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Review Article

Sources, Chemical and Biological Characteristics, and Industrial Potentials of Vegetable Tannins: A Scoping Review

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Abstract

Vegetable tannins are a diverse group of naturally-occurring polyphenolic compounds found widely in the plant kingdom, notable for their protein-precipitating and leather-tanning properties. First identified in oak bark and galls in the 18th century, tannins have since been extensively studied for their complex chemistry and multifaceted industrial relevance. This work reviews the plant sources, chemical structures, and classifications of vegetable tannins, emphasising their biosynthetic pathways, isolation, and characterization techniques. Special attention is given to hydrolysable tannins, which are more readily extractable and offer significant industrial advantages. The review also highlights the diverse bioactivities of tannins, supporting their applications in the food, pharmaceutical, and leather industries. By consolidating classical and contemporary insights, this work underscores the ongoing relevance and untapped potential of vegetable tannins in sustainable industrial processes, particularly in the pharmaceutical industry.

Keywords: Vegetable Tannins; Sources; Chemical and Biological Characteristics; Industrial Potentials

Introduction

Historical background

The term tannin was first introduced into the chemical literature by Seguin [1] to describe the chemical constituents of oak bark, with the characteristic of transforming putrescible animal skins into impermeable, stable leather products. Lewis [2] was the first to recognise the presence of an astringent principle in certain vegetable tissues, while De Morveau., *et al.* [3] were the first to report the isolation of tannic acid (Figure 1) from the oak galls. Their work was followed by that of Scheele [4] and Davy [5], who identified the astringent active principles in plant tissues as tannins, and were found to possess phenolic properties that account for the tanning properties.

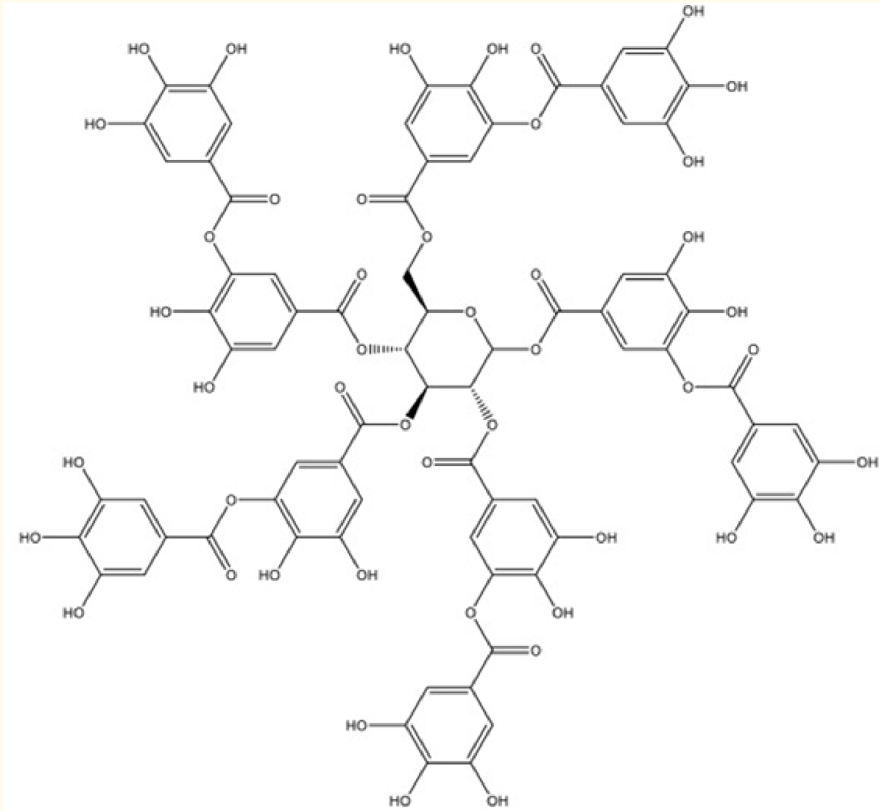


Figure 1: Tannic acid.

Early definitions [6] described tannins as naturally-occurring water-soluble phenolic compounds with molecular weights ranging from 500 to 30,000 Da, and have the ability to preserve animal skins, precipitate alkaloids, gelatin and other proteins. A more recent definition described tannins as natural polyphenolic compounds capable of complexing with other compounds such as proteins, cellulose, and minerals [7].

From the above, it is obvious they possess very complex chemical structures with phenolic groups [8]. As a result of their complex nature, the isolation, purification, and structure determination are difficult. However, because tannins have various industrial and medicinal applications, they have continued to attract the attention of researchers [9]. Both old and new methods of isolation and characterization have been applied, and tannins have found uses in many areas of the food and drug industries. Today, tannins are found in a wide range of plants and are known to have a variety of biological properties and industrial applications [10]. This review discusses the plant sources, approaches to extraction, isolation, and characterization, as well as the bioactivities and potential industrial applications of tannins with a view to enhance our understanding of this industrially important, but neglected group of natural products. Indeed, tannins have historically received relatively limited attention in chemical, biochemical, and biological research due to, i) their structural complexity, extensive heterogeneity, and tendency to form high-molecular-weight polymers which make isolation, purification, and characterization technically difficult, ii) their low bioavailability, strong protein-binding properties, and general assay interference, which complicate pharmacokinetic and biological evaluations, and were therefore historically valued industrially mainly for leather tanning and dye production, and iii) their long-standing classification as anti-nutritional factors in animal nutrition discouraged wider biological investigations. Today, however, with the availability of high-resolution analytical techniques and renewed interest in polyphenolic bioactivity tannin research has begun to expand significantly. The importance of the subclass, hydrolysable tannins, will be highlighted as they are more easily isolated and investigated [11].

Materials and Methods

Literature search strategy

A systematic search of secondary data sources was conducted to identify relevant publications on vegetable tannins. The search strategy included combinations of the following keywords: "vegetable tannins," "plant sources," "biosynthesis," "methods of extraction," "bioactivities," and "industrial applications".

The searches were performed across major databases and repositories, including Google Scholar, Scopus, ResearchGate, and journal publisher websites. Additional grey literature was obtained from textbooks, handbooks, manuals, industry magazines and reports, conference proceedings, and society newsletters.

Inclusion and exclusion criteria

Sources were included if they:

- Discussed the chemistry, biosynthesis, extraction, or applications of vegetable tannins;
- Were published in English; and
- Represented reliable scientific, technical, or historical documentation from the 1700s to 2025.

Irrelevant, duplicated, or non-scientific materials were excluded from analysis.

Data extraction and analysis

Relevant information was extracted, compared, and synthesized to identify patterns, advancements, and knowledge gaps in the field. Emphasis was placed on integrating historical perspectives with contemporary research to present a coherent understanding of the evolution and industrial significance of vegetable tannins.

Discussion

Classification of tannins

Vegetable tannins are broadly classified into hydrolysable and condensed tannins, based on their structures and chemical properties. That is, their classification is based on the type of phenolic nuclei involved and the way they are linked together to achieve the molecular size and reactivity. Recently, a third group known as complex tannins or phloro-tannins, with characteristics between hydrolysable and condensed tannins, has been added [12,13]. While hydrolysable and condensed tannins are common in plants, complex tannins occur in brown algae [14]. The chemical characteristics of the two major classes, the hydrolysable tannins (HTs) and the condensed tannins(CTs) are presented below.

Hydrolysable tannins (HTs)

They form a class of plant polyphenolic compounds that are susceptible to hydrolysis. They are mainly composed of gallic acid (Figure 2), or ellagic acid (Figure 3), units linked to a polyol core, such as glucose [15]. Unlike condensed tannins, they can be easily broken down into simpler compounds under acidic, alkaline, or enzymatic conditions [12,15]. When aqueous tannin (tannic acid) is heated to between 150 and 200°C, it decomposes to pyrogallol (Figure 4) by first undergoing hydrolysis to gallic acid, and then decarboxylation and carbanion transition to produce pyrogallol [7,16]. Hydrolysable tannins are widely distributed in various plant species [13].

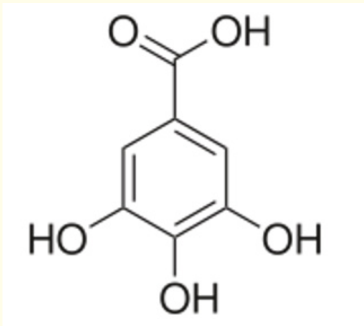


Figure 2: Gallic acid.

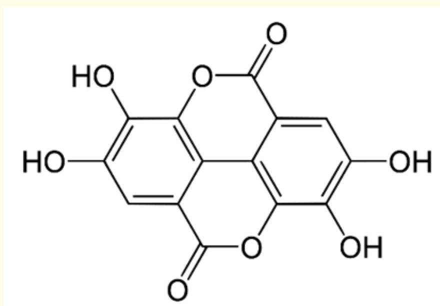


Figure 3: Ellagic acid.

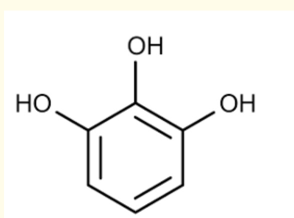


Figure 4: Pyrogallol.

Hydrolysable tannins are categorized based on their hydrolysis products: gallotannins**,** formed by the esterification of gallic acid molecules to a sugar (commonly glucose), and ellagitannins**,** in which hexahydroxydiphenoyl (HHDP) groups are present [13].

A typical example of gallotannins is schimperiin (Figure 5), isolated from the leaves of the Nigerian plant, *Anogeissus schimperii* (Combretaceae) [17]. The other group of hydrolysable tannins, the ellagitannins, are derived from the oxidative coupling of gallic acid units. An example of this class is punicalagin, (Figure 6), which occurs in pomegranates [18].

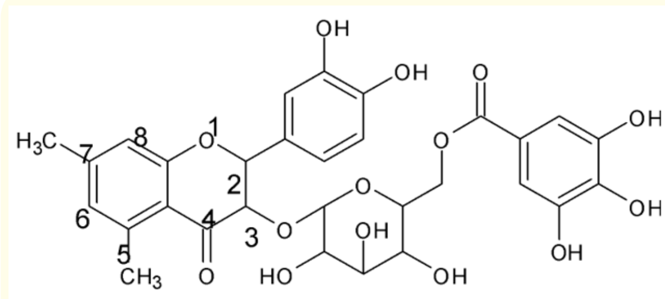


Figure 5: Schimperrin, a gallo-gluco-quercetin hydrolysable tannin.

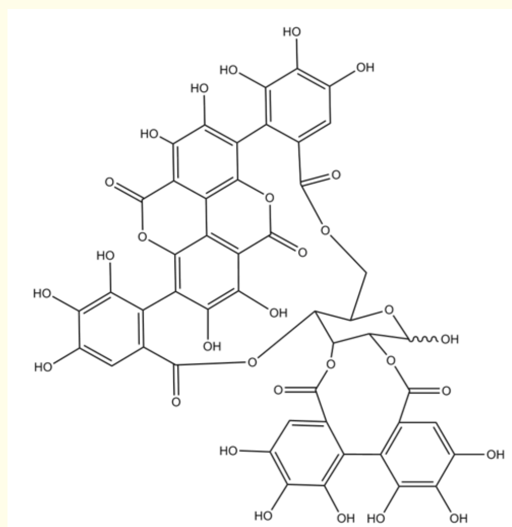


Figure 6: Punicalagin.

Condensed tannins

Condensed tannins, also known as proanthocyanidins, are a class of polyphenolic compounds found in many plant species. Structurally, condensed tannins are oligomers and polymers of flavan-3-ol units (Figure 7).

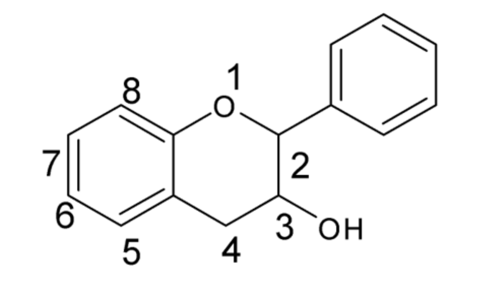


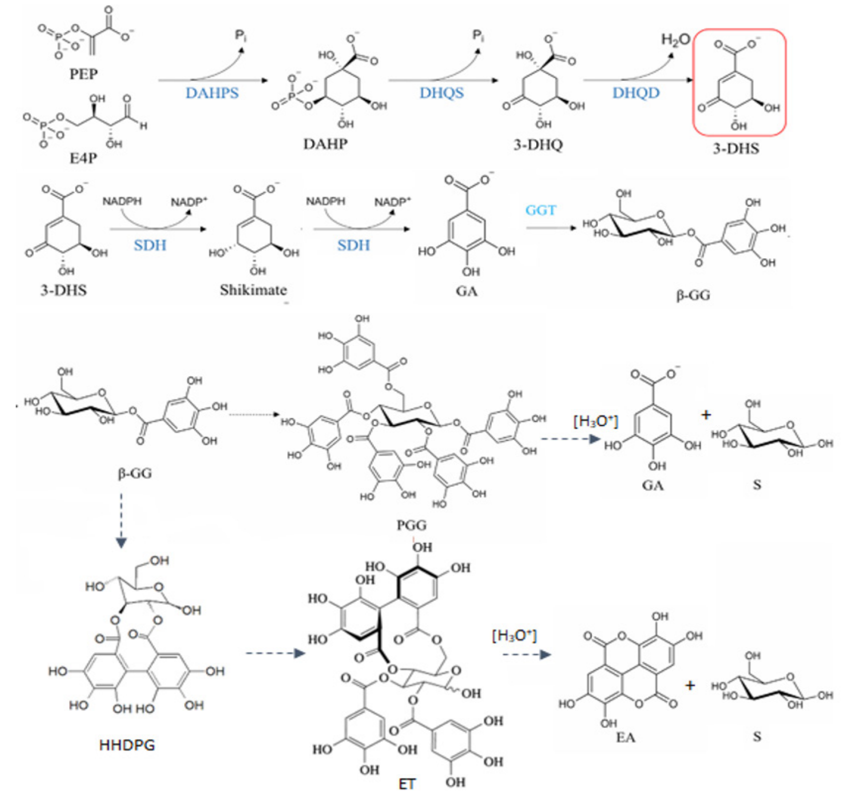
Figure 7: Flavan-3-ol.

These units are linked via carbon-carbon bonds, primarily at the C4–C8 or C4–C6 positions. The two main groups are procyanidins, derived from catechin or epicatechin units, and prodelphinidins**,** derived from gallocatechin units. Unlike hydrolyzable tannins, condensed tannins do not readily break down under acidic conditions, making them more stable. This is a major chemical characteristic that differentiates these two classes of tannins [19].

Biogenesis of vegetable tannins

Hydrolysable tannins

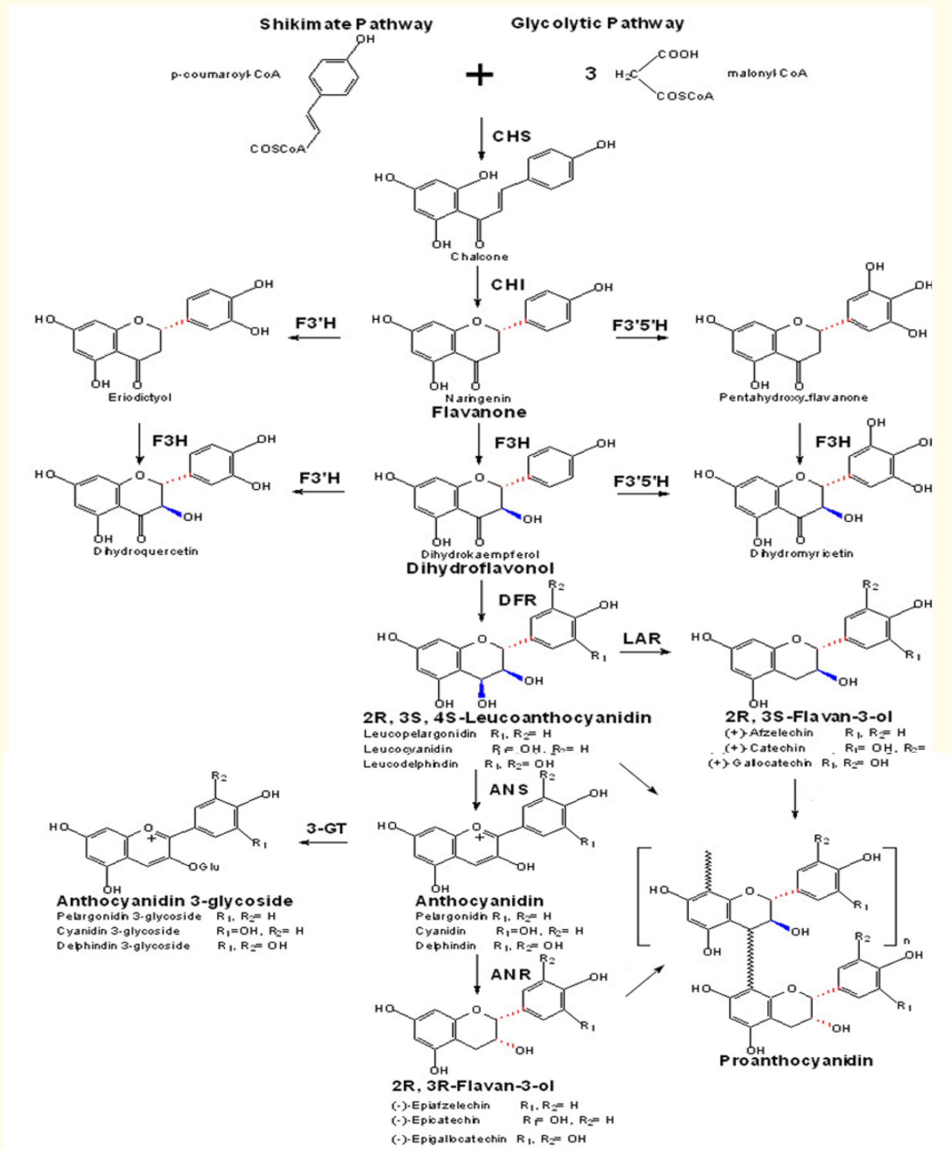
Hydrolysable tannins are direct products of plant metabolism and thus more amenable to biosynthetic study. Gallic acid and hexahydroxydiphenic acid are the principal phenolic constituents of gallotannins and ellagitannins encountered in plant tissues, either as esters with sugars or with flavan-3-ols as gallates. Gallotannins are derived from gallic acid**,** which originates via the shikimate pathway. This pathway begins with the conversion of phenylalanine to gallic acid through a series of reactions involving the enzyme phenylalanine ammonia-lyase (PAL), and the intermediates, trans-cinnamic acid and benzoic acid. Gallic acid is then esterified with glucose to form galloyl-glucose esters**.** Repeated esterification leads to complex gallotannins. Ellagitannins are formed when galloyl units (from gallotannins) undergo oxidative coupling to form hexahydroxydiphenoyl (HHDP) groups, which are then esterified to glucose or other polyols [18]. These pathways are shown in Scheme 1.



Scheme 1: Biogenesis of hydrolysable tannins via the shikimic acid pathway. Sources: Adapted from Haslam, E. [12] and Mora J., et al. [20]. Abbreviations: Phosphoenolpyruvate (PEP), erythrose4-phosphate (E4P), inorganicphosphate (Pi), 3-deoxy-D-arabino-heptulosonate-7-phosphate synthase (DAHPS), 3-deoxy-D-arabino-heptulosonate-7-phosphate(DAHP), dehydroquinate synthase (DHQS), 3-dehydroquinate (3-DHQ), 3-dehydroquinate dehydratase (DHQD), 3-dehydroshikimate (3-DHS), shikimate dehydrogenase (SDH), gallic acid (GA), β-glucogallin (β-GG), pentagalloylglucose (PGG), and β-glucogallin-dependent galloyltransferases (GGT), hexahydroxydiphenoyl glucocse (HHDPG), ellagitannin (ET), acid hydrolysis ([H3O+]), sugar unit (S), and ellagic acid (EA).

Condensed tannins

Condensed tannins are oligomers or polymers of flavan-3-ols such as catechin and epicatechin, synthesized through the flavonoid biosynthesis pathway**.** The biogenesis starts with phenylalanine, which is converted to cinnamic acid by phenylalanine lyase (PAL). Via chalcone synthase (CHS) and chalcone isomerase (CHI), the pathway yields flavonoids such as naringenin. Dihydroflavonol reductase (DFR) catalyzes the conversion of flavanones to flavan-3,4-diols, precursors of catechins. These are converted to catechins via leucoanthocyanidin reductase (LAR) and anthocyanidin reductase (ANR), and further polymerized into proanthocyanidins. Polymerization may involve both enzymatic and non-enzymatic steps [21]. These biogenetic processes are shown in Scheme 2.



Scheme 2: Biogenesis of proanthocyanidins via the shikimic acid and chalcone pathways. Source: Adapted from He F. [21]. Abbreviations: Chalcone synthase (CHS), chalcone isomerase (CHI), Flavonoid 3’-hydroxylase (F3’H), flavonoid 3’,5’-hydroxylase (F3’5’H), flavanone 3-β-hydroxylase (F3H), Dihydroflavonol reductase (DFR), leucoanthocyanidin reductase (LAR) and anthocyanidin reductase (ANR).

Sources of vegetable tannins

Tannins found in plants are commonly referred to as vegetable tannins and have been reported from various plant species (Table 1).

Botanical Name	Common Name	Plant Part Used	Tannin Type	Distribution/Origin	Notes/Traditional Uses
Acacia mearnsii	Black wattle/ Mimosa	Bark	Condensed tannins (proanthocyanidins)	Australia, Africa, South America	Widely used in leather tanning; gives reddish-brown tone.
Quercus robur	Oak	Bark, wood	Hydrolysable tannins (ellagitannins)	Europe	Traditional oak bark tanning; durable leather.
Rhus coriaria	Sumac	Leaves	Hydrolysable tannins (gallotannins)	Mediterranean region	Produces light, soft leathers; high-purity tannin.
Castanea sativa	Chestnut	Wood, bark	Hydrolysable tannins (ellagitannins)	Southern Europe	Used for heavy leather tanning; strong color.
Tara spinosa	Tara	Pods	Hydrolysable tannins (gallotannins)	South America (Peru, Bolivia)	Modern industrial source for vegetable tanning.
Schinopsis balansae	Quebracho	Heartwood	Condensed tannins	South America (Argentina, Paraguay)	Major commercial condensed tannin extract; red hue.
Ceriops tagal	Mangrove	Bark	Condensed tannins	Tropical Asia, Africa	Traditional source; yields dark, waterproof leather.
Valonia (Quercus aegilops acorn cups)	Valonia oak	Fruit cups	Hydrolysable tannins (ellagitannins)	Eastern Mediterranean	Used since antiquity for durable tannage.
Terminalia chebula	Myrobalan	Fruits	Hydrolysable tannins (gallotannins)	India, SE Asia	Light-colored tannin; used in blend for soft leather.
Punica granatum	Pomegranate	Rind, pericarp	Hydrolysable tannins	Mediterranean, Asia	Used in dyeing and tanning; bright, pale tannin extract.

Table 1: Tannin constituents of some species of plants.

Source: Adapted from Falcão, L., and Araújo, MEM. [7].

Table 1 shows a variety of plant sources, including the genera, plant parts and geographical locations. Thus, they are commonly found in the leaves, bark, fruits, pods and wood, but probably less commonly in the roots. Tannins are known to play important roles in plant defense mechanisms, nutrient absorption, and ecological interactions [22] and generally contribute to the bitterness and astringency of most plant sources [23].

The sources shown in Table 1 are just a few as berries such as cranberries, strawberries, blueberries, and blackberries also contain significant levels of tannins, contributing to their slightly tart taste [24]. Pomegranates are particularly rich in both ellagitannins and gallotannins, which contribute to their astringency and potential health benefits as shown in Table 1. Teas also contain significant amounts of tannins, especially catechins and other flavonoid tannins, which contribute to their characteristic bitterness and astringency [25]. Coffee contains tannins, though in lower amounts than tea, which contribute to the complex taste of brewed coffee [26]. Similarly, nuts such as walnuts and pecans are rich in tannins, particularly in their skins, accounting for the mild bitterness. A high level of tannins, particularly condensed tannins, has also been found in the bark and wood of oak trees and oak barrels, which are used to impart tannins to wine (Table 1). The chestnut (*Castanea* species) contains hydrolysable tannins, which are widely used in the leather tanning industry (Table 1). Species belonging to the genus *Eucalyptus* are known to possess medicinal properties and contain tannins, which are responsible for part of their antimicrobial activity [27].

Thus, some abundant local crops, spices, and trees contain tannins belonging to the two major classes and are therefore readily available for consumption as foods and beverages.

Methods of extraction, analysis, isolation, and characterization of tannins

Extraction

Various methods have been applied in the extraction of tannins in particular and of polyphenols generally. They include solvent extraction, supercritical fluid extraction, ultrasound-assisted extraction, and microwave-assisted extraction. The most common and affordable method is solvent extraction (Table 2) [28].

Tannin Extract Code	Phase	MC (%)	Tannins (T) %	Catechin number	Non-tannins (NT) %	Total solids %	Total solubles (Tso) %	Purity (T/Tso)	Extraction rate (T/NT)
70GPC6	Liquid	6.23	10.2	9.0	6.30	16.8	16.5	0.70	1.60
70GPC6	Solid	5.09	38.9	45.7	46.19	85.9	85.9	0.50	0.80
70GPM6	Liquid	6.35	16.4	16.5	16.40	31.4	26.3	0.60	1.70
70GPM6	Solid	4.36	46.8	52.8	34.40	89.8	81.2	0.50	1.00
70GPF6	Liquid	5.21	32.5	30.7	10.90	46.6	43.4	0.75	2.98
70GPF6	Solid	5.15	47.6	57.2	41.50	92.3	81.4	0.60	1.15

Table 2: Results of chemical analysis of tannins from three ANT pod fractions, liquid and spray-dried solid phases).

Source: Adapted from Osman, Z., *et al.* [28].

The other more sophisticated methods which are not easily accessible or affordable are also discussed here.

- **Solvent Extraction:** This method is widely employed in the industry [26]. In solvent-extraction, it involves soaking ground plant material in a solvent or mixture of solvents, including water, ethanol, methanol, acetone or mixtures of water and organic solvents. Factors, including temperature, pH, and solvent concentration, may affect the extract yield. It has been observed that hot water or aqueous ethanol is commonly used for eco-friendly extraction [29].
- **Ionic Liquids Extraction:** Ionic liquids are salts which exist in liquid state at room temperature or at least temperatures below 100°C. They are made purely of cations and anions and therefore highly polar. They have very low vapour pressure, high thermal stability, and a wide range of dissolving capacity. Imidazolium-based ionic liquids have been used in tannins extraction. When used with aqueous solvent, the problem of acidic pH may arise, causing rearrangements and condensation reactions to insoluble phlobaphene precipitates, making extraction less effective. The method is rather expensive for industrial-scale production [29].
- **Supercritical Fluid Extraction:** For supercritical fluid extraction, supercritical CO_2 is used as the extracting agent under high pressure and moderate temperature. The advantage is that it is eco-friendly and leaves no solvent residue. It is particularly used for extracting hydrolyzable tannins with minimal degradation. It is commonly used to obtain condensed tannins from grape seeds [30].
- **Ultrasound Extraction**: Ultrasound-assisted extraction has been applied to pomegranate peels with high efficiency as the procedure reduces both extraction time and solvent usage. Sound frequencies above 20 kHz from the ultrasound

machine cause mechanical vibration in the plant matrix allowing better penetration of solvents into the ruptured membrane and cell tissues for faster extraction. However, prolonged sonification could lead to degradation of the targeted tannins [29].

Other extraction methods

Microwave and enzyme- extractions have also been used in tannins extraction. The microwave method helps to heat the plant material and speeds up the process by improving solvent penetration [31].

Analysis of tannins

Some methods have been developed for the qualitative and quantitative analysis of tannins (Figure 8). They include:

- Folin-Ciocalteu method measures total tannins in a sample by their reduction of the Folin-Ciocalteu reagent, forming a blue complex that is spectrophotometrically quantified as tannic acid equivalents. It involves reacting tannins with the Folin-Ciocalteu reagent and sodium carbonate, followed by spectrophotometric analysis at 725 nm. To determine total tannin content specifically, the method can be adapted by precipitating condensed tannins with a complexing agent like polyvinylpyrrolidone (PVPP) or skin powder, then measuring the difference in total phenolic content before and after precipitation to isolate the tannin fraction [32].
- Vanillin assay is used specifically for condensed tannins. Vanillin reacts with flavonoid units in tannins, forming a coloured product measurable by spectrophotometry at about 500 nm. For quantification, a standard curve of known standards, such as catechin and tannic acid, are used for extrapolation [33].
- Chromatographic techniques like high-performance liquid chromatography (HPLC) and liquid chromatography-mass spectrometry (LC-MS), provide advanced methods for detailed tannin profiling [34].
- Protein precipitation assay in which tannins' ability to bind proteins is quantified using bovine serum albumin as a substrate [35].

Purification techniques

Total crude extracts of tannins often contain other phenolic compounds as impurities, requiring isolation techniques to purify them. The common isolation techniques include [28,36-38]:

- Precipitation with organic solvents like acetone, methanol or ethanol by adding the solvent to the total crude extract to selectively precipitate condensed tannins.
- Chromatographic techniques using, i) column chromatography based on molecular size or polarity using a stationery phase such as sephadex, silica gel and mobile phase solvents, ii) HPLC for qualitative and quantitative separation of tannins, allowing tannin fractions to be separated based on polarity and molecular weight, iii) Size-exclusion chromatography and it is useful for both hydrolysable and condensed tannins on the basis of molecular size, iv) thin-layer chromatography (TLC) and paper chromatography which are about the simplest and fastest and are used for both the preliminary and complete separation of tannin components.
- Membrane filtration in which ultrafiltration or nanofiltration membranes are used to concentrate some wine by-products based on their molecular weight.
- Liquid-liquid extraction or partition between two immiscible solvents based on solubility differences of tannins in those solvents and has been effectively applied by adjusting the pH to optimise solubility.

The structures of tannins have been determined using traditional chemical degradation methodologies as well as spectroscopic methods of analysis. This is usually not an easy task because of the complex nature of both condensed and hydrolysable tannins. In terms of chemical degradation of a hydrolysable tannin, the tannin is first subjected to alkaline or enzymatic hydrolysis, and then the products are extracted into an organic solvent. The recovered components are characterised using UV absorption, NMR, and mass spectral analysis. This process has been effectively used to characterise the hydrolysable tannin, schimperiin isolated from the Nigerian plant, *Anogeissus schimperii* (Combretaceae) [39].

Perhaps one of the most investigated plants for tannins is *Anogeissus schimperii* (Márkéé and Marken duutsee, in Hausa), syn. *leiocarpus* (Combretaceae). It is the only species growing in Nigeria. It is also found in the Savanna areas of Senegal, Sudan, and Ethiopia. Various parts of the Nigerian species have been investigated for tannins, non-tannins, and other characteristics of the leaves, including the effect of seasonal variation on quantity, and the peak of tannin production (Tables 3) [39].

1	2	3	4	5	6	7			8
Month	Total solubles %	Insolubles %	Tannins %	Non- tannins %	pH of analytical infusion	Colour of analytical Infusion (1.0cm cell)			Remarks
						Y	R	B	
June	25.82	74.18	17.41	8.41	4.55	29	5	0	
July	26.83	73.17	17.35	9.48	4.90	22	10	1	
August	21.75	78.25	12.30	9.45	4.60	17.4	4.8	0.6	
September	24.14	75.86	13.10	11.04	4.85	21	4	1	
October	22.10	77.90	12.59	9.51	4.60	24	3	1	
November	22.69	77.31	11.27	11.42	4.70	27	6	1	
December	23.18	76.82	11.65	11.53	4.70	27	6	1	
January	22.63	77.37	10.63	12.00	4.60	22	7	1	
February	21.15	78.85	10.75	10.40	4.60	20	6	1	
March	-	-	-	-	-	-	-	-	Emergence of new leaves and absence of old leaves
April	-	-	-	-	-	-	-	-	
May	-	-	-	-	-	-	-	-	

Table 3: Analysis of composite leaves of *Anogeissus schimperii.*

Note: Analytical figures represent monthly averages for two years (1983 and 1984). Results in columns (2) to (5) are expressed on moisture – free basis. Y (yellow), R (red), and B (blue).

Source: Adapted from Nduji and Okwute [39].

The studies established that the peak of tannin production is in June for the composite leaves, (Table 3), which also displayed very good shelf-life. Based on the above characteristics *A. schimperii* has been proposed as a good alternative to *Acacia nilotica* as a vegetable tanning material, and comparable industrially to chemical-based tannins [39].

The various methodologies involved in the extraction, purification, and analysis of tannins from plant materials are shown in Figure 8.

Bioactivities of tannins

Tannins exhibit a wide range of bioactivities, making them important in both plant defense and human health applications. These bioactivities stem from their ability to bind with proteins, polysaccharides, and other macromolecules. Table 4 [40] provides a survey of some of these bioactivities, including anti-oxidant, wound healing/anti-inflammatory, anti-microbial, antimalarial, antidiabetic, and anticancer.

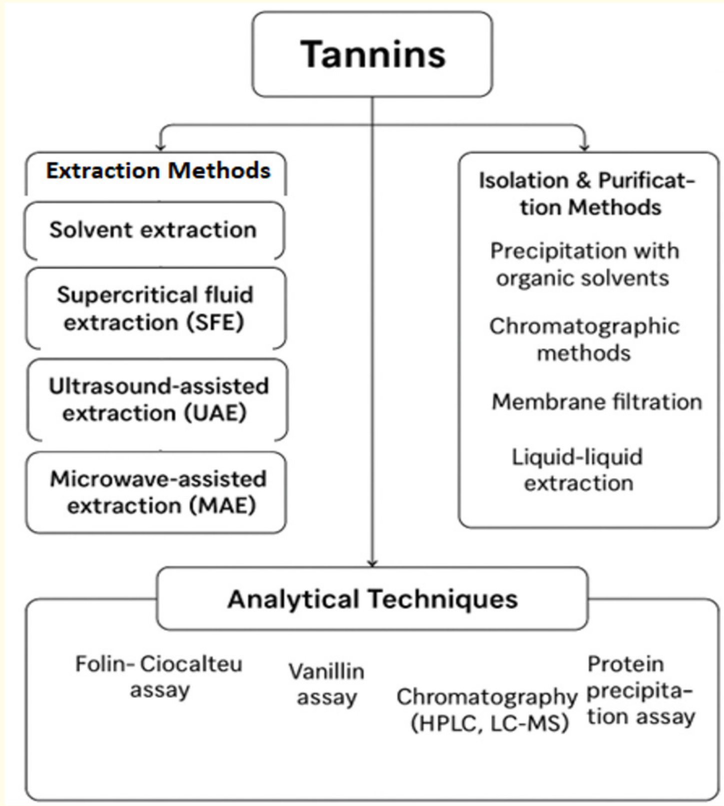


Figure 8: Methodologies for the extraction, isolation, and analysis of tannins from plants.

Source (Genus/ Species)	Tannin Classification	Major Compounds	Reported Bioactivities
Acacia sp. (e.g., *A. mearnsii*)	Condensed tannins (CT)	epi-FIS derivatives	Antioxidant, anti-inflammatory, antimicrobial
Acacia nilotica	CT	PoGG, EA, GA, diGA, epi/gallo-catechin, dicatechin derivatives	Antinociceptive, anti-inflammatory, antipyretic
Castanea sativa	Hydrolysable tannins (HT)	CAST, VES, EA, chestanin	Antioxidant, anti-inflammatory, antidiabetic, cardioprotective, antimicrobial, antifungal, antidiarrhoeal (veterinary)
Juglans regia	HT	EA, pedunculagin, casuariin	Antiplatelet, cardioprotective, antiatherogenic, anti-inflammatory

Table 4: Tannin-rich genera with some representatives, their tannin classification & compounds, and reported bioactivities.

Source: Adapted from Fraga-Corral M., *et al.* [40].

Wound healing and anti-inflammatory property

The wound-healing properties of the redox-active grape seed and the aqueous bark extract of *Rhizophora mangle*, which contain pro-anthocyanidins, have been reported [41]. Experiments with rodents using tannin extracts from *Myracrodruon urundeuva* stem bark showed that they possess anti-inflammatory and antiulcer activities. The plant is traditionally used in Northeast Brazil for managing wounds and gynaecological illnesses. For wound-healing and anti-inflammatory properties, some workers established a strong relationship between bioactivities and tannin content of the plants [42].

Antimicrobial property

A bioactivity commonly associated with tannins is their ability to fight infections. Tannins are known to possess strong antimicrobial properties against a range of bacteria, fungi, and viruses. This bioactivity is attributed to their ability to bind with microbial proteins and disrupt cell membranes. Thus, they are used as natural preservatives in food and beverages, and are ingredients in herbal medicines for treating infections. Examples are eucalyptus, tea, and pomegranate extracts [43]. Some tannins, particularly pro-anthocyanidins, and some hydrolysable tannins, particularly from pomegranate and gallnuts, have demonstrated anti-viral activity against flu, herpes, and HIV [43].

Anti-cancer property

Tannins, particularly condensed tannins, possess cytotoxic effects against cancer cells by inducing apoptosis and inhibiting tumor growth. Tannins are powerful antioxidants due to their polyphenolic structure, which allows them to scavenge free radicals and reduce oxidative stress. This activity is significant in preventing oxidative damage to cells and tissues, reducing the risk of chronic diseases, including cardiovascular diseases, cancer, and neurodegenerative conditions. The methanolic crude extracts of 12 traditionally used Indian medicinal plants were screened for their antioxidant and free radical scavenging properties using alpha-tocopherol and butylated hydroxytoluene (BHT) as standard antioxidants. Among the major phytocompounds implicated were tannins [44].

Economic and industrial potentials of vegetable tannins

Based on their chemical and biological characteristics above, tannins are a valuable resource, contributing to multiple industries and promoting sustainability in economic and industrial sectors. As they can be found in trees and herbs, they have been traditionally used for medicinal and other purposes of industrial and economic significance. The potential industrial and economic uses of vegetable tannins have been widely reported. They include leather, food, pharmaceuticals and neutraceuticals, adhesives, cosmetics, wines, and agriculture. The industrial and economic potentials are presented below, as well as summarised in Table 5 [40,45] and Figure 9.

Leather industry

Traditionally, vegetable tannins are used in the leather industry for eco-friendly tanning processes. They improve the durability and flexibility of leather. Plants have been exploited as vegetable tanning materials, including *Anogeissus latifolia* leaves possessing tannin content of 14-30%, *Acacia arabica* bark, 21%, *Rhizophora mucronota* bark,17%, *Cassia auriculate* bark, 17-22% and *Terminalia arjuna* bark, 19% which have been used extensively in South India tanning trade as well as pods, 42% and bark, 32-39%. The very young leaves of these plants have been found to offer the best promise as a potential tanning material with tannin content of 15-20% [39,45]. The chemical functionality of *Cassia singueana* bark tannin extract has been evaluated using FT-IR spectroscopy, and it showed that the physicochemical performance of the *Cassia singueana* extract tanned leather sample was scientifically comparable to the conventional mimosa-tanned leather sample [39].

Wood adhesives industry

Vegetable tannins are natural alternatives to synthetic adhesives in the wood industry as eco-friendly and sustainable materials. In addition, chemically modified thermosetting tannins for particleboard and plywood have been developed and industrially optimized. Tannin–urea–formaldehyde adhesives for corrugated board starch binders in plywood, and cold-setting tannin–resor-

Plant species	Type of tannin	Industrial/economic uses	Medicinal, food and drug uses	Agricultural uses	Other or special uses
Schinopsis spp. (Quebracho)	Condensed	Leather tanning, adhesives, corrosion inhibitors	Limited topical/traditional uses	Natural preservative potential	Commodity tannin export (South America)
Acacia mearnsii (Black wattle)	Condensed	Leather, wood adhesives, bio-resins	Antioxidant extracts, antimicrobial potential	Feed additive (antiparasitic, protein binding)	Major plantation economy crop
Castanea sativa (Chestnut)	Hydrolysable	Adhesives, wood protection, resins	Antioxidant, anti-inflammatory nutraceuticals	Natural fungicide, soil amendment	Timber and nut by-product valorization
Caesalpinia spinosa (Tara)	Hydrolysable	Leather, coatings, dyes	Antioxidant, antimicrobial food preservative	Botanical pesticide potential	Specialty export commodity
Terminalia spp. (Myrobalans)	Hydrolysable	Leather and dye industry	Antioxidant, antimicrobial, anti-inflammatory (Ayurvedic use)	Nematicidal/insecticidal effects	Herbal medicine trade
Vitis vinifera (Grape)	Condensed	Food antioxidant, cosmetic ingredient, biopolymer	Cardioprotective, antioxidant supplements	Compost/soil amendment	Wine by-product valorization
Camellia sinensis (Tea)	Mixed	Beverage industry, extracts for cosmetics	Health beverage, antioxidant, cardiometabolic benefits	Mulch, pest management	Global economic crop
Punica granatum (Pomegranate)	Hydrolysable	Natural colorant, preservative, cosmetics	Antioxidant, antimicrobial, wound-healing	Biopesticide, soil conditioner	Waste-to-value example (peel extracts)
Quercus spp. (Oak/Valonia)	Hydrolysable	Leather, dyeing, ink production	Astringent, antidiarrhoeal uses	Soil chemistry influence	Heritage craft material
Rhizophora spp. (Mangroves)	Condensed	Tanning, wood preservation, marine coatings	Antimicrobial folk uses	Antifouling, biocide potential	Important coastal resource

Table 5: Summary of major plant sources of vegetable tannins and their diverse applications.
Sources: Adapted from Fraga-Corral., *et al*. [40] and Pizzi A. [45].

Figure 9: A summary of economic potentials and industrial applications of vegetable tannins.

cinol–formaldehyde adhesives for glulam and finger-jointed lumber are available in the industry. However, due to the relative scarcity of tannins compared to synthetic adhesives, and to reduce the hazards of formaldehyde emissions, several studies are ongoing on extending their application in adhesives through copolymerization with other substances, such as lignin and furfuryl alcohol [45].

Foam Industry

Advancements in industrial development have led to tannin derivatives for use as substitutes for polyols in reactions with polymeric isocyanates to produce polyurethanes of different textures, densities, and fire-resistance properties for use in the polyurethane foam industry. This is because the tannin structure allows the formation of urethane (R-NH-CO-O-R') linkages at both the alcoholic C3 and phenolic -OH. These tannin-derived foams have found applications for acoustic insulation, and in bone repair by osteogenesis with stem cells as a biomaterial scaffold for osteo-competent cells, and biologically active agents that are biocompatible, and have the potential to be replaced by bone *in vivo* [45].

Foods and drugs

Tannins are used as natural preservatives due to their antioxidant and antimicrobial properties in the food industry [46]. They are also employed as clarifying agents in wine and beer production. The condensed tannins have a reduced astringent power, with a high ability to release the aromatic precursors present in wines. Proanthocyanidins are naturally present in grapes (*Vitis vinifera*), and release anthocyanins and other insoluble molecules when they are treated with acid hydrolysis. They are mainly diffused in the skins and seeds of grapes, and are therefore found in red wines [47]. The amount of tannins in wines and fruit juice are highly controlled to accelerate wine aging, make wine clearer by precipitating undesired biomolecules, and achieve the desired organoleptic taste. The cardioprotective properties of red wine are particularly attributed to the antioxidant properties of constituent or added tannins, which also help eliminate carbohydrates and proteins through precipitation [45]. Their ability to precipitate and form complexes with proteins and other biomolecules makes them excellent bacteriocides and antimicrobials. Its antioxidant potential in food preservation is being exploited in foodstuffs. Numerous experimental studies have also documented the pharmaceutical potential of tannins, including antiviral, antitumor, and anti-cancer properties. Hence, they hold great potential for incorporation into products for their health benefits, such as supplements to combat oxidative stress or formulations for antimicrobial treatments. Thus, managing infectious diseases and possibly exhibiting anticancer effects. Tannins are added in cosmetics for their astringent and antioxidant properties, supporting skin tightening and protection against environmental damage. Thus, they are generally of medicinal value.

Uses in agriculture

Tannins have uses in agriculture. Condensed tannins play important roles in plant defense mechanisms. For example, they act as herbivore deterrents due to their astringency, as well as inhibit the digestive enzymes in herbivore guts. Also, they have been found to absorb UV radiation, protecting plant tissues from damage, while their antimicrobial properties protect plants against pathogens. Condensed tannins promote animal nutrition by reducing protein degradation in ruminants' stomachs, improving protein utilization and reducing methane emissions [48].

Mineral mining, metal coating, and ink production

In the mining of fluorite, tannin extracts have been exploited as an agent to reduce the formation of unwanted calcite in the mineral recovery process. Likewise, tannin extracts have been used in the separation of germanium from copper in copper mines [45]. The anticorrosive properties of tannin-based primers for coating of metal surfaces, especially steel, have also been well studied. Tannins are able to form resistant orthodiphenol metal complexes with metal surfaces. Tannin-based anti-corrosion agents for metal coating are available commercially [45]. Its ability to form metal complexes has been exploited in antifouling agents for ship parts in seawater to reduce fouling. Tannin-copper antifouling formulations consume 40-fold less copper than copper-based paints. The same kind of complexation was also exploited in ferrous tannate-based ink, which was widely used in the Middle Ages up to the 19th century, and remains conservatively relevant today [45].

Waste management

Tannin powder and other formulations are used in industry for waste management as flocculants and purifiers for wastewater. Tannins are natural ion chelators and can remove heavy metal ions, especially Cu, Pb, and Sb ions from solutions and industrial waste. It has been used as a flocculant to remove clay suspensions in water treatment [45].

Conclusion

In conclusion, the review has provided a comprehensive overview of vegetable tannins, elucidating their sources, chemical structures, and significant industrial applications. As versatile polyphenolic compounds, vegetable tannins demonstrate remarkable properties that extend beyond traditional uses in leather tanning, showcasing their potential in various industries such as food and pharmaceuticals. The discussion on hydrolysable tannins highlights their advantageous extraction and application characteristics, making them particularly valuable in sustainable practices. As the global market increasingly prioritizes eco-friendly materials and processes, the relevance of vegetable tannins continues to grow. This review not only emphasizes the historical context of tannins but also points towards their promising future in innovative industrial applications. Future research should focus on further exploring the biological activities of tannins and optimizing their extraction and application methodologies to fully harness their capacity in advancing sustainable solutions across multiple sectors.

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