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Research Progress on the Extraction of Natural Tannins

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ABSTRACT

Natural tannins, as polyphenolic compounds widely present in plants, have garnered increasing attention due to their diverse biological activities and industrial applications. This paper systematically examines the current research landscape surrounding natural tannin extraction. Plants such as gallnuts, tea leaves, and tree barks serve as primary sources, with tannins classified into hydrolysable and condensed types based on their chemical structures. Various extraction techniques including solvent extraction, ultrasound-assisted extraction, and enzymatic methods have been developed, each demonstrating distinct advantages in terms of efficiency and environmental impact. Process optimization through parameter adjustment has shown significant improvements in yield and purity. Recent advancements highlight the potential of green extraction technologies that minimize chemical usage while maintaining extraction performance. The extracted tannins exhibit promising applications in leather production, food preservation, and pharmaceutical formulations due to their antioxidant and antimicrobial properties. Future research directions should focus on developing cost-effective large-scale extraction methods and exploring novel applications in emerging fields. Continuous innovation in extraction technologies coupled with sustainable sourcing strategies will be crucial for meeting the growing industrial demand while addressing environmental concerns.

KEYWORDS

Natural Tannins; Extraction Methods; Research Progress

1. RESEARCH BACKGROUND AND OBJECTIVES

Natural tannins have been recognized as valuable polyphenolic compounds with diverse applications across multiple industries. These plant-derived substances are increasingly important due to their unique biological properties, including antioxidant, antimicrobial, and anti-inflammatory effects. Historically, tannins have been utilized for centuries in traditional leather tanning processes, but recent scientific advancements have revealed their potential in modern applications such as food preservation, pharmaceuticals, and even wastewater treatment.

The growing demand for sustainable and eco-friendly materials has driven significant interest in tannin extraction research. As of 2025, industries are actively seeking alternatives to synthetic chemicals, and natural tannins present a viable solution due to their biodegradability and low toxicity. However, efficient extraction methods remain a key challenge, as traditional techniques often involve high energy consumption or the use of hazardous solvents. Recent developments in green chemistry have encouraged the exploration of environmentally friendly extraction approaches, such as ultrasound-assisted and enzyme-mediated processes, which aim to reduce environmental impact while maintaining high yield and purity.

The primary objective of this research is to systematically review the current state of natural tannin extraction, focusing on both conventional and innovative techniques. By analyzing the strengths and limitations of different methods, this study aims to identify optimal strategies for maximizing extraction efficiency while minimizing ecological harm. Additionally, the research seeks to highlight emerging applications of tannins in industrial and biomedical fields, providing insights into future development opportunities.

Another key goal is to assess the economic feasibility of large-scale tannin production, considering factors such as raw material availability, processing costs, and market demand. Given the increasing regulatory emphasis on sustainable practices, this study also evaluates the potential of tannins as a renewable resource in circular economy models. By addressing these aspects, the research contributes to a more comprehensive understanding of tannin extraction and its role in advancing green industrial processes.

Ultimately, this chapter sets the foundation for subsequent discussions on tannin sources, classification, and extraction optimization, while emphasizing the need for continued innovation in this field. The findings will be relevant to researchers, industry professionals, and policymakers working toward sustainable material development.

2. SOURCES AND CLASSIFICATION OF NATURAL TANNINS

2.1. Botanical Sources of Tannins

The botanical sources of natural tannins are diverse, spanning across various plant families and geographical regions. These polyphenolic compounds are primarily concentrated in specific plant organs as part of their defense mechanisms against herbivores and pathogens. The distribution of tannins within plant tissues follows distinct patterns, with higher concentrations typically found in protective or structural components.

Among the most significant tannin-rich plant materials are gallnuts, which represent abnormal growths induced by insect activity on oak trees (Quercus spp.) and other Fagaceae species. These pathological formations contain exceptionally high levels of hydrolysable tannins, particularly gallotannins and ellagitannins. The unique biological process of gall formation concentrates tannins to levels substantially higher than those found in normal plant tissues, making them valuable industrial sources [1].

Tree barks constitute another major category of tannin sources, with species such as Acacia (particularly Acacia mearnsii and Acacia mangium), Schinopsis, and Eucalyptus being commercially important. The bark of these species contains condensed tannins (proanthocyanidins) that have demonstrated significant antioxidant and antibacterial properties [1]. The outer bark layers generally show higher tannin content than inner tissues, reflecting their protective function against environmental stressors and microbial invasion.

Leaves of certain plant species serve as accessible tannin sources, with tea (Camellia sinensis) being the most prominent example. Tea leaves contain both hydrolysable and condensed tannins, contributing to their characteristic astringency and health benefits. Other notable leaf sources include sumac (Rhus spp.) and eucalyptus leaves, which have been traditionally used for their tannin content in various cultures.

Fruits and seeds represent additional botanical sources, though their tannin content is generally lower compared to gallnuts or barks. Pomegranate (Punica granatum) rinds, persimmon (Diospyros kaki) fruits, and the seeds of Saraca asoca contain appreciable amounts of tannins with demonstrated biological activities [2]. The tannins in these plant parts often play roles in seed protection and fruit ripening processes.

Wood and roots of certain species also contribute to tannin production, though these sources are less commonly exploited commercially due to extraction challenges. The heartwood of quebracho (Schinopsis spp.) trees contains particularly high concentrations of condensed tannins, while the roots of plants like kino (Pterocarpus marsupium) have been used in traditional medicine for their tannin content.

The geographical distribution of tannin-rich plants shows distinct patterns, with tropical and subtropical regions hosting particularly diverse sources. This distribution reflects evolutionary adaptations to specific environmental conditions, where tannins provide competitive advantages against herbivory and microbial attack in warm, humid climates. However, temperate species like oak and chestnut also contribute significantly to global tannin production.

Seasonal variations affect tannin content in plant materials, with concentrations typically peaking during active growth periods or in response to environmental stressors. This temporal variability necessitates careful consideration in harvesting strategies to maximize yield and maintain consistent quality in industrial applications. Recent research has focused on identifying optimal collection periods for various tannin sources to balance ecological sustainability with extraction efficiency.

The selection of botanical sources for tannin extraction involves multiple considerations, including tannin type and concentration, availability, and ecological impact. Sustainable harvesting practices have gained importance as demand increases, with particular attention to preserving biodiversity while meeting industrial needs. This balance is crucial for maintaining long-term viability of tannin production systems in various ecosystems.

2.2. Chemical Classification and Structural Diversity

The chemical classification of natural tannins is primarily based on their structural characteristics and hydrolysis behavior, dividing them into two major categories: hydrolysable tannins and condensed tannins. This fundamental classification reflects significant differences in their chemical composition, stability, and biological activities, which directly influence their extraction methods and industrial applications.

Hydrolysable tannins consist of a central polyol core, typically glucose, esterified with gallic acid (gallotannins) or hexahydroxydiphenic acid (ellagitannins). These compounds are characterized by their ability to undergo hydrolysis under acidic or alkaline conditions, or through enzymatic action, yielding simpler phenolic compounds. The galloyl groups in gallotannins may form complex oligomeric structures through depside bonds, creating diverse molecular configurations. Ellagitannins, which represent more advanced structural forms, contain additional C-C couplings between galloyl groups that form hexahydroxydiphenoyl units. This structural complexity contributes to their varied biological activities and influences their solubility properties during extraction processes [3].

Condensed tannins, also known as proanthocyanidins, exhibit fundamentally different structural characteristics. These polymers consist of flavan-3-ol units linked through carbon-carbon bonds, forming oligomeric or polymeric structures that are resistant to hydrolysis. The basic building blocks include catechin, epicatechin, and their galloylated derivatives, which polymerize through interflavan bonds at C4-C8 or C4-C6 positions. The degree of polymerization significantly affects their physical and chemical properties, with higher molecular weight polymers demonstrating increased astringency and decreased solubility in polar solvents. The presence of stereochemical variations at C2 and C3 positions further adds to their structural diversity [4].

Recent research has identified intermediate forms that challenge this traditional dichotomy. Some plant-derived tannins exhibit characteristics of both classes, containing both hydrolysable ester linkages and condensed-type interflavan bonds. These complex tannins, found in certain plant families, demonstrate unique physicochemical properties that require specialized extraction approaches. Their structural hybrid nature may offer synergistic biological effects, making them particularly interesting for pharmaceutical applications.

The structural diversity within each tannin class leads to substantial variations in their physical and chemical properties. Molecular weight distribution, degree of galloylation, and the presence of glycosidic modifications all influence solubility, stability, and reactivity. These factors are crucial for extraction process design, as they determine optimal solvent systems, temperature ranges, and pH conditions. For instance, highly galloylated tannins show increased affinity for polar organic solvents, while polymeric condensed tannins often require aqueous-organic mixtures for efficient extraction.

Spatial conformation represents another critical aspect of tannin structure that affects both extraction and application. The three-dimensional arrangement of hydroxyl groups creates specific patterns of hydrogen bonding and hydrophobic interactions that influence molecular recognition processes. This structural feature underpins tannins' ability to form complexes with proteins, polysaccharides, and metal ions—a property extensively utilized in leather tanning and pharmaceutical formulations.

Structural modifications occurring during plant growth and processing further complicate the tannin landscape. Oxidation, polymerization, and enzymatic transformations can alter native tannin structures, affecting both their yield during extraction and their subsequent performance in applications. Recent studies emphasize the importance of controlling these modifications through optimized extraction protocols to preserve desired structural features.

The structural characteristics of tannins directly correlate with their biological activities and industrial utility. Antioxidant capacity, for example, depends on the number and arrangement of phenolic hydroxyl groups, while antimicrobial properties relate to molecular size and flexibility. These structure-activity relationships guide the selection of tannin sources and extraction methods for specific applications, from food preservation to biomedical uses.

Advanced analytical techniques have significantly enhanced our understanding of tannin structural diversity. Modern spectroscopic methods and chromatographic separations allow detailed characterization of complex tannin mixtures, revealing subtle structural variations that were previously unrecognized. This improved resolution supports more targeted extraction strategies and quality control measures in industrial production.

Emerging research continues to uncover novel tannin structures with unique properties, expanding the potential applications of these natural compounds. The discovery of tannins with unusual substitution patterns or novel linkage types in previously unstudied plant species highlights the ongoing potential for structural innovation in this field. These findings underscore the importance of maintaining structural integrity during extraction to preserve valuable functional groups and molecular configurations [5].

The structural complexity of tannins presents both challenges and opportunities for extraction technology development. While it necessitates careful process optimization to achieve high yields of desired components, it also offers possibilities for selective extraction strategies targeting specific structural features. Future research directions include the development of structure-guided extraction protocols that maximize recovery of tannins with preferred characteristics for particular applications.

3. EXTRACTION TECHNIQUES AND OPTIMIZATION

3.1. Conventional Extraction Methods

Conventional extraction methods for natural tannins have formed the foundation of industrial production for decades, relying on well-established principles of solubility and mass transfer. These traditional techniques remain widely used due to their operational simplicity, scalability, and relatively low equipment requirements. The most prevalent conventional approaches include solvent extraction, hot water extraction, and alkaline/acid hydrolysis, each demonstrating distinct advantages for specific tannin types and source materials [6].

Solvent extraction represents the most extensively employed conventional method, utilizing organic solvents or aqueous-organic mixtures to dissolve tannins from plant matrices. The process typically involves maceration or percolation of raw materials in selected solvents, followed by filtration and concentration steps. Ethanol-water mixtures have proven particularly effective for both hydrolysable and condensed tannins, balancing polarity requirements with environmental and safety considerations. Methanol demonstrates superior extraction efficiency for certain tannin classes but faces increasing regulatory restrictions due to toxicity concerns. The solvent-to-material ratio, extraction duration, and temperature constitute critical parameters that significantly influence yield and quality. Industrial operations often employ multi-stage countercurrent extraction systems to maximize efficiency while minimizing solvent consumption.

Hot water extraction serves as another fundamental technique, especially suitable for tannins with high water solubility. This method harnesses the temperature-dependent solubility of polyphenolic compounds, typically operating at 60-100°C under atmospheric or pressurized conditions. The process offers advantages in terms of environmental compatibility and food-grade applicability, making it preferred for tannins destined for food or pharmaceutical uses. However, prolonged exposure to elevated temperatures may degrade heat-sensitive tannin structures, necessitating careful control of processing conditions. Variations incorporating sequential temperature steps have shown improved selectivity for different tannin fractions while reducing thermal degradation risks [7].

Alkaline and acid hydrolysis methods target specific tannin classes through pH-mediated structural modifications. Alkaline extraction (pH 8-11) effectively solubilizes condensed tannins by breaking hydrogen bonds and facilitating phenolic group ionization, while mild acid treatment (pH 2-5) preferentially extracts hydrolysable tannins through controlled ester bond cleavage. These approaches require precise pH control to prevent excessive degradation of target compounds, with neutralization steps often incorporated post-extraction. The choice between alkaline and acid conditions depends on both the tannin type and intended application, as the extraction medium can induce structural changes that alter biological activity and industrial performance.

The selection of raw material pretreatment methods significantly impacts conventional extraction efficiency. Size reduction through grinding or milling increases surface area for solvent contact, while drying protocols affect cellular structure and tannin accessibility. Recent studies emphasize the importance of moisture content optimization, as excessively dry materials may exhibit reduced permeability while overly moist samples can dilute solvent effectiveness. Some traditional practices incorporate fermentation or enzymatic pretreatment to weaken cell wall structures, though these approaches require extended processing times compared to mechanical methods.

Filtration and clarification represent critical downstream steps in conventional extraction workflows. The colloidal nature of tannin solutions necessitates careful removal of suspended particulates and macromolecular impurities through centrifugation, diatomaceous earth filtration, or membrane processes. These operations influence both product purity and subsequent concentration efficiency. Evaporation under reduced pressure remains the standard concentration method, though thermal sensitivity considerations have prompted increased adoption of low-temperature alternatives such as freeze concentration in premium applications.

Comparative studies of conventional methods reveal clear trade-offs between extraction efficiency, operational complexity, and product quality. While solvent extraction generally delivers higher yields, hot water methods produce extracts with broader regulatory acceptance for sensitive applications. The economic viability of conventional techniques benefits from established infrastructure and straightforward scalability, though rising solvent costs and environmental regulations are driving process optimizations. Modern adaptations often combine conventional principles with moderate technological enhancements, such as improved heat exchangers or solvent recovery systems, to maintain competitiveness against emerging green technologies.

Process optimization in conventional extraction focuses primarily on parameter interactions rather than individual variable adjustment. The interplay between solvent composition, temperature, and extraction time follows complex response patterns that modern experimental design approaches help elucidate. Statistical modeling techniques have identified optimal operating windows that balance tannin yield with energy and solvent consumption, particularly important for cost-sensitive industries. These optimizations have demonstrated significant improvements in both economic and environmental performance metrics without requiring fundamental process changes.

Quality control in conventional tannin extraction faces challenges related to batch variability and structural alteration risks. Standardized protocols for raw material assessment and process monitoring help mitigate these issues, with particular attention to preventing oxidation during processing. The use of inert atmospheres and antioxidant additives during extraction has become more prevalent in quality-conscious operations. Analytical techniques including spectrophotometry and HPLC support real-time process adjustments to maintain consistent product specifications.

Despite the emergence of innovative extraction technologies, conventional methods maintain industrial relevance through continuous incremental improvements. Their robust performance across diverse raw material types and straightforward scalability ensure continued use, particularly in regions with limited access to advanced extraction equipment. The ongoing integration of basic automation and process control systems has further enhanced the reliability and consistency of conventional approaches, bridging the gap between traditional practices and modern production requirements.

The environmental footprint of conventional extraction methods has received increased scrutiny in recent years, prompting various mitigation strategies. Solvent recovery systems, energy-efficient evaporation technologies, and waste valorization approaches have significantly reduced the ecological impact of these traditional processes. Life cycle assessment studies indicate that optimized conventional methods can compete favorably with some novel technologies when considering full-process environmental burdens, particularly when using renewable energy sources and closed-loop solvent systems.

Future developments in conventional extraction are likely to focus on hybrid systems that combine traditional principles with selected green chemistry elements. Examples include solvent systems incorporating biodegradable surfactants or mild bio-based solvents that maintain extraction performance while addressing environmental concerns. Such evolutionary rather than revolutionary adaptations may prove particularly valuable for industries requiring gradual technological transitions while maintaining product quality standards and supply chain stability.

3.2. Innovative and Green Extraction Technologies

Recent advancements in tannin extraction have focused on developing environmentally sustainable methods that reduce chemical usage and energy consumption while maintaining high efficiency. These innovative approaches address growing environmental concerns and regulatory pressures while meeting industrial demand for natural tannins. As of mid-2025, several green extraction technologies have emerged as promising alternatives to conventional methods, demonstrating significant improvements in sustainability metrics without compromising product quality.

Ultrasound-assisted extraction (UAE) has gained prominence as an efficient green technology for tannin recovery. This method utilizes high-frequency sound waves to create cavitation bubbles that disrupt plant cell walls, enhancing solvent penetration and mass transfer. The mechanical effects of ultrasound allow for reduced processing temperatures and shorter extraction times compared to conventional methods, leading to lower energy consumption. Recent optimizations have shown particular success with hydrolysable tannins from gallnuts and tea leaves, where controlled ultrasound parameters prevent excessive degradation of sensitive compounds. The technique's adaptability to aqueous systems eliminates the need for hazardous organic solvents, aligning with green chemistry principles [3].

Enzyme-assisted extraction represents another sustainable approach that has shown remarkable selectivity for target tannin compounds. Specific enzymes such as cellulases, pectinases, and tannases selectively degrade plant cell wall components, releasing bound tannins while minimizing co-extraction of undesirable compounds. This biological method operates under mild temperature and pH conditions, preserving tannin structural integrity better than harsh chemical treatments. The enzymatic process has demonstrated particular effectiveness with condensed tannins from tree barks, where traditional methods often struggle with efficient extraction due to the tannins' complex interactions with lignocellulosic matrices. Recent advances in enzyme engineering have improved stability and activity, making the technology more economically viable for large-scale applications [8].

Supercritical fluid extraction, particularly using carbon dioxide (CO_2), has emerged as a clean technology for tannin isolation. The tunable solvent properties of supercritical CO_2 allow selective extraction by adjusting pressure and temperature parameters. This method completely avoids organic solvents and leaves no toxic residues, producing high-purity tannin extracts suitable for pharmaceutical and food applications. The technology has shown promising results with heat-sensitive tannins, as the low operating temperatures prevent thermal degradation. Recent process optimizations have improved yield efficiency through modifier additives that enhance CO_2 polarity, making the method more competitive with conventional techniques.

Microwave-assisted extraction (MAE) has evolved as an energy-efficient alternative that significantly reduces processing time. The targeted heating mechanism of microwaves directly energizes polar molecules in plant matrices, causing rapid cell rupture and tannin release. Modern MAE systems incorporate precise temperature control and automated power modulation to prevent localized overheating that could degrade tannin quality. This technology has proven particularly effective for simultaneous extraction and partial purification, as the selective heating can help precipitate non-target compounds during processing. The reduced solvent requirements and shorter extraction cycles contribute to lower overall environmental impact compared to traditional methods.

Recent developments in aqueous two-phase systems (ATPS) offer innovative solutions for tannin extraction and preliminary purification in a single step. These water-based systems utilize the selective partitioning behavior of tannins between immiscible aqueous phases formed by specific polymer-salt or polymer-polymer combinations. ATPS demonstrates advantages in maintaining tannin bioactivity while eliminating organic solvents, and the method's inherent scalability shows promise for industrial adoption. The technology has shown particular potential for separating tannin fractions based on molecular weight and polarity characteristics, which could enable more targeted applications [9].

Emerging membrane technologies are being adapted for tannin extraction and concentration processes. Nanofiltration and reverse osmosis systems allow selective separation of tannins from extraction solutions while operating at ambient temperatures. These methods significantly reduce energy consumption compared to thermal evaporation and can achieve simultaneous concentration and partial purification. Recent membrane material developments have improved resistance to fouling by tannin-protein complexes, enhancing process efficiency and lifespan. The closed-system design minimizes solvent losses and environmental emissions, contributing to sustainable production practices.

Integration of these green technologies with process intensification strategies has shown synergistic effects in recent studies. Combined approaches such as ultrasound-enzyme sequential treatments or microwave-assisted supercritical fluid extraction demonstrate enhanced efficiency through complementary mechanisms. These hybrid systems often achieve higher yields than individual methods while further reducing environmental impacts. The development of modular extraction units incorporating multiple technologies allows flexible adaptation to different tannin sources and product requirements.

Recent research emphasizes the importance of life cycle assessment (LCA) in evaluating green extraction technologies. Comprehensive analyses consider not only extraction efficiency but also energy sources, solvent recyclability, and waste management aspects. Such evaluations help identify truly sustainable solutions rather than merely displacing environmental burdens to other process stages. Studies indicate that the most promising green methods achieve significant reductions in carbon footprint and water usage while maintaining or improving product quality compared to conventional approaches [10].

The adoption of these innovative technologies faces challenges related to initial capital investment and process scale-up. However, decreasing costs of green technology components and increasing regulatory pressures are accelerating industrial implementation. Future developments will likely focus on further improving energy efficiency, developing biodegradable solvent alternatives, and optimizing integrated systems for specific tannin applications. Continuous innovation in green extraction methodologies remains crucial for meeting the growing global demand for natural tannins in an environmentally responsible manner.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The comprehensive review of natural tannin extraction reveals significant advancements in both understanding and technological applications as of mid-2025. Current research demonstrates that tannins from diverse botanical sources can be efficiently extracted through optimized conventional methods and emerging green technologies. The structural diversity of hydrolysable and condensed tannins continues to inform extraction protocol development, with each class requiring tailored approaches for maximum yield and quality. Conventional solvent and hot water extraction remain industrially relevant, particularly when integrated with modern optimization strategies, while innovative methods like ultrasound-assisted and enzyme-mediated extraction show growing promise for sustainable production.

Recent progress highlights the successful implementation of environmentally friendly technologies that reduce chemical usage and energy consumption without compromising efficiency. The transition toward green extraction aligns with global sustainability goals, addressing critical concerns about resource depletion and pollution. Particularly noteworthy is the development of hybrid systems combining multiple green technologies, which have demonstrated synergistic effects in improving both economic and environmental performance metrics. These advancements have facilitated tannin utilization in high-value applications such as pharmaceuticals and functional foods, where purity and structural integrity are paramount.

Future research should prioritize several key areas to address existing challenges and unlock new opportunities. The development of cost-effective large-scale extraction systems remains a critical need, particularly for industries requiring bulk tannin supplies. Innovations in continuous processing equipment and automation could significantly enhance production efficiency while maintaining consistent quality. Another important direction involves the exploration of non-traditional tannin sources, including agricultural byproducts and invasive plant species, which could expand raw material availability while contributing to waste valorization efforts.

The integration of artificial intelligence and machine learning in extraction process optimization presents a promising frontier. These technologies could enable real-time monitoring and adaptive control of extraction parameters, responding to natural variations in raw material composition. Additionally, there is growing interest in developing extraction methods specifically designed to preserve or enhance particular bioactive properties of tannins for targeted applications. Such precision extraction approaches could open new markets in personalized medicine and nutraceuticals.

Advances in analytical techniques will play a crucial role in future tannin research. Improved characterization methods are needed to better understand structure-activity relationships and guide extraction process development. The application of high-throughput screening technologies could accelerate the discovery of novel tannin structures with unique functional properties. Furthermore, standardized quality assessment protocols would facilitate comparison between different extraction methods and support the establishment of industry-wide quality benchmarks.

Sustainability considerations will continue to drive innovation in tannin extraction. Future efforts should focus on closed-loop systems that minimize waste generation and maximize resource efficiency. The incorporation of renewable energy sources into extraction processes could further reduce environmental impact. There is also a need for comprehensive life cycle assessments that evaluate the sustainability of extraction methods from raw material harvesting to final product delivery, ensuring truly green solutions rather than merely shifting environmental burdens.

The exploration of novel applications represents another important direction for future research. Tannins show potential in emerging fields such as biodegradable materials, energy storage devices, and water purification systems. Their natural origin and multifunctional properties make them attractive alternatives to synthetic compounds in various technological applications. Collaborative research between academia and industry will be essential to translate laboratory-scale discoveries into commercially viable products and processes.

Long-term success in tannin research and application will require interdisciplinary approaches that combine botany, chemistry, engineering, and environmental science. The establishment of international research networks could facilitate knowledge sharing and accelerate progress, particularly in addressing global challenges related to sustainable material development. As the field progresses, maintaining a balance between technological advancement, economic viability, and ecological responsibility will be crucial for realizing the full potential of natural tannins in various industries.

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