are stable, low in toxicity, and easy to process. Jeon et al. introduced urushiol as a polyol component into aqueous polyurethane–urea dispersions. Increasing the urushiol content improved both thermal stability and antibacterial activity; at 22.2 wt% urushiol, the material showed strong inhibition against *E. coli* and *S. aureus* [30]. Jeong et al. reacted urushiol with silane coupling agents to obtain solid urushiol powders (YPUOH) powders, which retained antibacterial function even after high-temperature processing, making them suitable as masterbatches for food packaging or coatings [27]. More advanced molecular designs take advantage of urushiol's catechol structure to construct functional polymers. Chen et al. prepared UBCP via Mannich reaction, forming low-surface-energy networks that achieved nearly complete inhibition against the two tested bacteria and also exhibited excellent marine antifouling properties [29]. Bai et al. designed Fe_3O_4 @urushiol–Fe core–shell nanoparticles capable of rapid photothermal sterilization under near-infrared irradiation, with effectiveness main-

tained over multiple cycles [30,31]. Taken together, these studies show a progression from single-function antibacterial materials toward multifunctional urushiol-based polymers that integrate covalent incorporation, metal coordination, and photothermal nanocomposite strategies.

3.3. Construction of Functional Surface Materials

Efficient oil–water separation and environmentally friendly materials are increasingly required in industrial applications, thereby driving extensive research on surfaces with special wettability. In the context of this review, “superwetting” refers specifically to superhydrophobic–superoleophilic surfaces that are water-repellent while being oil-adhesive—a combination that is particularly effective for oil–water separation. Urushiol is well suited for this field due to its unique molecular structure. The combination of catechol groups and long alkyl side chains endows urushiol with inherent hydrophobic characteristics. Its reactive hydroxyl groups and alkyl chains can covalently or coordinately interact with amines, metal ions and other modifiers, allowing the construction of coatings with controllable micro- and nanoscale roughness. The integration of structural features and multifunctional reactivity enables urushiol-based coatings to achieve superhydrophobic–superoleophilic or underwater superoleophobic properties, exhibiting promising potential for oil–water separation and self-cleaning applications [32–35].

Urushiol@TiO₂ coatings possess excellent superhydrophobicity and high separation efficiency, and maintain stable performance under strongly acidic and alkaline environments [34]. To date, urushiol-based superwetting coatings have been successfully fabricated on various substrates. Fang et al. modified melamine sponges through the thermal self-polymerization of urushiol, obtaining a water contact angle of approximately 139°. The modified sponges exhibited an oil adsorption capacity of 181 g/g and a separation flux of 18,356 L·m⁻²·h⁻¹·bar⁻¹ [32]. Zeng et al. constructed coral-like micro-/nano-structured coatings via one-step copolymerization of urushiol and 1,6-hexanediamine, achieving a water contact angle of 145° and stable superhydrophobicity across a wide pH range [33]. Bai et al. prepared urushiol@TiO₂-coated cotton fabrics with a contact angle of 146.1 ± 0.3°, which remained stable under extreme acid and alkali conditions [34]. Zhu et al. anchored SiO₂ particles on stainless steel meshes using urushiol-based benzoxazine, achieving over 96% separation efficiency for oil–water mixtures and 99.7% efficiency for oil-in-water emulsions [35]. Beyond superwetting surfaces, urushiol catechol groups can act as bidentate ligands for metal chelation, enabling selective ion adsorption. For example, Shi et al. synthesized urushiol–oxime functional polymers (UOXP) for heavy metal removal. The materials displayed adsorption capacities of 42.6, 87.3, 110, 25.3, and 92.8 mg/g toward Fe³⁺, Pb²⁺, Cd²⁺, Hg²⁺, and Cu²⁺, respectively, while retaining thermal stability below 180 °C [36]. Electrospun chitosan–urushiol composite membranes (CS-U) remove Cr(VI) from wastewater through combined electrostatic and redox effects, allowing the recovery of high-purity Cr₂O₃ (Figure 4) [37]. Overall, urushiol acts as a versatile and green functional platform. It endows materials with tunable superwetting behaviors for oil–water separation and selective metal chelating ability for wastewater treatment, without complicated chemical modification procedures.

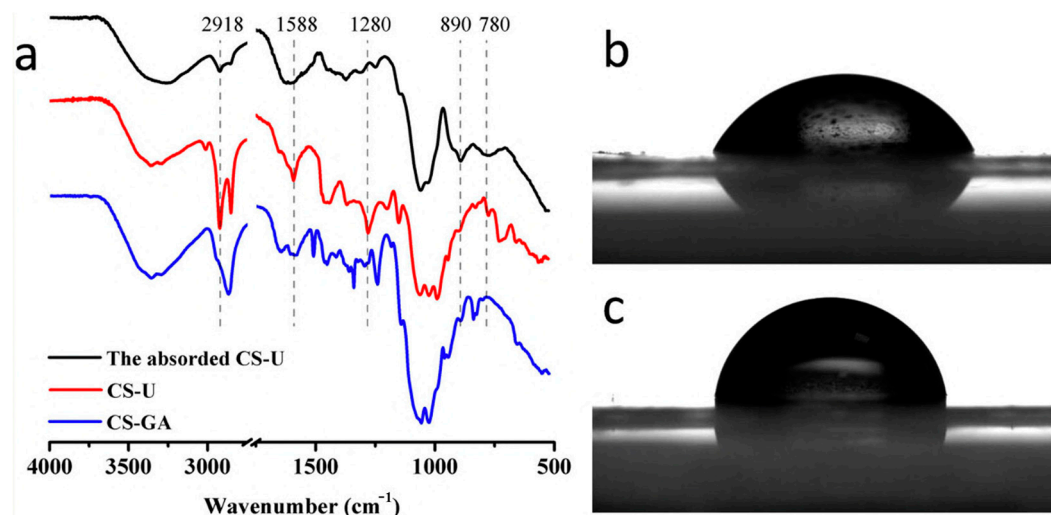


Figure 4. (a) FT-IR spectra of the chitosan–glutaraldehyde (CS-GA), chitosan–urushiol (CS-U), and adsorbed CS-U membranes (b,c) water contact angles of the CS-GA and the CS-U nanofiber membranes, respectively [37].

3.4. Preliminary Exploration in Biomedical Applications

Urushiol and its derivatives feature a distinctive catechol structure and amphiphilic properties, which have prompted a number of *in vitro* investigations into their biomedical potential. It should be noted, however, that most of the available evidence is derived from laboratory-scale studies. Current studies mainly focus on two aspects. The first explores the inherent bioactivities of urushiol, including antiviral activity such as anti-HIV performance and antitumor effects, as assessed in cell-based assays. The second takes advantage of its biocompatibility and reactive hydroxyl groups to develop drug delivery systems and tissue engineering scaffolds at the prototype level [38–42]. These functions are fundamentally attributed to the catechol backbone and long alkyl side chains. In an *in vitro* enzyme inhibition assay, Kadokura et al. isolated four urushiol compounds, including two newly identified substances, from lacquer tree leaves. Among them, compound 2, a dihydrobenzofuran-type analog, exhibited strong inhibitory activity against HIV-1 reverse transcriptase, with an IC_{50} value of 12.6 μ M. Its potency was approximately 2.5 times higher than that of doxorubicin (IC_{50} = 31.9 μ M) [38]. In *in vitro* cytotoxicity screening, Hong et al. evaluated four urushiol compounds from raw lacquer sap against 29 human cancer cell lines covering prostate, brain, kidney, lung and leukemia. All samples presented GI_{50} values lower than 4 μ g/mL [39]. Lee et al. further investigated the underlying mechanism and confirmed that urushiol induces apoptosis in MCF-7 breast cancer cells by downregulating the anti-apoptotic protein Bcl-2 and cleaving PARP. Modification of the aromatic side chain can improve compound stability and antitumor activity, suggesting potential directions for further structural optimization [26].

Apart from direct pharmacological effects, the catechol groups and amphiphilicity of urushiol also make it suitable for fabricating drug carriers and bioactive scaffolds. Zhuang et al. synthesized recyclable magnetic nanocarriers (DU@Fe, average diameter: 281.6 nm) using urushiol and dextran. The carriers achieved rapid and selective delivery of vancomycin, and retained over 85% antibacterial activity after six reuse cycles, demonstrating the feasibility of this approach in *in vitro* settings [40]. Qi et al. prepared pH-responsive nanomicelles (BPAU-NH₂-Gal) based on triene urushiol boronic acid amine derivatives. The micelles released more drugs at pH 4.5 than at pH 7.4, showed enhanced cellular uptake by HepG2 cells, and exerted low cytotoxicity on normal LO2 hepatocytes [41]. To restrain oxidative polymerization of urushiol, electrospinning with polyvinyl alcohol and polyvinylpyrrolidone was adopted to realize controlled drug release and reduce aller-

genicity. Xue et al. fabricated $\text{Fe}_3\text{O}_4@\text{PUs}$ magnetic molecularly imprinted polymers. The urushiol layer served as high-affinity binding sites for vancomycin, with an equilibrium adsorption capacity of 49.4 mg/g. The materials removed more than 60% of vancomycin in complex aqueous samples, proving their applicability for targeted drug separation and controlled release [42]. Overall, urushiol is a promising multifunctional bioactive scaffold and raw material for drug delivery. It integrates intrinsic pharmacological activity and material design, expanding the application scope in the biomedical field.

Overall, the studies summarized above are predominantly *in vitro* investigations using cell lines or purified enzymes. While these findings are encouraging and provide a useful chemical foundation, they should be viewed as preliminary proof-of-concept results. Further evaluation of *in vivo* efficacy and safety would be necessary before any therapeutic translation could be considered.

4. Mechanisms and Mitigation Strategies for Urushiol Allergenicity: Structure–Activity Relationships

The above sections systematically summarize green extraction technologies and diversified applications of urushiol. Extraction approaches have evolved from traditional solvent extraction and column chromatography, which suffer from low efficiency and heavy environmental impact, to emerging auxiliary methods, including ultrasound-assisted extraction, microwave-assisted extraction, vortex-assisted matrix solid-phase dispersion and ball-milling-coupled vortex microextraction. In terms of application, urushiol is no longer confined to conventional coating materials, and has been developed for antibacterial products, functional surfaces, and preliminary biomedical research. Its unique catechol structure endows the molecule with excellent adhesion, coordination capacity and bioactivity.

Nevertheless, the strong allergenicity of urushiol remains a major obstacle to its safe and large-scale utilization. It not only threatens the health of operators, but also restricts the application of urushiol in biomedical and other high-safety scenarios. Accordingly, the core research target is to reduce allergenicity while preserving its original performance. Against this background, this section first elaborates the molecular mechanisms of urushiol-induced allergic reactions, followed by a review of chemical modification strategies for allergenicity mitigation. Finally, prospects for future research are proposed, covering high-throughput structure–activity screening, interdisciplinary research, and life-cycle assessment.

4.1. Molecular Mechanisms of Urushiol Allergenicity

Urushiol is the main active component in raw lacquer and a strong allergen, though it does not act directly. Instead, it follows the classic hapten pathway. Once it enters the skin, enzymatic or oxidative conversion turns it into reactive quinone intermediates. These intermediates then bind to nucleophilic groups—such as amino or thiol groups—on keratin proteins, forming complete antigens that trigger an immune response. Langerhans cells take up these antigens and present them to naïve T cells in the lymph nodes, which then differentiate into effector T cells. Upon later exposure, those effector T cells provoke a type IV hypersensitivity reaction, causing symptoms like redness, itching, and blisters [26].

Other studies have found that side-chain unsaturation also matters. More double bonds increase the electron density of the catechol ring, facilitating its oxidation to reactive o-quinone and enhancing covalent binding to skin proteins—which directly amplifies the immune response [4].

In summary, urushiol sensitization involves two key steps: oxidation of the catechol ring to an o-quinone, followed by covalent attachment to skin proteins. These same steps offer clear targets for designing approaches to reduce allergenic risk.

4.2. Strategies for Reducing Allergenicity via Molecular Design and Modification

Based on the structure–function relationships summarized in Table 3, researchers have developed three main strategies to reduce urushiol’s allergenicity while preserving its functional properties: hydroxyl protection, site blocking at the C5 and C6 positions of the catechol ring, and full synthesis of low-allergen urushiol analogs.

Table 3. Summary of structural features of urushiol and their contributions to functionality and allergenicity.

Structural Feature	Key Property/Function	Representative Application
Catechol core	Strong adhesion, metal chelation, redox activity, ROS generation for antibacterial effects	Traditional coatings, metal-phenolic networks, antibacterial materials
Unsaturated C15–C17 side chain	Flexibility, hydrophobicity, membrane disruption—also enhances allergenicity (more double bonds, stronger sensitization)	Traditional coatings, super-wetting surfaces, antibacterial membranes
Hydroxyl protection (methylation/methoxylation)	Reduces allergenicity by blocking oxidation to quinones; retains anti-oxidant activity	Low-allergen urushiol derivatives
C5/C6 site modification	Reduces allergenicity by preventing nucleophilic attack by skin proteins; can induce immune tolerance	Low-allergen urushiol analogs
Complete methylation of hydroxyl groups	Eliminates allergenicity while preserving antioxidant function (detoxification without functional loss)	Safe urushiol-based materials for biomedical use
Catechol + long side chain (synergy)	Amphiphilicity, enabling multi-functional applications across coatings, antibacterials, and drug delivery	UV-curable coatings, antibacterial polymers, drug delivery systems, oil–water separation

Hydroxyl protection relies on methylation or methoxylation to block the conversion of phenolic hydroxyls into reactive quinones. He et al. modified catechol hydroxyls into stable methylene ethers, which reduced sensitization while preserving the majority of the native molecular structure [13]. Kim et al. further demonstrated that complete methylation could eliminate allergenicity while retaining antioxidant performance, achieving effective detoxification without functional loss [43].

Blocking the C5 and C6 reactive sites provides another feasible route. These two sites are susceptible to nucleophilic attack and dominate covalent binding with skin proteins. Early studies by Liberato confirmed that amino and thiol nucleophiles preferentially target these positions. Accordingly, structural modification of the electronic or steric environment at C5/C6 can effectively inhibit protein conjugation [44]. Based on this principle, Dunn et al. synthesized 5,6-dimethyl-3-pentadecylcatechol, which exhibited significantly reduced sensitization and even induced immune tolerance [45].

A more fundamental strategy is the rational design and total synthesis of low-allergen urushiol analogs. The systematic preparation of alkylated catechols and diaryl ether

derivatives (CTUDs) indicates that side-chain length strongly regulates allergenicity. Both excessively short and long alkyl chains suppress sensitization, whereas the catechol core is essential for maintaining antioxidant activity [43]. Total synthetic routes, such as the 6-chlorohexan-1-ol-based method reported by Tyman, enable precise fabrication of urushiol analogs with tunable side-chain structures [46]. In addition, conjugation of urushiol with N-acetylcysteine yields water-soluble, low-allergen derivatives capable of inducing immune tolerance, transforming urushiol from a sensitizer into a potential therapeutic candidate [47]. Physical treatments such as ionization also achieve effective allergenicity reduction in animal models. Collectively, these chemical, synthetic, and physical strategies provide versatile tools for developing safe urushiol-based materials for industrial, biomedical and consumer applications.

5. Technical Challenges and Prospects for Industrial Translation

5.1. Technical Challenges

Current molecular modification strategies can effectively reduce urushiol allergenicity while retaining its core functional properties. Nevertheless, two key bottlenecks still restrict the large-scale application of urushiol-derived materials: the insufficient scalability of laboratory extraction techniques, and the lack of systematic evidence supporting long-term material stability and biological safety. Green microextraction approaches, including ultrasound-assisted extraction, vortex-based matrix solid-phase dispersion, and ball-milling-assisted vortex microextraction, have demonstrated high efficiency and environmental friendliness under laboratory conditions. However, their stable performance and feasibility in industrial-scale production remain to be further validated.

For ultrasonic extraction, uneven cavitation energy distribution severely limits scale-up potential. Although flow-cell reactors provide feasible optimization directions, most available studies remain confined to laboratory exploration. The absence of systematic scale-up parameters restricts the batch stability and reproducibility of extraction results [7,48]. Similarly, microwave-assisted extraction is hindered by uneven heat and mass transfer in solid plant matrices, creating difficulties for industrial amplification [32]. As a technique initially designed for trace analysis, vortex-assisted microextraction also faces practical challenges in large-scale operation, including difficult adsorbent recovery, unavoidable magnetic material loss, and technical barriers in continuous solid–liquid separation. Overall, the industrialization of green urushiol extraction requires optimized reactor configuration, systematic pilot-scale verification, and the establishment of high-throughput, low-consumption, and cost-stable processing systems.

Beyond extraction limitations, long-term operational stability is another essential prerequisite for the practical promotion of urushiol-based functional materials. Thermal stability, UV resistance, and mechanical performance jointly determine the service reliability of coating and biomedical products. Compound modification with alkali lignin increases the thermal decomposition temperature of urushiol composites to approximately 517 °C, while excessive lignin addition leads to heterogeneous crosslinking and deteriorated comprehensive performance [22,49]. UV-curable urushiol/lignin systems achieve a char yield of 35.7%, whereas excessive lignin incorporation delays free radical generation and slows the curing process due to enhanced UV shielding. In contrast, the introduction of modified cellulose nanofiber photoinitiators into urushiol epoxy acrylate coatings improves hardness, adhesion, and long-term anti-corrosion capacity. Nevertheless, overloading the nanofiller causes particle aggregation and declines mechanical performance [6].

Biological safety evaluation is equally critical. Chitosan–urushiol composite nanofibers maintain structural stability under strongly acidic conditions (pH = 1) and exhibit negligible cytotoxicity. Meanwhile, triene-type urushiol derivatives selectively inhibit tu-

mor cell growth with limited damage to normal hepatocytes (Figure 5) [8]. Although these findings are promising, most current evidence is derived from short-term in vitro experiments. Systematic data regarding long-term in vivo biosafety and chronic toxicity remain insufficient, forming a critical research gap between laboratory exploration and practical clinical or industrial application.

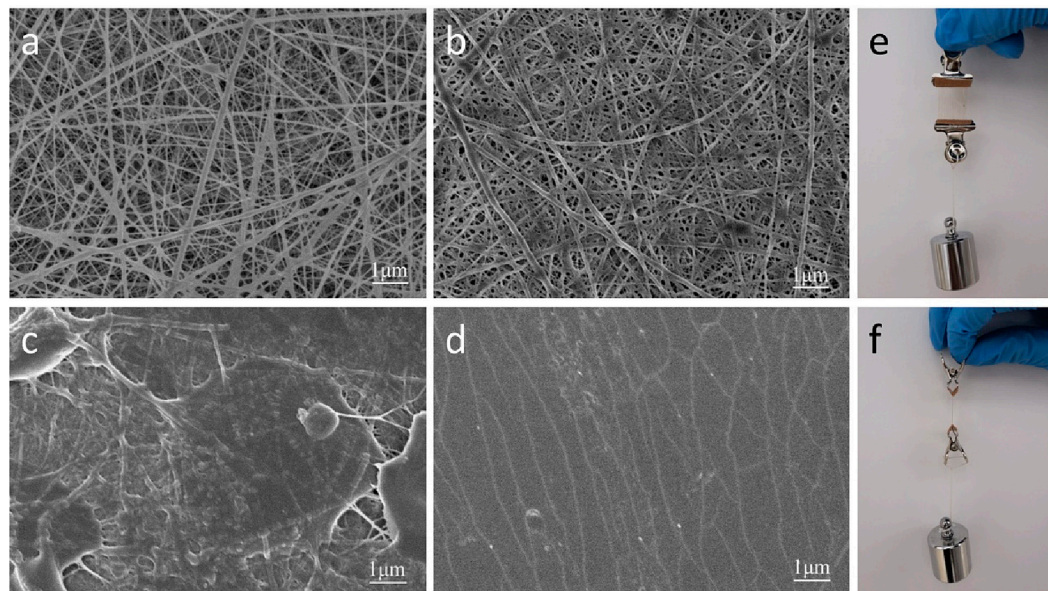


Figure 5. Morphology and mechanical strength of chitosan–urushiol composite nanofiber membrane after acid treatment. (a–d) SEM images of CS-U0.3 membrane after immersion in distilled water for 20 min, pH 4 HCl for 5 min and 20 min, and pH 1 HCl for 5 min, respectively; (e,f) the acid-treated membrane lifting a 100 g weight [8].

5.2. Future Research Directions

To translate lab achievements of urushiol-based functional materials into real-world applications, cross-disciplinary collaboration between synthetic biology and computational chemistry is indispensable. Such integration enables precise molecular design and scalable green manufacturing, and also complements high-throughput structure–activity–toxicity screening to accelerate the development of low-allergen and high-activity derivatives. Computational tools such as the relative alkylation index (RAI) and QSAR modeling can predict protein alkylation behaviors and allergenic risks. Meanwhile, activity screening clarifies how side-chain unsaturation affects the antibacterial and antioxidant properties of urushiol derivatives [50,51]. Synthetic biology supports the reconstruction of urushiol metabolic pathways, while computational chemistry reveals the structure–performance relationship. Relevant theories can then be transformed into functional coatings and polymers via materials science. Existing studies on lacquer tree enzymes at the gene level and hairy root culture systems have laid a foundation for metabolic engineering and pathway optimization (Figure 6) [52,53]. Furthermore, closed-loop life-cycle assessment (LCA) helps maintain sustainability across the entire industrial chain, from raw material cultivation to waste disposal. LCA on biomass-based coatings has quantified greenhouse gas emissions, resource consumption, and environmental impacts during processing. When combined with the carbon sequestration capacity of lacquer forests, the ecological and economic value of such materials becomes more prominent [54,55]. To translate these research advances into commercial reality, a phased scale-up pathway is worth considering. This would typically begin with pilot-scale validation of the most promising green extraction method (e.g., ultrasound-assisted or vortex-assisted MSPD), followed by the development of continuous-flow extraction equipment tailored to urushiol’s physico-

chemical properties, and ultimately the establishment of industry-compatible quality control protocols. Some urushiol-based products, such as antifouling coatings and oil–water separation materials, are already under active industrial development, suggesting that the technical barriers, while substantial, are surmountable through targeted engineering and cross-sector collaboration. Combining the above technical routes forms a complete development roadmap for sustainable, safe, and high-performance urushiol-based materials. Future research should advance extraction, functional modification and life-cycle management in a coordinated manner, rather than conducting isolated studies, so as to finally realize circular and green production.

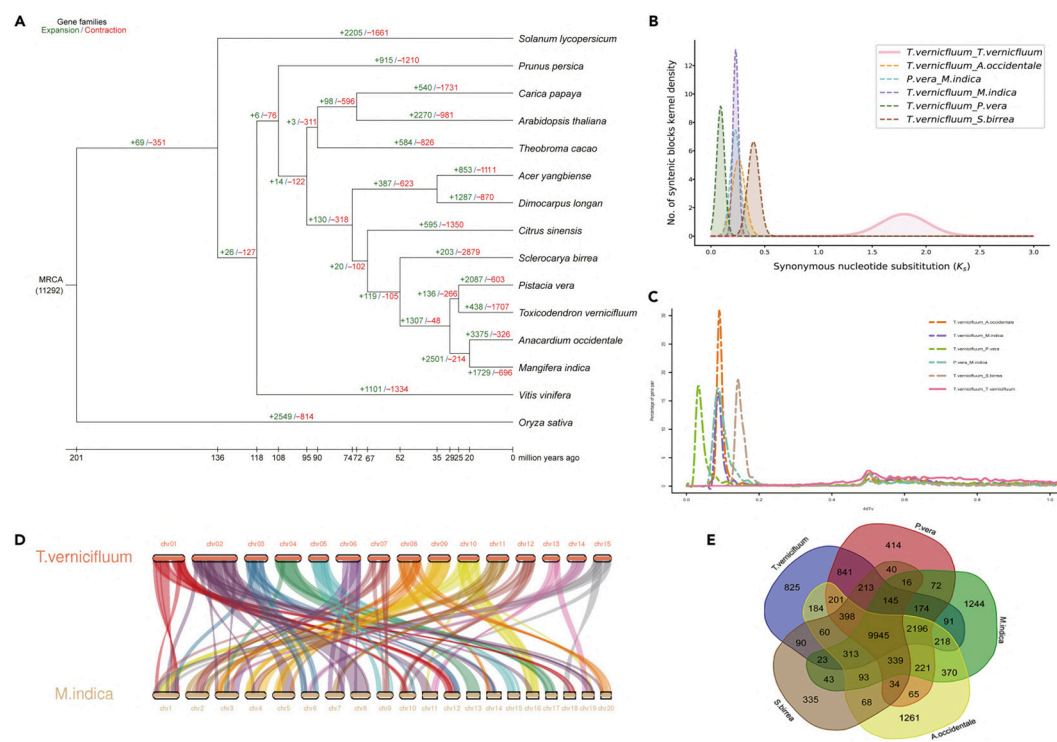


Figure 6. Comparative genomic analysis of the lacquer tree genome [52]. (A) Gene family expansion and contraction among 15 plants. Green and red numbers on the branches represent the expansion and contraction gene families in each species. (B) WGD analysis of *T. vernicifluum*. (C) 4dTv distributions of syntenic blocks for *T. vernicifluum* paralogs and orthologs with other species of family Anacardiaceae are represented. (D) Synteny and microsynteny among *M. indica* and *T. vernicifluum*. (E) Venn diagram of *A. occidentale*, *M. indica*, *P. vera*, *S. birrea*, and *T. vernicifluum*. Each number in the diagram is the number of gene families within a group.

6. Conclusions

Urushiol is the primary bioactive constituent of raw lacquer and has evolved beyond traditional coating applications to serve as a versatile molecular platform. This review systematically summarizes recent advances in its green extraction technologies and functional polymeric applications, focusing on the structure–function and structure–allergenicity relationships of urushiol. Traditional solvent extraction and column chromatography can produce high-purity urushiol but suffer from low efficiency, excessive solvent consumption and unavoidable occupational risks. In contrast, auxiliary extraction techniques including ultrasound and microwave extraction exhibit improved performance. Emerging microextraction methods, such as vortex-assisted MSPD and ball-milling-based vortex extraction, enable rapid, low-solvent, and safe urushiol recovery, representing a substantial advancement toward sustainable extraction protocols.

The multifunctional characteristics of urushiol originate from its inherent catechol skeleton and long alkyl side chains, which dominate its overall performance. Modified urushiol-based polymers have achieved diverse functionalization, including fast-curing and corrosion-resistant UV-curable coatings with enhanced mechanical properties. Further applications cover metal-coordinated and intrinsic antibacterial systems, super-wetting membranes for oil–water separation, and selective adsorption materials for heavy metal and rare-earth ion enrichment. Recent biomedical studies also demonstrate the potential of urushiol as a bioactive scaffold, drug carrier and low-toxic therapeutic precursor. To balance material functionality and biosafety, multiple modification strategies have been developed, including hydroxyl protection, C5/C6 site blocking, and low-allergen analog synthesis.

Nevertheless, several challenges still restrict its industrial translation. The scale-up of green extraction remains difficult, while long-term structural stability and systematic biocompatibility and chronic toxicity data are still insufficient. Future research should focus on high-throughput structure–activity–toxicity screening, interdisciplinary integration of synthetic biology, computational chemistry, and materials science, and full-life-cycle environmental assessment. Overall, urushiol-based materials represent a sustainable and multifunctional platform for coatings, functional surfaces, and biomedical devices, well conforming to green chemistry principles and molecular-guided material design.

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References

1. Gao, R.; Wang, L.; Lin, Q. Effect of hexamethylenetetramine on the property of Chinese lacquer film. *Prog. Org. Coat.* **2019**, *133*, 169–173.
2. Harigaya, S.; Honda, T.; Rong, L.; Miyakoshi, T.; Chen, C. Enzymatic dehydrogenative polymerization of urushiols in fresh exudates from the lacquer tree, *Rhus vernicifera* DC. *J. Agric. Food Chem.* **2007**, *55*, 2201–2208.
3. ElSohly, M.A.; Turner, C.E. GLC analysis of poison ivy and poison oak urushiol components in vegetable oil preparations. *J. Pharm. Sci.* **1980**, *69*, 587–589.
4. Ma, X.; Lu, R.; Miyakoshi, T. Recent Advances in Research on Lacquer Allergy. *Allergol. Int.* **2012**, *61*, 45–50.
5. Yang, J.; Deng, J.; Zhu, J.; Liu, W.; Zhou, M.; Li, D. Thermal polymerization of lacquer sap and its effects on the properties of lacquer film. *Prog. Org. Coat.* **2016**, *94*, 41–48.
6. Wu, H.; Han, X.; Zhao, W.; Zhang, Q.; Zhao, A.; Xia, J. Mechanical and electrochemical properties of UV-curable nanocellulose/urushiol epoxy acrylate anti-corrosive composite coatings. *Ind. Crops Prod.* **2022**, *181*, 114805.
7. Cauduro, V.; Gohlke, G.; Da Silva, N.; Cruz, A.; Flores, E. A review on scale-up approaches for ultrasound-assisted extraction of natural products. *Curr. Opin. Chem. Eng.* **2025**, *48*, 101120.
8. Jie, X.; Shiu, B.; Zhang, Y.; Wu, H.; Ye, Y.; Fang, R. Chitosan-Urushiol nanofiber membrane with enhanced acid resistance and broad-spectrum antibacterial activity. *Carbohydr. Polym.* **2023**, *312*, 120792.

9. Shen, L.; Pang, S.; Zhong, M.; Sun, Y.; Qayum, A.; Liu, Y.; Ren, X. A comprehensive review of ultrasonic assisted extraction (UAE) for bioactive components: Principles, advantages, equipment, and combined technologies. *Ultrason. Sonochem.* **2023**, *101*, 106646.
10. Cao, S.; Liang, J.; Chen, M.; Xu, C.; Wang, X.; Qiu, L.; Zhao, X.; Hu, W. Comparative analysis of extraction technologies for plant extracts and absolutes. *Front. Chem.* **2025**, *13*, 1536590.
11. Yadav, P.; Nousiainen, P.; Farooq, M. Environmental impact and cost of bio-based hydrophobic multifunctional coatings. *Environ. Sci. Pollut. Res.* **2026**, *33*, 6657–6677.
12. Vogl, O. Oriental lacquer, poison ivy, and drying oils. *J. Polym. Sci. Part A Polym. Chem.* **2000**, *38*, 4327–4335.
13. Yuan-Feng, H.; Cheng-Zhang, W.; Rong, L.U. Identification of Chemical Structure of Urushiol from Maoba Lacquer by HPLC-MS. *Chem. Ind. For. Prod.* **2012**, *32*, 47–51.
14. Xia, F.; He, H.; Ma, J.; Jin, Y.; Qiao, Q.; Long, P.; Li, P.; Sun, R. Optimization of Ultrasonic-Assisted Extraction of Diene Urushiol from Lacquer Tree Leaves Using Response Surface Methodology. *Molecules* **2025**, *30*, 13.
15. Juric, M.; Golub, N.; Galic, E.; Radić, K.; Maslov Bandić, L.; Vitali Čepo, D. Microwave-Assisted Extraction of Bioactive Compounds from Mandarin Peel: A Comprehensive Biorefinery Strategy. *Antioxidants* **2025**, *14*, 722.
16. Wong, Y.; Yusoff, R.; Ngoh, G. Phenolic compounds extraction by assistive technologies and natural deep eutectic solvents. *Rev. Chem. Eng.* **2024**, *40*, 229–246.
17. Laina, K.; Drosou, C.; Stergiopoulos, C.; Eleni, P.; Krokida, M. Optimization of Combined Ultrasound and Microwave-Assisted Extraction for Enhanced Bioactive Compounds Recovery from Four Medicinal Plants: Oregano, Rosemary, Hypericum, and Chamomile. *Molecules* **2024**, *29*, 5773.
18. Zgola-Grześkowiak, A.; Grześkowiak, T.; Ligor, M.; Frankowski, R. Achievements and Challenges of Matrix Solid-Phase Dispersion Usage in the Extraction of Plants and Food Samples. *Processes* **2024**, *12*, 1146.
19. Chen, H.; Zhou, H.; Qi, Z.; Xue, X.; Wang, C. Vortex-blending matrix solid-phase dispersion and UPLC-Q-TOF/MS were proposed to extract and examine the urushiols from *Toxicodendron vernicifluum* bark. *J. Pharm. Biomed. Anal.* **2024**, *242*, 116066.
20. Yan, C.; Zhang, Y.; Du, K.; Guo, J.; He, J.; Li, J.; Chang, Y. A ball mill-assisted vortex-enhanced matrix solid-phase dispersion method for the extraction and determination of five phenolic compounds from Rubi Fructus by high-performance liquid chromatography. *Sep. Sci. Plus* **2021**, *4*, 211–221.
21. Li, D.; Zhang, J.; Zhang, T.; Li, Y.; Xue, X.; Qi, Z. Research Progress on Polymerization and Curing Technology of Urushiol and Its Application in Functional Polymers. *Chem. Ind. For. Prod.* **2024**, *44*, 129–137.
22. Shin, Y.; Lee, S.; Lee, J.; Moon, J.; Hwang, G.; Lee, H.; Jeong, Y. Sustainable UV-curable coatings based on urushiol and lignin: From radical crosslinking to functional performance. *Prog. Org. Coat.* **2026**, *212*, 109883.
23. Li, D.; Li, K.; Fang, J. Research Progress on Modification and Application of Raw Lacquer. *ChemistrySelect* **2022**, *7*, e202200943.
24. Hou, J.; Wang, Y.; Wang, T.; Xu, G.; Feng, X.; Liu, X. The Effects of Repeated Kurome Treatment on Chinese Lacquer and Its Film Properties. *Polymers* **2025**, *17*, 1481.
25. Wang, T.; Hou, J.; Wang, Y.; Feng, X.; Liu, X. Urushiol-Based Antimicrobial Coatings: Molecular Mechanisms, Structural Innovations, and Multifunctional Applications. *Polymers* **2025**, *17*, 1500.
26. Qi, Z.; Wang, C.; Jiang, J. Research Progress on Biochemical Activity and Application of Urushiol. *Biomass Chem. Eng.* **2018**, *52*, 60–66.
27. Jeong, S.; Kim, D.; Seo, J. Preparation and the antioxidant and antibacterial activities of urushiol powders (YPUOH). *Prog. Org. Coat.* **2014**, *77*, 981–987.
28. Suk, K.; Kim, H.; Kim, M.; Kim, J.; Uh, Y.; Jang, I.; Kim, S.; Choi, E.; Kim, M.; Joo, J.; et al. In vitro Antibacterial and Morphological Effects of the Urushiol Component of the Sap of the Korean lacquer tree (*Rhus vernicifera* Stokes) on *Helicobacter pylori*. *J. Korean Med. Sci.* **2010**, *25*, 399–404.
29. Chen, J.; Jian, R.; Yang, K.; Bai, W.; Huang, C.; Lin, Y.; Zheng, B.; Wei, F.; Lin, Q.; Xu, Y. Urushiol-based benzoxazine copper polymer with low surface energy, strong substrate adhesion and antibacterial for marine antifouling application. *J. Clean. Prod.* **2021**, *318*, 128527.
30. Kim, H.; Yeum, J.; Choi, S.; Lee, J.; Cheong, I. Urushiol/polyurethane-urea dispersions and their film properties. *Prog. Org. Coat.* **2009**, *65*, 341–347.
31. Bai, W.; Zhang, X.; Chen, X.; Li, P.; Huang, J.; Chen, J.; Zheng, S.; Li, X.; Lin, Y.; Jian, R. Magnetic bio-based Fe₃O₄@urushiol-Fe polymeric nanoparticles for efficient photothermal sterilization. *J. Environ. Chem. Eng.* **2024**, *12*, 113523.
32. Fang, Y.; Yan, L.; Liu, H. Facile Preparation of Hydrophobic Melamine Sponges using Naturally Derived Urushiol for Efficient Oil/Water Separation. *ACS Appl. Polym. Mater.* **2020**, *2*, 3781–3788.

33. Zeng, H.; Zhang, Y.; Wu, H.; Ye, Y.; Zhang, W.; Fang, R. Preparation of highly hydrophobic melamine sponge for oil-water separation through copolymerization deposition. *J. Environ. Chem. Eng.* **2024**, *12*, 114906.
34. Bai, W.; Chen, K.; Chen, J.; Xu, J.; Lin, H.; Lin, Y.; Xu, Y.; Lin, J. Natural Highly-hydrophobic urushiol@TiO₂ coated cotton fabric for effective oil-water separation in highly acidic alkaline and salty environment. *Sep. Purif. Technol.* **2020**, *253*, 117495.
35. Zhu, Y.; Li, Y.; Xiao, J.; Li, J.; Yu, S. Facile Preparation of Robust Superhydrophobic Stainless Steel Mesh Coated with Urushiol-based Polybenzoxazine and SiO₂ for Efficient Oil/water Separation. *J. Wuhan Univ. Technol. Mater. Sci. Ed.* **2025**, *40*, 842–851.
36. Shi, B. Synthesis and Characteristics of Urushiol-Quinoline Functional Polymer. *J. Funct. Mater.* **2025**, *40*, 727–729.
37. Jie, X.; Shiu, B.-C.; Wu, H.; Zhang, Y.; Ye, Y.; Lin, C.; Fang, R. Adsorption and recovery of Cr(VI) from wastewater by Chitosan–Urushiol composite nanofiber membrane. *e-Polymers* **2023**, *23*, 20230157.
38. Kadokura, K.; Suruga, K.; Tomita, T.; Hiruma, W.; Yamada, M.; Kobayashi, A.; Takatsuki, A.; Nishio, T.; Oku, T.; Sekino, Y. Novel urushiols with human immunodeficiency virus type 1 reverse transcriptase inhibitory activity from the leaves of *Rhus verniciflua*. *J. Nat. Med.* **2015**, *69*, 148–153.
39. Hong, D.; Han, S.; Lee, C.; Park, S.; Jeon, Y.; Kim, M.; Kim, H. Cytotoxicity of urushiols isolated from sap of Korean lacquer tree (*Rhus vernicifera* Stokes). *Arch. Pharmacol. Res.* **1999**, *22*, 638–641.
40. Xue, X.; Qi, Z.; Wang, Z.; Tao, R.; Zhou, H.; Chen, H.; Lei, J.; Wang, C. Urushiol-dextran SPIONs magnetic recyclable nanoparticles immobilizing vancomycin (V@DU@Fe) for antibacterial application. *Int. J. Biol. Macromol.* **2025**, *304*, 140847.
41. Qi, Z.; Zhou, H.; Chen, H.; Zhang, C.; Deng, T.; Wang, C. pH Responsiveness and Their in vitro Properties of Urushiol-based BPAU-NH₂-Gal Paclitaxel-loaded Micelle. *Chem. Ind. For. Prod.* **2020**, *40*, 121–128.
42. Xue, X.; Qi, Z.; Zhou, H.; Chen, H.; Wang, Z.; Wang, C. Preparation of Urushiol Magnetic Imprinted Polymer and Its Specific Adsorption of Vancomycin. *Chem. Ind. For. Prod.* **2025**, *45*, 116–124.
43. Kim, J.; Cho, J.; Ma, Y.; Lee, Y.; Moon, J. Nonallergenic urushiol derivatives inhibit the oxidation of unilamellar vesicles and of rat plasma induced by various radical generators. *Free Radic. Biol. Med.* **2014**, *71*, 379–389.
44. Liberato, D.J.; Byers, V.S.; Dennick, R.G.; Castagnoli, N. Regiospecific attack of nitrogen and sulfur nucleophiles on quinones derived from poison oak/ivy catechols (urushiols) and analogs as models for urushiol-protein conjugate formation. *J. Med. Chem.* **1981**, *24*, 28–33.
45. Dunn, I.S.; Liberato, D.J.; Castagnoli, N.; Byers, V.S. Influence of chemical reactivity of urushiol-type haptens on sensitization and the induction of tolerance. *Cell. Immunol.* **1986**, *97*, 189–196.
46. Tyman, J.H.P.; Schofield, B.G.; Khor, C.H. A synthesis of the phenolic lipid, 3-[(Z)-pentadec-8-enyl] catechol, (15:1)-urushiol. *Chem. Phys. Lipids* **2002**, *120*, 101–108.
47. ElSohly, M.A.; Adawadkar, P.D.; Benigni, D.A.; Watson, E.; Little, T.L., Jr. Analogs of poison ivy urushiol. Synthesis and biological activity of disubstituted n-alkylbenzenes. *J. Med. Chem.* **1986**, *29*, 606–611.
48. Belwal, T.; Chemat, F.; Venskutonis, P.; Cravotto, G.; Jaiswal, D.K.; Bhatt, I.D.; Luo, Z. Recent advances in scaling-up of non-conventional extraction techniques: Learning from successes and failures. *TrAC Trends Anal. Chem.* **2020**, *127*, 115895.
49. Narita, C.; Yamada, K. Development of glossy and UV-resistant urushi coatings by thermal polymerization. *Prog. Org. Coat.* **2024**, *186*, 108032.
50. Roberts, D.W.; Benezra, C. Quantitative structure-activity relationships for skin sensitization potential of urushiol analogues. *Contact Dermat.* **1993**, *29*, 78–83.
51. He, Y. Structural Modification and Bioactivity of Urushiol from Lacquer Sap. Master's Thesis, Chinese Academy of Forestry, Beijing, China, 2013.
52. Bai, G.; Chen, C.; Zhao, C.; Zhou, T.; Li, D.; Zhou, T.; Li, S. The chromosome-level genome for *Toxicodendron vernicifluum* provides crucial insights into Anacardiaceae evolution and urushiol biosynthesis. *iScience* **2022**, *25*, 104512.
53. Zhou, H.; Wang, C.; Deng, T.; Tao, R.; Li, W. Novel urushiol derivatives as HDAC8 inhibitors: Rational design, virtual screening, molecular docking and molecular dynamics studies. *J. Biomol. Struct. Dyn.* **2018**, *36*, 1966–1978.
54. Yao, K.; Tian, J.; Huang, P. Urushiol-Based Antimicrobial Coatings for Lacquer Art Applications: A Review of Mechanisms, Durability, and Safety. *Coatings* **2026**, *16*, 198.
55. Li, J.; Sun, W.; Lichtfouse, E.; Maurer, C.; Liu, H. Life cycle assessment of biochar for sustainable agricultural application: A review. *Sci. Total Environ.* **2024**, *951*, 175448.

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