Life Sci. Res. Commn., 2026; 2(3):222-243.
https://lifesci.com.sg

Review Article

Phenolic Compounds in Medicinal Plants: Chemistry, Pharmacological Activities and Health Benefits

Praveen Kumar Ashok[1,*], Babita[1], Vartika Lohani[1], Reetika Gupta[1], Jhuma Samanta[1], Kumud Upadhyaya[2]

[1]School of Pharmaceutical Sciences, Jigyasa University (Formerly Himgiri Zee University), Dehradun, Uttarakhand, INDIA.
[2]Department of Pharmaceutical Sciences, Faculty of Technology, Kumaun University, Nainital, Uttarakhand, INDIA.

Correspondence:
Prof. (Dr.) Praveen Kumar Ashok
School of Pharmaceutical Sciences, Jigyasa University (Formerly Himgiri Zee University), Dehradun, Uttarakhand, INDIA.
Email: pkashok157@gmail.com

Received: 14-07-2026;
Revised: 24-08-2026;
Accepted: 05-10-2026.

ABSTRACT

Phenolic compounds are important secondary metabolites found widely in medicinal plants. They include phenolic acids, flavonoids, tannins, stilbenes, lignans, coumarins, and related compounds. These compounds have attracted considerable research interest because of their diverse biological properties. Their chemical structures influence their solubility, stability, antioxidant capacity, and biological activity. Medicinal plants provide a rich and natural source of these compounds. This review discusses the major classes of phenolic compounds found in medicinal plants. It also describes their basic chemical characteristics, distribution, and important plant sources. Special attention is given to their pharmacological activities. These include antioxidant, anti-inflammatory, antimicrobial, antiviral, antidiabetic, hepatoprotective, cardioprotective, neuroprotective, and anticancer effects. The possible mechanisms responsible for these activities are also discussed. Phenolic compounds can influence oxidative stress, inflammatory mediators, cellular signaling pathways, and other biological processes. The review also highlights the importance of phenolic compounds in human health and their potential applications in pharmaceutical, nutraceutical, and functional food products. Their bioavailability, metabolism, safety, and current research challenges are also discussed. A better understanding of these compounds may contribute to the development of plant-based therapeutic agents and health-promoting products.

Keywords: Antioxidant activity, Flavonoids, Health benefits, Medicinal plants, Pharmacological activities, Phenolic acids, Phenolic compounds, Tannins.

INTRODUCTION

Medicinal plants have been used as sources of food and medicine for centuries. Different parts of these plants contain numerous biologically active compounds. Leaves, flowers, fruits, seeds, stems, bark, and roots may contain phenolic compounds and other secondary metabolites. These compounds contribute to the biological properties of many medicinal plants (Sun and Shahrajabian, 2023; Kumar *et al*., 2021).

Phenolic compounds are a large group of plant secondary metabolites. They contain one or more hydroxyl groups attached to an aromatic ring. Their structures range from simple phenolic molecules to complex polymers. More than 8,000 naturally occurring phenolic compounds have been described. This structural diversity contributes to their different biological functions (Tsitsin *et al*., 2023; Zhang *et al*., 2022).

DOI: 10.5530/lsrc.2.3.26

Copyright Information :
Copyright Author (s) 2026 Distributed under Creative Commons CC-BY 4.0

Publishing Partner : Manuscript Technomedia. [www.mstechnomedia.com]

Phenolic compounds are broadly divided into flavonoid and non-flavonoid groups. Important classes include phenolic acids, flavonoids, tannins, stilbenes, lignans, and coumarins. Phenolic acids are mainly represented by hydroxybenzoic and hydroxycinnamic acids. Flavonoids include flavones, flavonols, flavanones, flavan-3-ols, isoflavones, and anthocyanins (Sun and Shahrajabian, 2023; de la Rosa *et al*., 2022).

The formation of phenolic compounds is closely related to plant secondary metabolism. The phenylpropanoid pathway plays a central role in their biosynthesis. Phenylalanine is converted into important intermediates through the action of enzymes such as phenylalanine ammonia-lyase, cinnamate 4-hydroxylase, and 4-coumarate-CoA ligase. These intermediates contribute to the formation of phenolic acids, flavonoids, lignin, and other phenolic metabolites (Gligor *et al*., 2019).

Phenolic compounds have attracted considerable interest because of their diverse pharmacological activities. Studies have reported antioxidant, anti-inflammatory, antimicrobial, antiviral, antidiabetic, cardioprotective, neuroprotective, and anticancer effects. These activities are associated with their ability to influence oxidative stress, inflammatory responses, cellular

signaling, and other biological processes (Sun and Shahrajabian, 2023; Rana *et al.*, 2022).

The antioxidant properties of phenolic compounds are particularly important. Some phenolics can directly interact with reactive oxygen species. Others may support endogenous antioxidant systems. These effects may help protect cells against oxidative damage. Such mechanisms have been investigated in relation to cardiovascular, neurological, metabolic, and other chronic disorders (Santos *et al.*, 2021).

Phenolic compounds are also important from a nutritional perspective. They occur in many fruits, vegetables, cereals, herbs, spices, beverages, and medicinal plants. Their biological effects, however, cannot be judged only by their concentration in foods or plant extracts. Absorption, metabolism, intestinal microbiota, and chemical structure can strongly influence their activity in the human body (Del Bo' *et al.*, 2019; Fraga *et al.*, 2019).

Despite extensive research, several challenges remain. Many biological effects have been demonstrated in cell and animal models. Their translation to human health requires further clinical evidence. Low bioavailability is another important limitation for several phenolic compounds. Individual differences in metabolism and gut microbiota may also influence their biological effects (Fraga *et al.*, 2019; Mutha *et al.*, 2022).

Phenolic Compounds in Medicinal Plants

Phenolic compounds are a large and diverse group of secondary metabolites found in plants. They generally contain an aromatic ring with one or more hydroxyl groups. Their structures vary from simple phenolic molecules to complex polymeric compounds. More than 8,000 naturally occurring phenolic compounds have been described. They are widely distributed in medicinal plants and contribute to several biological and physiological functions (Tungmunnithum *et al.*, 2018; Sun and Shahrajabian, 2023).

Phenolic compounds occur in different plant tissues. They have been reported in leaves, flowers, fruits, seeds, stems, bark, and roots. Their concentration can vary between plant species and plant parts. Environmental conditions can also influence their production and accumulation. Light, temperature, ultraviolet radiation, water availability, and other stress factors may alter the phenolic profile of plants (Tsitsin *et al.*, 2023).

These compounds perform several important functions in plants. They can contribute to plant defense against pathogens and herbivores. Some phenolics also participate in plant growth and development. They may protect plant tissues against ultraviolet radiation and oxidative stress. Their antioxidant properties are also important for maintaining cellular protection under stressful conditions (Sun and Shahrajabian, 2023; Tsitsin *et al.*, 2023).

Phenolic compounds are chemically diverse. Major groups include phenolic acids, flavonoids, tannins, coumarins, lignans, stilbenes, quinones, curcuminoids, and related compounds. Phenolic acids are mainly divided into hydroxybenzoic acids and hydroxycinnamic acids. Gallic acid, vanillic acid, protocatechuic acid, caffeic acid, ferulic acid, and p-coumaric acid are common examples (Kumar and Goel, 2019; Sun and Shahrajabian, 2023).

Flavonoids represent one of the largest groups of plant phenolics. They include flavones, flavonols, flavanones, flavan-3-ols, isoflavones, and anthocyanins. Their structural differences are mainly related to the substitution pattern and oxidation state of their carbon rings. These structural variations influence their biological properties and distribution in plants (Tungmunnithum *et al.*, 2018; Sun and Shahrajabian, 2023).

Medicinal plants are important sources of phenolic compounds. Many traditional medicinal plants contain several phenolic classes at the same time. The chemical composition may differ according to species, geographical origin, plant part, harvesting stage, and environmental conditions. Therefore, the selection and authentication of plant material are important when studying phenolic-rich medicinal plants (Tungmunnithum *et al.*, 2018; Kisiriko *et al.*, 2021).

The biological importance of phenolic compounds has increased interest in medicinal plant research. Phenolic-rich extracts and individual compounds have been investigated for antioxidant, anti-inflammatory, antimicrobial, antiviral, cardioprotective, neuroprotective, antidiabetic, and anticancer activities. However, the biological response depends on the chemical structure and concentration of the compound. Absorption and metabolism can also influence its activity in the human body (Mutha *et al.*, 2021; Sun and Shahrajabian, 2023).

The diversity of phenolic compounds makes them valuable for pharmaceutical and health-related research. Their presence in medicinal plants provides a basis for investigating new natural products. However, the reported biological activity of a plant extract should not be attributed to a single phenolic compound without adequate chemical and biological evidence. Standardized extraction, accurate identification, and suitable biological models are therefore important for reliable research.

Definition and General Characteristics

Phenolic compounds are a large and diverse group of plant secondary metabolites. They are characterized by the presence of at least one hydroxyl group attached directly to an aromatic ring. Their structures range from simple phenolic acids to complex compounds such as tannins and other polymers. More than 8,000 phenolic structures have been reported in plants (Albuquerque *et al.*, 2021; Al Mamari, 2021).

Phenolic compounds are widely distributed in the plant kingdom. They occur in leaves, flowers, fruits, seeds, stems, bark, and roots. They may be present as free compounds or in bound forms. Many phenolics also occur as glycosides. The distribution and

concentration of these compounds vary among plant species and plant tissues (Kisiriko *et al.*, 2021).

The chemical diversity of phenolic compounds is considerable. It results from differences in the number of aromatic rings, hydroxyl groups, substituents, and linkages between structural units. Important groups include phenolic acids, flavonoids, tannins, coumarins, lignans, stilbenes, quinones, and curcuminoids. This structural diversity is closely related to their biological properties (Sun and Shahrajabian, 2023; Tsitsin *et al.*, 2023).

Phenolic compounds have important functions in plants. They participate in plant defense and protection against pathogens and herbivores. They can also protect plant tissues from ultraviolet radiation and oxidative stress. Some phenolics act as pigments and contribute to the colour of flowers and fruits. Others participate in plant growth, development, seed germination, and adaptation to environmental stress (Kisiriko *et al.*, 2021).

The production of phenolic compounds is influenced by several factors. These include plant species, genetic characteristics, geographical location, maturity, temperature, light, water availability, and exposure to biotic or abiotic stress. Such factors can change both the amount and composition of phenolic compounds in medicinal plants (Tsitsin *et al.*, 2023).

Phenolic compounds are also important because of their potential biological activities. Many phenolics can act as antioxidants by donating hydrogen or electrons to reactive species. Some compounds can also influence cellular antioxidant systems. Their biological effects are therefore not limited to direct radical scavenging. They may also involve regulation of cellular signaling and endogenous defense mechanisms (Albuquerque *et al.*, 2021; Sun and Shahrajabian, 2023).

In medicinal plants, phenolic compounds may occur as individual molecules or as complex mixtures within plant extracts. Their biological effects may result from a single compound or from interactions among several constituents. Therefore, chemical characterization is important when evaluating the pharmacological potential of phenolic-rich medicinal plants. Extraction method, plant material, and analytical technique can also influence the detected phenolic profile (Table 1) (Kisiriko *et al.*, 2021; Alara *et al.*, 2021).

Classification of Phenolic Compounds

Phenolic compounds show considerable structural diversity. Their classification is mainly based on their carbon skeleton, number of aromatic rings, and the groups connecting these rings. They are broadly divided into flavonoids and non-flavonoid phenolics. The major groups include phenolic acids, flavonoids, tannins, coumarins, lignans, stilbenes, quinones, xanthones, and curcuminoids (Kisiriko *et al.*, 2021; Sun and Shahrajabian, 2023).

Phenolic Acids

Phenolic acids contain a phenolic ring and a carboxylic acid group. They are mainly divided into hydroxybenzoic acids and hydroxycinnamic acids. Hydroxybenzoic acids have a C6-C1 skeleton. Gallic acid, vanillic acid, protocatechuic acid, syringic acid, and p-hydroxybenzoic acid are common examples. Hydroxycinnamic acids have a C6-C3 skeleton. Caffeic acid, ferulic acid, p-coumaric acid, and sinapic acid belong to this group (Sun and Shahrajabian, 2023).

Flavonoids

Flavonoids form one of the largest groups of plant phenolics. They generally possess a C6-C3-C6 skeleton. The basic structure contains two aromatic rings connected through a three-carbon bridge. Major subclasses include flavones, flavonols, flavanones, flavan-3-ols, isoflavones, anthocyanins, and related compounds. Small structural changes can produce major differences in their biological properties (Zhang *et al.*, 2022; Sun and Shahrajabian, 2023).

Tannins

Tannins are high-molecular-weight phenolic compounds. They are known for their ability to bind proteins and other macromolecules. Tannins are commonly divided into hydrolysable tannins and condensed tannins. Hydrolysable tannins contain phenolic acids linked to a sugar or related core. Condensed tannins are also known as proanthocyanidins. Their structures are formed mainly from flavonoid units (Kisiriko *et al.*, 2021).

Table 1: General characteristics of phenolic compounds.

Characteristic	Description
Chemical nature	Plant secondary metabolites
Basic structural feature	Aromatic ring with one or more hydroxyl groups
Major forms	Free, bound, glycosylated, monomeric, and polymeric forms
Major classes	Phenolic acids, flavonoids, tannins, coumarins, lignans, stilbenes, quinones, and curcuminoids
Plant distribution	Leaves, flowers, fruits, seeds, stems, bark, and roots
Major plant functions	Defense, UV protection, antioxidant protection, pigmentation, and adaptation to stress
Important biological properties	Antioxidant, anti-inflammatory, antimicrobial, antiviral, and other pharmacological activities

Stilbenes

Stilbenes contain two aromatic rings connected by a two-carbon bridge. Resveratrol is one of the best-known members of this group. Stilbenes occur in several medicinal plants and are produced as part of plant defense responses. Their reported biological activities have generated considerable interest in pharmaceutical research (Teka *et al.*, 2022).

Lignans and Neolignans

Lignans are formed from two phenylpropanoid units. The units are generally linked through their β-carbons. Neolignans have related structures but differ in the pattern of linkage between their phenylpropanoid units. These compounds occur in several medicinal plants and have been investigated for antioxidant, anti-inflammatory, antimicrobial, and other biological activities (Kisiriko *et al.*, 2021).

Coumarins

Coumarins are benzopyrone derivatives. They may occur as free compounds or as glycosides. Important groups include simple coumarins, furanocoumarins, pyranocoumarins, and related derivatives. Coumarins have been identified in several medicinal plant families. Their structural diversity is associated with a broad range of biological activities (Kisiriko *et al.*, 2021).

Other Phenolic Compounds

Other important phenolic groups include quinones, xanthones, curcuminoids, biflavonoids, and lignins. These compounds differ considerably in their structures and biological properties. Curcuminoids, for example, include curcumin and related compounds. Quinones include several naturally occurring aromatic compounds with important biological functions. Lignin is a complex phenolic polymer that contributes to plant cell-wall structure (Table 2) (Sun and Shahrajabian, 2023).

Chemical Structure and Properties

The chemical structure of phenolic compounds varies considerably. This variation is mainly related to the number and position of aromatic rings and hydroxyl groups. Other structural groups, such as methoxy, carbonyl, carboxyl, and glycosyl groups, also influence their properties. These structural differences contribute to the wide biological diversity of plant phenolics (Kisiriko *et al.*, 2021; Tsitsin *et al.*, 2023).

The basic structural feature of a phenolic compound is an aromatic ring containing at least one hydroxyl group. Simple phenolics may contain only one aromatic ring. More complex compounds contain several aromatic rings. Flavonoids generally have a C6-C3-C6 carbon skeleton. Phenolic acids commonly possess C6-C1 or C6-C3 skeletons. Tannins may contain multiple phenolic units linked together (Kisiriko *et al.*, 2021).

The number and position of hydroxyl groups can affect the chemical behaviour of phenolic compounds. Hydroxyl groups can donate hydrogen atoms or electrons to reactive species. Their position within the molecule can also influence radical stabilization. In flavonoids and phenolic acids, hydroxylation patterns are therefore important determinants of antioxidant activity (Rice-Evans *et al.*, 1996; Heim *et al.*, 2002).

Methoxy groups can modify the physical and biological properties of phenolic compounds. They can increase lipophilicity and alter membrane partitioning. Glycosylation is another important structural modification. Attachment of a sugar moiety can change solubility, stability, absorption, and metabolism. Therefore, the aglycone and glycoside forms of the same phenolic compound may show different biological behaviour (Heim *et al.*, 2002).

Phenolic compounds can occur in free, esterified, glycosylated, or polymeric forms. Phenolic acids may be linked to cell-wall components or other molecules. Flavonoids commonly occur as

Table 2: Major classes of phenolic compounds found in medicinal plants.

Phenolic class	Main structural feature	Representative compounds	Examples of medicinal plant sources
Phenolic acids	C6-C1 or C6-C3 skeleton	Gallic acid, caffeic acid, ferulic acid	Syzygium aromaticum, Salvia officinalis, Zingiber officinale
Flavonoids	C6-C3-C6 skeleton	Quercetin, kaempferol, catechin, apigenin	Camellia sinensis, Ginkgo biloba, Ocimum basilicum
Tannins	Polyphenolic structures	Tannic acid, proanthocyanidins	*Terminalia* spp., *Acacia* spp.
Stilbenes	C6-C2-C6 skeleton	Resveratrol, pterostilbene	*Vitis vinifera, Pinus* spp.
Lignans	Two phenylpropanoid units	Sesamin, podophyllotoxin	*Sesamum indicum, Podophyllum* spp.
Coumarins	Benzopyrone nucleus	Coumarin, esculetin, scopoletin	*Cinnamomum* spp., *Angelica* spp.
Quinones	Quinone aromatic system	Juglone, lawsone	*Juglans* spp., *Lawsonia inermis*
Curcuminoids	Diarylheptanoid-type structure	Curcumin, demethoxycurcumin	Curcuma longa
Xanthones	Xanthone nucleus	Mangiferin, α-mangostin	*Mangifera indica, Garcinia* spp.

glycosides in plants. Tannins contain several phenolic units and can form complexes with proteins and other macromolecules. These different forms influence extraction, stability, bioavailability, and biological activity (Kisiriko *et al.*, 2021).

The conjugated structures of many phenolic compounds also influence their optical and redox properties. Extended conjugation can facilitate electron delocalization. This property is important for the stabilization of phenoxy radicals. It also contributes to the colour of several plant phenolics, particularly anthocyanins and related pigments (Tsitsin *et al.*, 2023).

Solubility is another important property. Phenolic compounds with several hydroxyl groups are generally more hydrophilic. Methoxylation and other structural modifications can increase lipophilicity. Glycosylation may improve water solubility in some compounds. These differences influence extraction efficiency and the behaviour of phenolics in biological systems (Heim *et al.*, 2002; Albuquerque *et al.*, 2021).

The chemical structure also affects the stability of phenolic compounds. Factors such as pH, temperature, oxygen, light, and metal ions may influence their stability. The response differs between individual phenolic classes. Therefore, processing and storage conditions can change the phenolic profile of medicinal plant extracts (Table 3 and Figure 1) (Tsitsin *et al.*, 2023).

Distribution and Major Plant Sources

Phenolic compounds are widely distributed in medicinal plants. They can occur in leaves, flowers, fruits, seeds, stems, bark, and roots. However, their concentration is not uniform throughout the plant. Different tissues may contain different phenolic profiles. This variation is related to the physiological role of each plant part and its exposure to environmental conditions (Kisiriko *et al.*, 2021).

Leaves are important sources of flavonoids and phenolic acids. Flowers may contain high levels of flavonoids and anthocyanins. Fruits commonly contain phenolic acids, flavonoids, and tannins. Roots and bark can contain tannins, lignans, coumarins, and other phenolic constituents. The distribution also varies between plant species and even between different tissues of the same species.

Phenolic compounds may occur in both free and bound forms. Free phenolics can be extracted relatively easily from plant tissues. Bound phenolics are associated with cell-wall components or other macromolecules. They may require additional treatment for their release. This difference is important when comparing the total phenolic content of medicinal plant materials (Wang *et al.*, 2020).

The phenolic profile of a medicinal plant is affected by several factors. These include genetic characteristics, geographical origin, soil conditions, plant age, maturity, harvesting time, and plant tissue. Environmental factors are also important. Temperature, light, water availability, salinity, and other stresses can modify secondary metabolite production (Pant *et al.*, 2021).

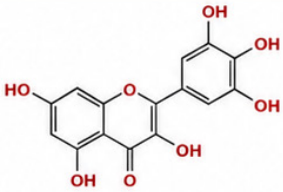
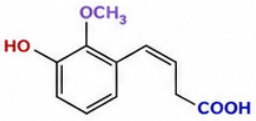
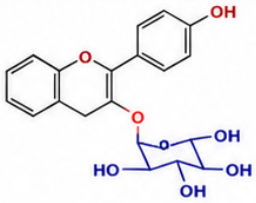
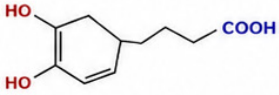
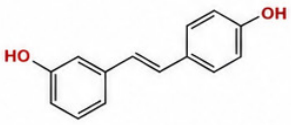
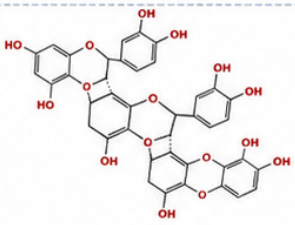
Geographical variation can produce considerable differences in phenolic content. Plants of the same species grown in different regions may show different chemical profiles. Differences in rainfall, temperature, soil composition, and altitude can contribute to this variation. Therefore, geographical origin should be considered during the quality assessment of phenolic-rich medicinal plants.

Plant stress can also influence phenolic accumulation. Phenolic compounds participate in plant protection against several environmental challenges. Recent research indicates that changes in temperature, drought, carbon dioxide, and other climate-related factors can modify secondary metabolite production in medicinal plants. Such changes may affect both the quantity and composition of bioactive compounds (Jangpangi *et al.*, 2025).

Environmental contamination can further alter phenolic metabolism. Exposure to heavy metals may affect enzymes

Table 3: Important structural features of phenolic compounds and their effects.

Structural feature	Examples	Possible influence
Hydroxyl groups	Phenolic acids, flavonoids	Hydrogen donation and radical stabilization
Number of aromatic rings	Flavonoids, tannins	Influences molecular size and biological interactions
Methoxy groups	Ferulic acid, methoxylated flavonoids	Can increase lipophilicity and alter reactivity
Glycosyl groups	Rutin, quercetin glycosides	Can affect solubility, stability, absorption, and metabolism
Carboxyl group	Gallic, caffeic, ferulic acids	Influences polarity and chemical reactivity
Conjugated system	Flavonoids, anthocyanins, stilbenes	Supports electron delocalization and colour formation
Polymerization	Tannins, proanthocyanidins	Increases molecular size and affects protein binding

Structural Feature	Representative Example (Class)	Structural Illustration (General)	Influence on Physicochemical Properties					Possible Biological Implications
			Solubility	Lipophilicity	Stability	Acid–Base Behavior	Reactivity	
Number and position of hydroxyl (–OH) groups	Quercetin (Flavonol)		↑ Increases with more –OH	↓ Decreases with more –OH	↑ Enhances radical stability	↑ Increases acidity (weak acid)	↑ Enhances antioxidant activity	• Strong free radical scavenging • Metal chelation • Anti-inflammatory and protective effects
Methoxy ($-OCH_3$) substitution	Ferulic acid (Phenolic acid)		↓ Decreases	↑ Increases	↑ Improves chemical stability	↑ Slightly reduces acidity	↑ May modify antioxidant activity	• Better membrane permeability • Modulation of bioavailability
Glycosylation (sugar moiety)	Rutin (Flavonoid glycoside)		↑ Increases (water solubility)	↓ Decreases	↑ Improves stability in vitro	≈ Minimal effect	≈ May reduce antioxidant potency	• Affects absorption and transport • Acts as reservoir in plants • Influences metabolism
Carboxyl group (–COOH)	Caffeic acid (Phenolic acid)		↑ Increases (polarity)	↓ Decreases	≈ Moderate effect	↑ Increases acidity	↑ Enhances metal chelation	• Improves antioxidant activity • Important in detoxification
Conjugated system (π–electron delocalization)	Resveratrol (Stilbene)		≈ Moderate	↑ Increases	↑ Enhances stability of phenoxy radicals	≈ Minimal effect	↑ Enhances antioxidant activity	• Potent antioxidant • Modulation of cell signaling pathways
Polymerization (high molecular weight)	Procyanidin B2 (Condensed tannin)		↑ Generally increases	↓ Decreases	↑ Very stable structures	≈ Minimal effect	↑ Strong protein binding	• Astringent properties • Antimicrobial and antidiarrheal effects • Modulation of proteins/enzymes

↑ Increase ↓ Decrease ≈ Little or no change

Note: Arrows indicate the general trend of influence of the structural feature on the property. Actual effect may vary with other structural and environmental factors.

Figure 1: Relationship between phenolic structure and major physicochemical properties.

involved in phenolic biosynthesis. Changes have been reported in enzymes such as phenylalanine ammonia-lyase and chalcone synthase. Therefore, cultivation and harvesting conditions are important for maintaining the chemical quality of medicinal plant materials (Vinogradova *et al.*, 2023).

The distribution of phenolic compounds is therefore not a fixed characteristic. It represents the combined effect of plant genetics, tissue type, developmental stage, environment, and cultivation conditions. This variation has important implications for the standardization of medicinal plants and herbal preparations (Table 4 and Figure 2).

Biosynthesis and Formation of Phenolic Compounds

The biosynthesis of phenolic compounds is closely linked to primary plant metabolism. Two important pathways are involved.

These are the shikimate pathway and the phenylpropanoid pathway. The shikimate pathway provides aromatic amino acids. Phenylalanine is particularly important because it acts as a major precursor for many phenolic compounds (Maeda and Dudareva, 2012; Tohge and Fernie, 2017).

The shikimate pathway converts phosphoenolpyruvate and erythrose-4-phosphate into chorismate. Chorismate is an important precursor for aromatic amino acids. These include phenylalanine, tyrosine, and tryptophan. The pathway therefore provides essential building blocks for several plant secondary metabolites (Maeda and Dudareva, 2012).

Phenylalanine enters the phenylpropanoid pathway through the action of Phenylalanine Ammonia-Lyase (PAL). PAL converts phenylalanine into cinnamic acid. This reaction represents an important entry point into phenolic metabolism. Cinnamic acid is then hydroxylated by Cinnamate 4-Hydroxylase (C4H) to form p-coumaric acid. The enzyme 4-Coumarate-Coa Ligase (4CL) subsequently converts p-coumaric acid into p-coumaroyl-CoA (Vogt, 2010; Tohge and Fernie, 2017).

p-Coumaroyl-CoA is a central intermediate in phenolic biosynthesis. It can enter several branches of the pathway. These branches produce flavonoids, lignin precursors, stilbenes, coumarins, phenolic acids, and other phenylpropanoid derivatives. This branching pattern contributes greatly to the chemical diversity of plant phenolics (Vogt, 2010).

Flavonoid biosynthesis represents one of the major branches. Chalcone Synthase (CHS) combines p-coumaroyl-CoA with malonyl-CoA to form chalcone. Chalcone is then converted into different flavonoid precursors. Further enzymatic reactions produce flavones, flavonols, flavanones, anthocyanins, and other flavonoids (Chen *et al.*, 2023).

Table 4: Distribution of major phenolic groups in medicinal plant parts.

Plant part	Common phenolic groups	Representative examples
Leaves	Flavonoids, phenolic acids	Quercetin, rutin, caffeic acid
Flowers	Flavonoids, anthocyanins, phenolic acids	Kaempferol, anthocyanins, gallic acid
Fruits	Phenolic acids, flavonoids, tannins	Chlorogenic acid, quercetin, catechins
Seeds	Phenolic acids, flavonoids, lignans	Ferulic acid, catechins, lignans
Bark	Tannins, phenolic acids, flavonoids	Tannins, gallic acid, catechins
Roots	Phenolic acids, flavonoids, lignans, coumarins	Caffeic acid derivatives, lignans, coumarins
Stems	Phenolic acids, flavonoids, tannins	Ferulic acid, flavonoids, condensed tannins

Plant Part	Major Phenolic Classes								Notes
	Phenolic Acids	Flavonoids	Tannins	Stilbenes	Lignans	Coumarins	Anthocyanins	Quinones and others	
Leaves	●●	●●●	●	●	●	●	●	–	Rich in flavonoids and phenolic acids
Flowers	●	●●	●	●	●	●	●●●	●	High in flavonoids and anthocyanins
Fruits	●●	●●	●●	●	●	●	●●	●	Abundant in phenolic acids, flavonoids and tannins
Seeds	●	●●	●	●	●●	●	–	●	Contains lignans and phenolic acids
Bark	●	●	●●●	●	●●	●●	–	●●	Rich source of tannins and coumarins
Roots	●	●	●	●	●●	●●	–	●	Contains lignans, coumarins and phenolic acids
Stems	●	●	●	●	●	●	–	●	Moderate amounts of phenolics

Relative abundance: ●●● High ●● Moderate ● Low – Absent / Very low

Note: Distribution may vary with species, variety, geographical origin, maturity stage, season, and environmental conditions.

Figure 2: Distribution of major phenolic classes across different medicinal plant parts.

Table 5: Major extraction methods used for phenolic compounds from medicinal plants.

Extraction method	Main principle	Major advantages	Important limitations
Maceration	Soaking plant material in solvent	Simple and inexpensive	Long extraction time
Percolation	Continuous passage of solvent through plant material	Better solvent contact	Time and solvent requirements
Soxhlet extraction	Repeated hot-solvent extraction	Exhaustive extraction	Prolonged heating
UAE	Ultrasonic cavitation improves mass transfer	Rapid and lower solvent use	Requires process optimization
MAE	Microwave energy provides rapid heating	Short extraction time	Possible thermal degradation
PLE	High pressure and temperature improve extraction	Efficient and reproducible	Higher equipment cost
SFE	Supercritical fluid extracts target compounds	Selective and low solvent residue	Less suitable for highly polar compounds
EAE	Enzymes disrupt plant cell-wall components	Mild conditions and improved release	Enzyme cost
DES extraction	Tunable alternative solvent systems	Potentially greener and selective	High viscosity and optimization requirements

The pathway also contributes to the formation of lignin and related phenolic polymers. Enzymes such as cinnamoyl-CoA reductase and cinnamyl alcohol dehydrogenase participate in the formation of monolignols. These compounds are important precursors of lignin. Other branches produce stilbenes, coumarins, and additional specialized phenolic metabolites (Vogt, 2010).

Phenolic biosynthesis is strongly regulated. Genetic factors influence the expression of biosynthetic enzymes. Transcription factors also regulate important pathway genes. Environmental conditions can further modify this process. Light, ultraviolet radiation, temperature, drought, salinity, and pathogen attack may change phenolic accumulation in plant tissues (Tsitsin *et al.*, 2023).

Recent advances in transcriptomics, metabolomics, and other omics technologies have improved the understanding of phenolic biosynthesis. These approaches help identify genes, enzymes, and metabolites involved in specific pathways. They may also support metabolic engineering for increased production of valuable phenolic compounds in medicinal plants (Zhang *et al.*, 2023).

The biosynthetic pathway therefore provides a useful link between plant metabolism and the chemical diversity of medicinal plants. Understanding this pathway is important for studying the accumulation of phenolic compounds and for improving their production through cultivation, elicitation, and biotechnological approaches (Figure 3).

Extraction, Identification and Characterization

Extraction is an important step in the study of phenolic compounds from medicinal plants. The extraction method can affect the yield, composition, and biological activity of the final extract. No single extraction method is suitable for all plant materials. Phenolic compounds differ in polarity, stability, molecular size, and location within plant tissues. Therefore, the extraction procedure should be selected according to the target compounds and plant material (Alara *et al.*, 2021; Zhang *et al.*, 2018).

Conventional Extraction Methods

Maceration is one of the simplest methods used for plant extraction. The powdered plant material is mixed with a suitable solvent for a defined period. The mixture is usually stirred or shaken during extraction. The method requires simple equipment and is suitable for heat-sensitive compounds. However, it may require a long extraction time and relatively large amounts of solvent.

Percolation is another traditional method. In this process, the solvent passes slowly through the powdered plant material. It provides continuous contact between the solvent and plant matrix. Soxhlet extraction uses repeated cycles of hot solvent. It can provide efficient extraction but may expose phenolic compounds to prolonged heating. This can be a limitation for thermolabile compounds (Alara *et al.*, 2021).

The choice of solvent is particularly important. Water, ethanol, methanol, acetone, and their mixtures are commonly used for phenolic extraction. Ethanol-water mixtures are frequently preferred because they can extract a broad range of phenolic compounds and are more suitable for food and pharmaceutical applications than some toxic organic solvents (Mokrani and Madani, 2016; Do *et al.*, 2014).

Ultrasound-Assisted Extraction

Ultrasound-Assisted Extraction (UAE) uses ultrasonic energy to improve the transfer of compounds from plant tissues into the solvent. Cavitation produced by ultrasound can disrupt plant

cells and improve solvent penetration. UAE can reduce extraction time and solvent consumption. It is therefore considered a useful alternative to conventional extraction methods (Ameer *et al.*, 2017).

The efficiency of UAE depends on several factors. These include ultrasound frequency, extraction temperature, extraction time, solvent composition, and solid-to-liquid ratio. Excessive ultrasound intensity or prolonged treatment may cause degradation of some sensitive compounds. Optimization is therefore necessary for individual plant materials.

Microwave-Assisted Extraction

Microwave-Assisted Extraction (MAE) uses microwave energy to heat the solvent and plant matrix. Rapid heating can improve the release of phenolic compounds from plant tissues. MAE generally requires less time and solvent than several conventional methods. However, excessive heating may affect thermolabile compounds. Careful control of microwave power and extraction temperature is therefore important (Alara *et al.*, 2021).

Pressurized Liquid Extraction

Pressurized Liquid Extraction (PLE) uses elevated temperature and pressure to improve solvent penetration and solute transfer. The method can reduce extraction time and solvent use. It has been investigated for the recovery of phenolic compounds and other bioactive constituents from food and herbal materials. Solvent composition, temperature, pressure, and extraction cycles influence the final recovery (Mustafa and Turner, 2011).

Supercritical Fluid Extraction

Supercritical Fluid Extraction (SFE) commonly uses supercritical carbon dioxide. The method provides good selectivity and uses relatively mild temperatures. It is particularly useful for compounds that are compatible with carbon dioxide. However, the low polarity of carbon dioxide can limit the extraction of highly polar phenolic compounds. Co-solvents may therefore be required for some applications (Herrero *et al.*, 2010).

Enzyme-Assisted Extraction

Enzyme-Assisted Extraction (EAE) uses enzymes to break down components of the plant cell wall. This can improve the release of phenolic compounds that are trapped within the plant matrix. Cellulases, pectinases, and related enzymes may be used. The method can operate under relatively mild conditions. However, enzyme cost and optimization requirements can limit its wider application.

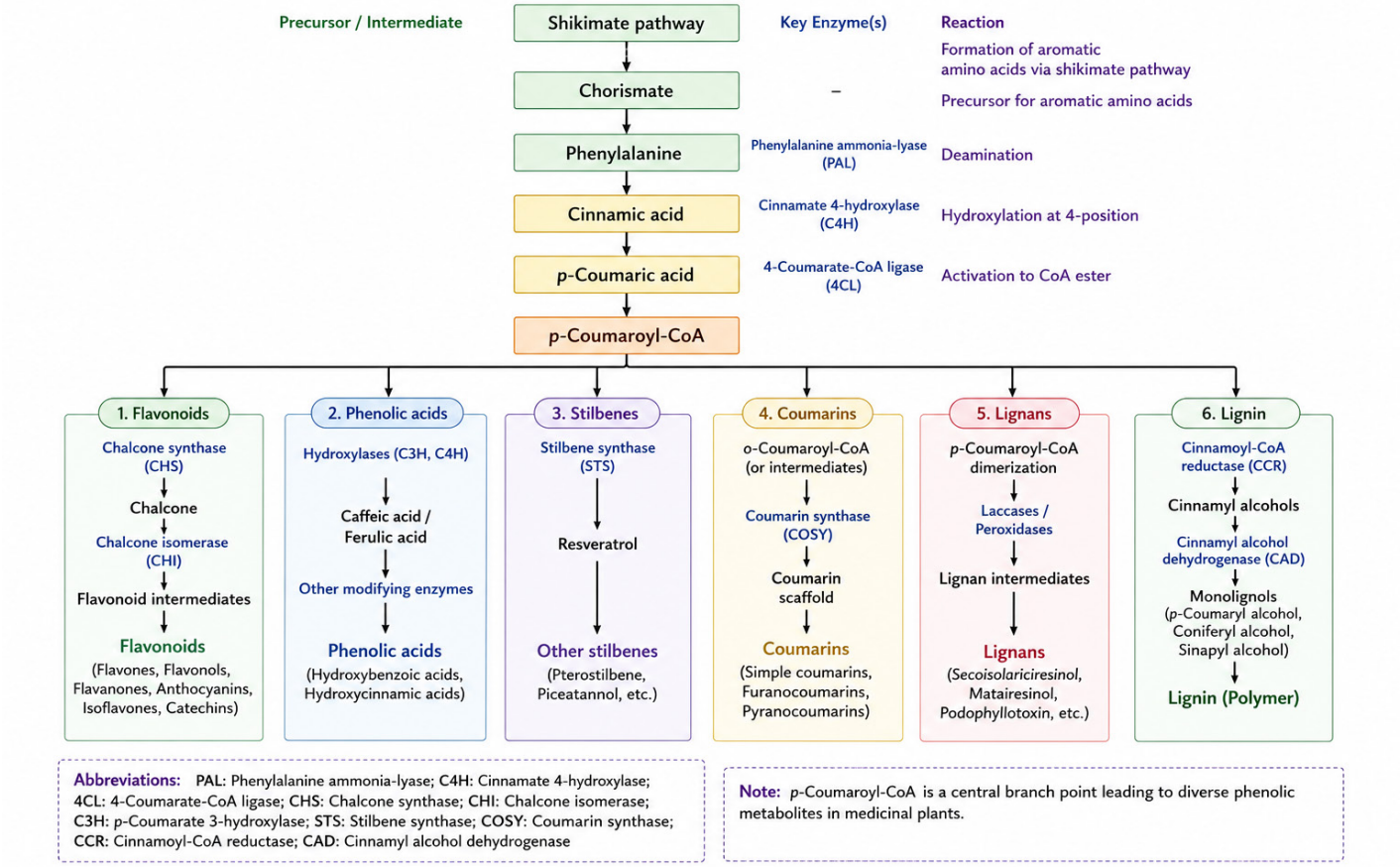


Figure 3: Biosynthetic pathway of major phenolic compounds in medicinal plants.

Deep Eutectic Solvents

Deep Eutectic Solvents (DES) have gained attention as alternative solvents for phenolic extraction. They can be prepared from suitable hydrogen-bond donors and acceptors. DES may offer advantages such as low volatility, tunable polarity, and potential biodegradability. Their combination with UAE or MAE can further improve phenolic recovery (Serna-Vázquez *et al.*, 2021; Aktaş and Kurek, 2024).

However, DES-based extraction also has limitations. High viscosity can reduce mass transfer. Solvent composition, water content, temperature, extraction time, and solvent-to-sample ratio require optimization. The suitability of a DES should therefore be assessed for the target phenolic compounds and plant matrix (Siddiqui *et al.*, 2025).

Green Extraction Approaches

Green extraction aims to reduce solvent consumption, energy use, waste generation, and environmental impact. UAE, MAE, PLE, SFE, pressurized hot water extraction, and DES-based approaches are among the important techniques investigated for polyphenol recovery. These methods can provide shorter extraction times and improved recovery compared with some conventional procedures.

The selection of an extraction method should therefore consider both extraction efficiency and the intended application. Pharmaceutical preparations may require high purity and reproducibility. Food applications may place greater emphasis on solvent safety. Large-scale production also requires consideration of energy consumption, equipment cost, solvent recovery, and process scalability (Table 5 and Figure 4).

Chromatographic Techniques

Chromatographic techniques are important for the separation, identification, and quantification of phenolic compounds in

Table 6: Major chromatographic techniques used for phenolic compounds.

Technique	Major application	Information obtained
HPLC	Separation and quantification	Individual phenolic compounds
HPTLC	Separation and fingerprinting	Characteristic bands and quantitative data
LC-MS	Identification of phenolics	Molecular mass and chromatographic profile
LC-MS/MS	Detailed identification	Molecular mass and fragmentation pattern
GC-MS	Analysis of volatile or derivatized phenolics	Retention behaviour and mass spectral information
Chromatographic fingerprinting	Quality control and authentication	Overall chemical profile

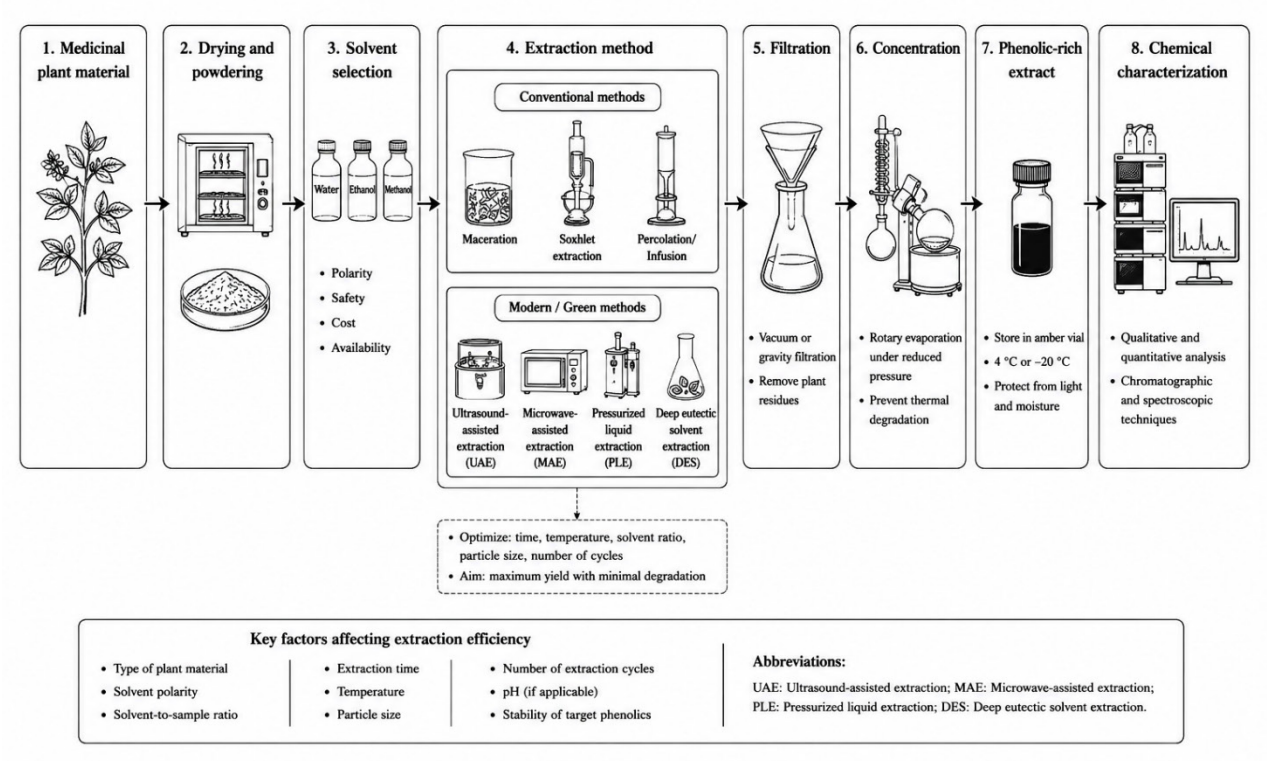


Figure 4: Selection of extraction methods for phenolic compounds from medicinal plants.

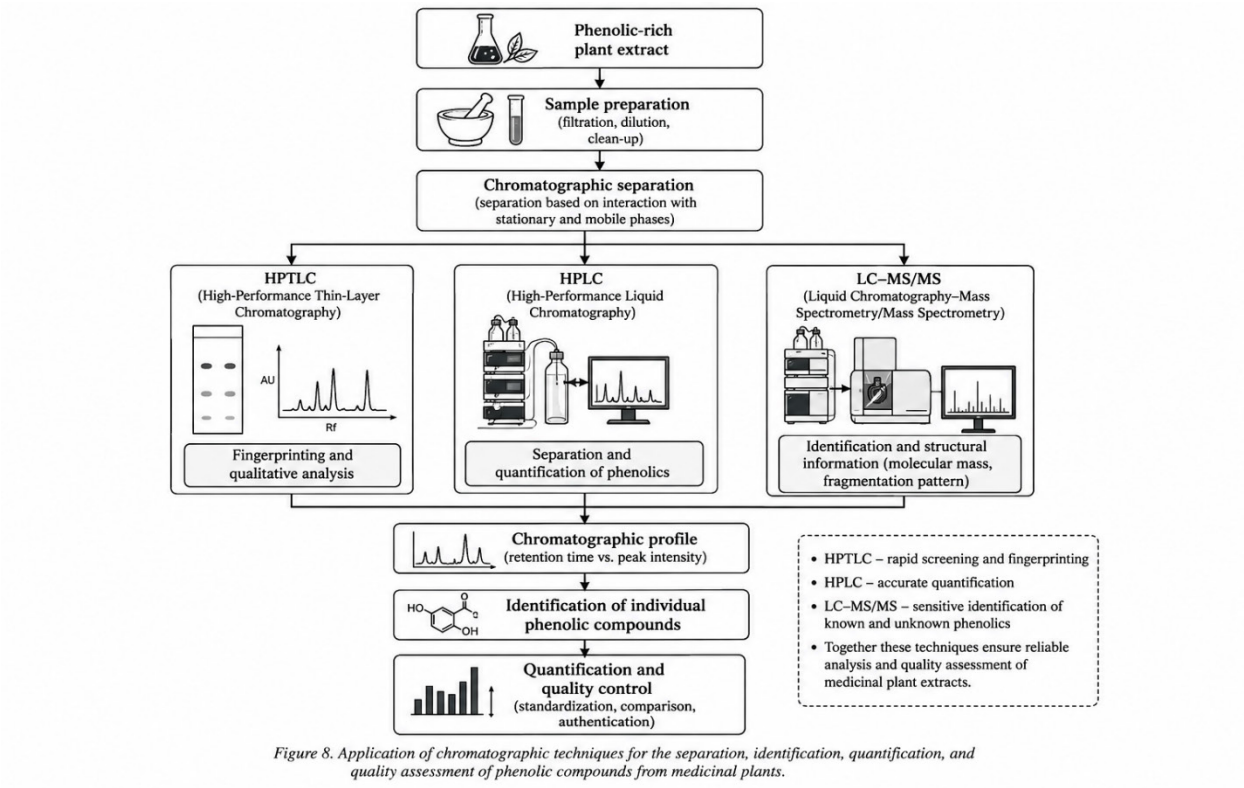


Figure 8. Application of chromatographic techniques for the separation, identification, quantification, and quality assessment of phenolic compounds from medicinal plants.

Figure 5: Application of chromatographic techniques for the separation, identification, quantification, and quality assessment of phenolic compounds from medicinal plants.

medicinal plants. These techniques provide better information than general colorimetric assays. They can help distinguish individual phenolic compounds present in a complex plant extract (Zhang *et al*., 2022; Al Mamari, 2021).

High-Performance Liquid Chromatography

High-Performance Liquid Chromatography (HPLC) is widely used for the analysis of phenolic compounds. It can separate compounds according to their interaction with the stationary and mobile phases. Reverse-phase HPLC is commonly used for phenolic acids and flavonoids. Detection is often performed using ultraviolet or diode-array detection. HPLC can provide both qualitative and quantitative information (Zhang *et al*., 2022).

HPLC is useful for determining individual compounds in medicinal plant extracts. Commonly analyzed compounds include gallic acid, caffeic acid, ferulic acid, chlorogenic acid, quercetin, kaempferol, and rutin. The method can also be used for the development of chemical fingerprints. Such fingerprints are useful for comparing plant materials and supporting quality control.

High-Performance Thin-Layer Chromatography

High-Performance Thin-Layer Chromatography (HPTLC) is another useful technique for phenolic analysis. It allows simultaneous separation of several compounds on a chromatographic plate. Different phenolic constituents produce characteristic bands at specific positions. Densitometric measurement can be used for quantitative analysis.

HPTLC is particularly useful for herbal materials because several samples can be analyzed under the same conditions. It can also provide a characteristic fingerprint of a medicinal plant extract. This makes the technique useful for authentication and quality assessment.

Liquid Chromatography-Mass Spectrometry

Liquid Chromatography-Mass Spectrometry (LC-MS) combines chromatographic separation with mass-based detection. It provides information about the molecular mass of compounds and their fragmentation patterns. This improves the identification of phenolic constituents in complex extracts.

LC-MS/MS provides additional structural information through fragmentation analysis. It is therefore useful for identifying minor phenolic compounds that may not be easily characterized by conventional HPLC detection. The technique has become an important tool in the detailed analysis of plant phenolics and metabolite profiling (Zhang *et al*., 2022).

Gas Chromatography

Gas Chromatography (GC) can be used for the analysis of phenolic compounds that are sufficiently volatile or can be converted into suitable derivatives. Derivatization may improve volatility and chromatographic behaviour. GC coupled with mass

spectrometry can provide additional information for compound identification.

However, many phenolic compounds are non-volatile and thermally unstable. Therefore, GC is less suitable for direct analysis of several high-molecular-weight or highly polar phenolics. Liquid chromatographic techniques are generally more appropriate for such compounds.

Chromatographic Fingerprinting

Chromatographic fingerprinting provides an overall chemical profile of a plant extract. It is useful when the therapeutic activity is associated with several constituents rather than a single marker compound. HPLC and HPTLC fingerprints can help compare different batches of medicinal plant material.

Fingerprint analysis can also support authentication and detection of adulteration. Differences in chromatographic profiles may indicate variations in plant species, geographical origin, harvesting conditions, processing, or storage. Therefore, chromatographic fingerprinting has an important role in the standardization of medicinal plant preparations (Table 6 and Figure 5).

Spectroscopic and Spectrometric Techniques

Spectroscopic and spectrometric techniques provide important information about the chemical characteristics of phenolic compounds. They are useful for preliminary screening, functional-group identification, structural elucidation, and confirmation of individual compounds. These techniques are often used together with chromatographic methods for reliable characterization of complex medicinal plant extracts (Al Mamari, 2021; Zhang *et al.*, 2022).

UV-visible Spectroscopy

UV-visible spectroscopy is a simple technique for the preliminary analysis of phenolic compounds. Many phenolics contain conjugated aromatic systems. These structures show characteristic absorption in the ultraviolet or visible region. The absorption pattern can provide useful information about the presence of phenolic constituents.

UV-visible spectroscopy is also widely used in total phenolic content assays. The Folin-Ciocalteu method is commonly applied for this purpose. The result is generally expressed as gallic acid equivalents. However, the assay is not completely specific for phenolics. Other reducing substances may also contribute to the measured response (Zhang *et al.*, 2022).

Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy provides information about functional groups present in plant extracts. Phenolic compounds commonly show absorption associated with hydroxyl, aromatic, carbonyl, and C-O groups. The resulting spectrum can therefore provide a characteristic chemical profile.

FTIR is useful for rapid screening and comparison of plant extracts. It can also support authentication and quality assessment. However, FTIR alone may not always allow identification of individual phenolic compounds in a complex extract.

Nuclear Magnetic Resonance Spectroscopy

Nuclear Magnetic Resonance (NMR) spectroscopy is a powerful technique for structural characterization. It provides information about the chemical environment of hydrogen and carbon atoms. Therefore, ^{1}H-NMR and ^{13}C-NMR can provide detailed structural information about phenolic compounds.

NMR can help distinguish closely related compounds and identify structural modifications. It is particularly valuable when combined with chromatographic and mass spectrometric data. Its major limitation is the relatively high amount of purified sample required for detailed analysis.

Mass Spectrometry

Mass Spectrometry (MS) provides molecular mass information and is particularly useful for the identification of phenolic compounds. It can detect compounds at relatively low

Table 7: Spectroscopic and spectrometric techniques used for phenolic characterization.

Technique	Major application	Information obtained
UV-visible spectroscopy	Preliminary screening and total phenolic estimation	Absorption characteristics
FTIR	Functional-group analysis	Characteristic chemical bonds
^1H-NMR	Structural analysis	Hydrogen environment
^13C-NMR	Structural analysis	Carbon environment
MS	Compound identification	Molecular mass
MS/MS	Structural confirmation	Fragmentation pattern
HPLC-DAD	Separation and detection	Retention time and UV spectrum
LC-MS/MS	Detailed characterization	Retention time, molecular mass, and fragments

Table 8: **Major phenolic compounds with reported antioxidant activity.**

Phenolic compound/group	Major antioxidant mechanism	Representative source
Gallic acid	Radical scavenging and electron donation	Medicinal plants and fruits
Caffeic acid	Radical scavenging and metal interaction	Leaves, fruits and herbs
Ferulic acid	Radical scavenging and oxidative protection	Cereals and medicinal plants
Quercetin	Radical scavenging and metal chelation	Leaves, fruits and medicinal plants
Kaempferol	Radical scavenging and cellular antioxidant effects	Leaves and flowers
Catechins	Radical scavenging and protection against lipid oxidation	Tea and medicinal plants
Tannins	Radical scavenging and metal chelation	Bark, leaves and fruits
Resveratrol	Antioxidant and cellular protective effects	Selected medicinal plants

Table 9: **Major anti-inflammatory mechanisms of phenolic compounds.**

Mechanism	Major effect
NF-κB modulation	Reduced inflammatory signalling
Cytokine regulation	Reduced TNF-α and IL-6
iNOS/NO modulation	Reduced excessive NO production
COX/LOX modulation	Reduced inflammatory mediators
Antioxidant action	Reduced oxidative stress

concentrations. Fragmentation patterns can provide additional structural information.

LC-MS and LC-MS/MS are especially useful for complex medicinal plant extracts. Chromatographic separation reduces sample complexity before mass-based detection. MS/MS fragmentation can help differentiate compounds with similar molecular masses. This approach is therefore valuable for the characterization of both known and previously unreported phenolic constituents (Zhang *et al.*, 2022).

Combined Analytical Approaches

No single analytical technique can provide all information required for complete characterization. UV-visible spectroscopy is useful for preliminary assessment. FTIR provides functional-group information. NMR provides detailed structural information. MS provides molecular mass and fragmentation data.

Combining these techniques with HPLC or HPTLC improves the reliability of phenolic identification. A combined approach is particularly important for medicinal plants because their extracts contain numerous compounds with similar chemical properties (Table 7 and Figure 6).

Pharmacological Activities of Phenolic Compounds

Antioxidant Activity

Oxidative stress occurs when the production of Reactive Oxygen Species (ROS) exceeds the antioxidant capacity of the body. Excessive ROS can damage lipids, proteins, and nucleic acids. Persistent oxidative damage is associated with several chronic diseases. Phenolic compounds are therefore of interest because of their antioxidant properties (Sun and Shahrajabian, 2023; Rana *et al.*, 2022).

Phenolic compounds can act as antioxidants through several mechanisms. Their hydroxyl groups can donate hydrogen atoms or electrons to reactive species. This can convert highly reactive radicals into more stable molecules. The resulting phenoxyl radicals can be stabilized by resonance within the aromatic structure. This property contributes to the radical-scavenging activity of many phenolic compounds (Rice-Evans *et al.*, 1996).

The antioxidant activity of phenolics is strongly influenced by their chemical structure. The number and position of hydroxyl groups can affect their ability to neutralize free radicals. Conjugation and substitution patterns also influence antioxidant efficiency. Flavonoids with suitable hydroxyl arrangements may show strong radical-scavenging activity. Structure-activity relationships are therefore important when comparing different phenolic compounds (Heim *et al.*, 2002; Rice-Evans *et al.*, 1996).

Phenolic compounds can also interact with metal ions. Some phenolics are capable of chelating transition metals such as iron and copper. Metal chelation may reduce metal-catalyzed formation of highly reactive radicals. This provides another pathway through which phenolic compounds may limit oxidative damage.

The antioxidant effects of phenolics are not limited to direct radical scavenging. Some compounds may influence endogenous antioxidant defense systems. They can affect cellular pathways involved in antioxidant protection and oxidative stress responses. These effects may increase the overall antioxidant capacity of cells (Sun and Shahrajabian, 2023).

Flavonoids are among the most extensively studied phenolic antioxidants. Quercetin, catechins, kaempferol, luteolin, and related compounds have demonstrated antioxidant effects in experimental studies. Phenolic acids such as gallic acid, caffeic acid, and ferulic acid also show radical-scavenging properties.

Tannins can contribute to antioxidant activity because of their high number of phenolic hydroxyl groups.

The antioxidant activity of medicinal plant extracts depends on their chemical composition. Extraction solvent, plant part, geographical origin, harvesting conditions, and processing can influence phenolic concentration. Consequently, extracts obtained from the same plant may show different antioxidant capacities (Kisiriko *et al.*, 2021).

Several laboratory methods are used to evaluate antioxidant activity. Common assays include DPPH radical-scavenging, ABTS radical-scavenging, ferric reducing antioxidant power, and reducing power assays. These methods measure different aspects of antioxidant behaviour. Results obtained from different assays should therefore not be considered directly equivalent.

Phenolic compounds may provide protection against oxidative damage in several biological systems. Their antioxidant effects have been investigated in relation to cardiovascular, metabolic, hepatic, and neurological disorders. However, results from chemical and experimental models cannot be directly translated into clinical benefits. Absorption, metabolism, bioavailability, and tissue distribution can influence their effects in humans (Del Bo' *et al.*, 2019; Fraga *et al.*, 2019).

Overall, the antioxidant activity of phenolic compounds results from a combination of direct and indirect mechanisms. Radical scavenging, metal chelation, and modulation of cellular antioxidant defenses may all contribute. Their structural diversity provides a broad range of antioxidant properties. Further studies are required to establish how these effects translate into meaningful health benefits in humans (Table 8, Figure 7).

Anti-inflammatory Activity

Phenolic compounds have demonstrated anti-inflammatory activity in several experimental studies. Their effects are associated with the regulation of oxidative stress and inflammatory signalling. Many phenolics can reduce inflammatory mediators

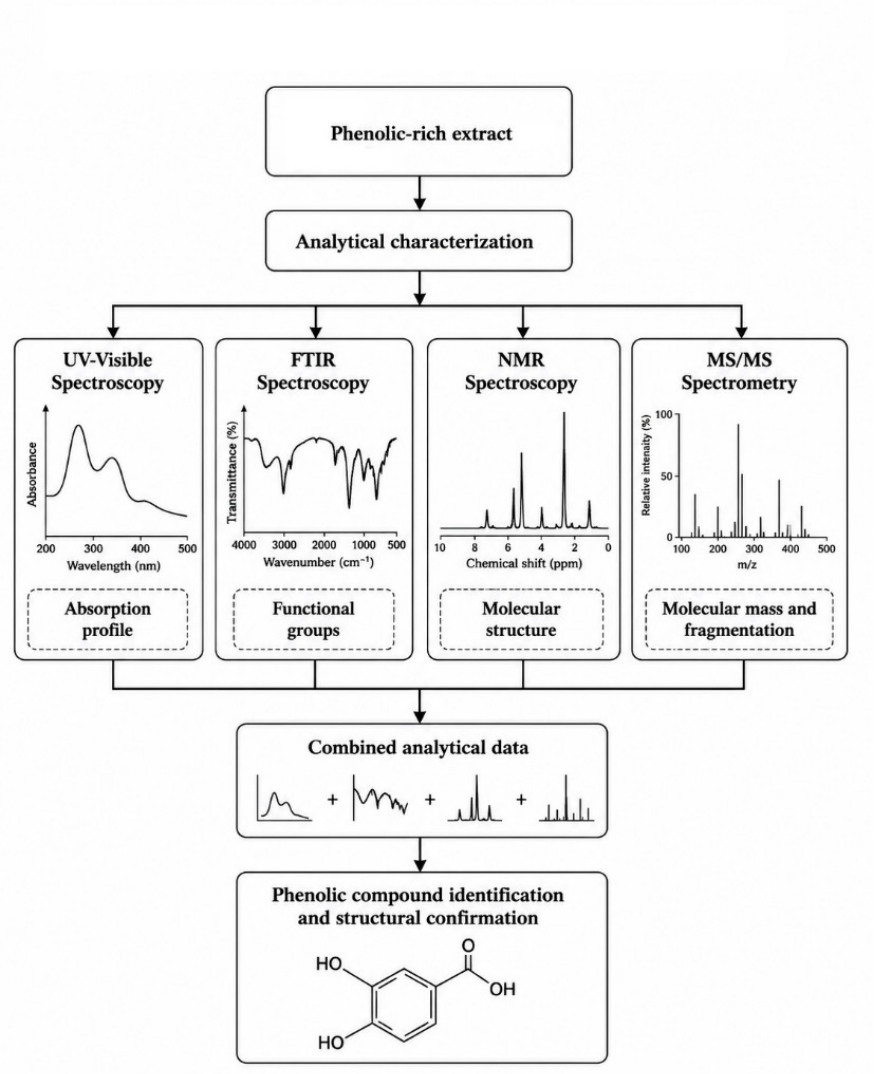


Figure 6: Spectroscopic and spectrometric approaches for the characterization of phenolic compounds from medicinal plants.

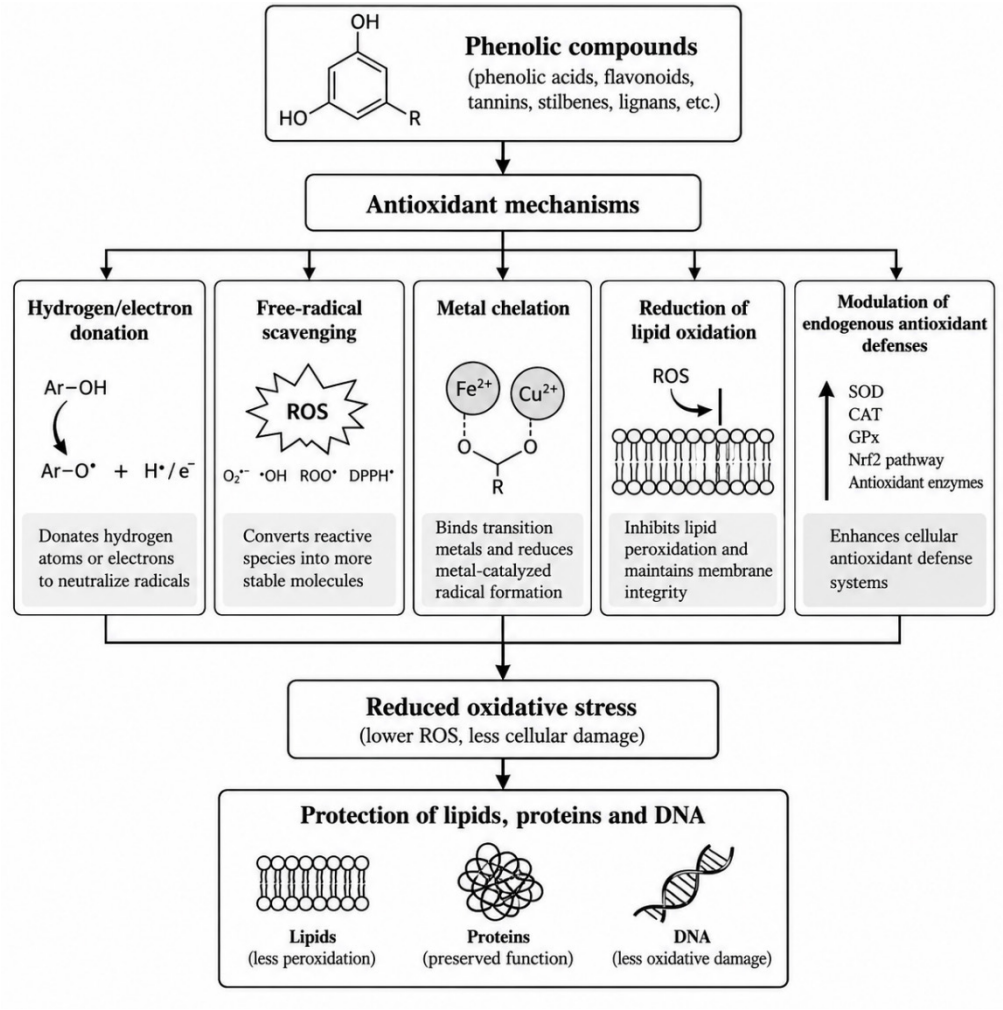


Figure 7: Antioxidant mechanisms of phenolic compounds.

Table 10: Major antimicrobial and antiviral mechanisms of phenolic compounds.

Activity	Proposed mechanism
Antibacterial	Membrane disruption and enzyme inhibition
Antifungal	Alteration of fungal membranes and cellular functions
Antiviral	Interference with viral attachment and replication
Antioxidant-mediated protection	Reduction of oxidative damage associated with infection

such as Tumour Necrosis Factor-alpha (TNF-α), Interleukin-6 (IL-6), and Nitric Oxide (NO). They may also modulate pathways such as Nuclear Factor-Kappa B (NF-κB) and enzymes involved in inflammation (Sun and Shahrajabian, 2023; Rana *et al.*, 2022).

Flavonoids, phenolic acids, tannins, and other phenolic compounds have shown anti-inflammatory effects in cell and animal models. These effects may help reduce oxidative and inflammatory tissue damage. However, the response depends on the chemical structure, concentration, bioavailability, and composition of the plant extract (Table 9) (Oluwole *et al.*, 2022; Sun and Shahrajabian, 2023).

Antimicrobial and Antiviral Activities

Phenolic compounds have shown antimicrobial activity against a wide range of microorganisms. Their effects may involve disruption of microbial membranes, alteration of cellular proteins, and interference with microbial enzymes. Flavonoids, phenolic acids, tannins, and related compounds have been investigated for these activities (Rana *et al.*, 2022; Sun and Shahrajabian, 2023).

Phenolics may also show antiviral effects. Proposed mechanisms include interference with viral attachment, entry, replication, and viral enzyme activity. However, the activity varies among individual compounds and viral species. The chemical structure and concentration of the phenolic compound are important factors.

Tannins and flavonoids are particularly interesting because they can interact with proteins and other biological targets. Phenolic-rich plant extracts have therefore been studied as potential sources of antimicrobial and antiviral agents. However,

much of the current evidence is based on laboratory and experimental models. Further studies are required to establish their clinical relevance (Table 10).

Antidiabetic Activity

Phenolic compounds have shown promising antidiabetic effects in experimental studies. Their activity may involve regulation of glucose metabolism, improvement of insulin sensitivity, and reduction of oxidative stress. Some phenolics can also influence carbohydrate-digesting enzymes such as α-amylase and α-glucosidase (Rana *et al.*, 2022; Sun and Shahrajabian, 2023).

Flavonoids and phenolic acids are among the major compounds investigated for these effects. They may help regulate glucose uptake and protect pancreatic β-cells from oxidative damage. Some compounds may also influence pathways involved in lipid metabolism and insulin signalling.

Phenolic-rich medicinal plant extracts have therefore attracted interest as potential supportive agents for diabetes management. However, most evidence comes from *in vitro* and animal studies. Differences in absorption, metabolism, dose, and bioavailability may affect their activity in humans. Clinical studies are required to confirm their antidiabetic potential (Table 11).

Hepatoprotective Activity

Phenolic compounds have shown promising hepatoprotective effects in experimental studies. Their activity is mainly associated with the reduction of oxidative stress and inflammation. Phenolics can scavenge reactive oxygen species, reduce lipid peroxidation, and support endogenous antioxidant defenses. These actions help protect hepatocytes from chemical and metabolic injury (Salehi *et al.*, 2019; Sun and Shahrajabian, 2023).

Flavonoids, phenolic acids, tannins, and other polyphenols may also regulate inflammatory pathways involved in liver injury.

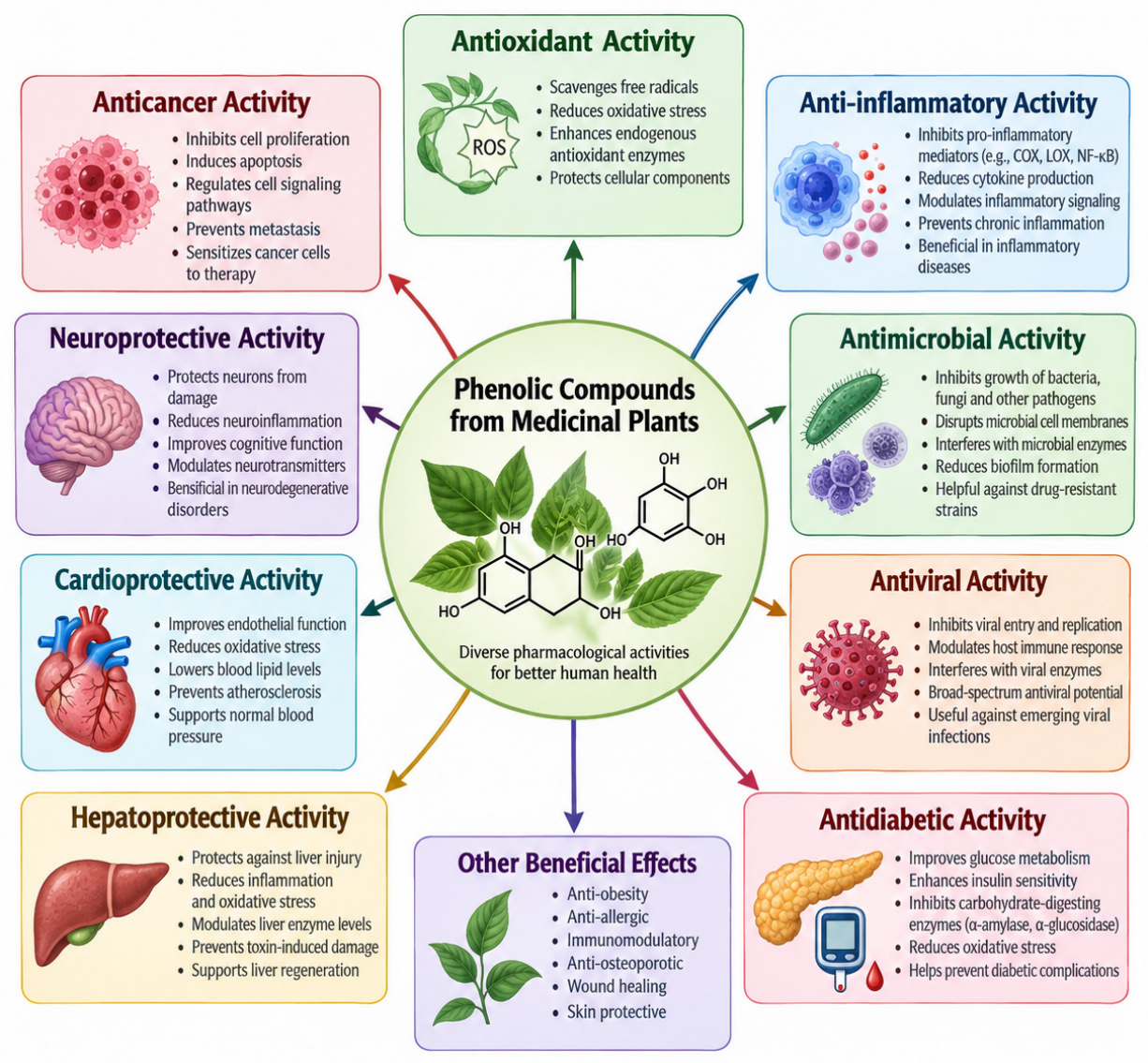


Figure 8: Overview of the Major Pharmacological Activities of Phenolic Compounds in Medicinal Plants.

Some compounds can reduce the release of inflammatory mediators and help maintain hepatocyte membrane integrity. Phenolic-rich extracts have therefore been investigated in models of drug-induced, alcohol-induced, and metabolic liver injury.

The hepatoprotective effects reported for medicinal plants are generally reflected by reduced serum alanine Aminotransferase (ALT), aspartate Aminotransferase (AST), Alkaline Phosphatase (ALP), and bilirubin levels, together with improved liver histology. However, most evidence remains preclinical. Differences in phenolic composition, dose, metabolism, and bioavailability may influence the observed effects. Further well-designed clinical studies are needed to confirm their therapeutic potential (Table 12).

Cardioprotective Activity

Phenolic compounds may provide cardioprotective effects through antioxidant, anti-inflammatory, and lipid-regulating actions. They can reduce oxidative stress and lipid peroxidation, which are important factors in cardiovascular damage. Flavonoids and phenolic acids have also been associated with improved endothelial function and vascular protection (Rana *et al.*, 2022; Sun and Shahrajabian, 2023).

Table 11: Major antidiabetic actions of phenolic compounds.

Action	Proposed effect
α-Amylase inhibition	Reduced carbohydrate digestion
α-Glucosidase inhibition	Delayed glucose release
Improved insulin signalling	Better glucose utilization
Antioxidant action	Protection of pancreatic β-cells

Some phenolic compounds may help regulate blood lipid levels and inhibit oxidation of Low-Density Lipoprotein (LDL). They may also reduce inflammatory signalling involved in atherosclerosis. These effects suggest a possible role of phenolic-rich medicinal plants in maintaining cardiovascular health.

However, the available evidence is largely based on experimental and observational studies. Differences in compound structure, dose, metabolism, and bioavailability can affect the response. More clinical studies are required to establish the cardiovascular benefits of individual phenolic compounds (Table 13).

Neuroprotective Activity

Phenolic compounds have attracted interest for their potential neuroprotective effects. Their antioxidant activity may help reduce oxidative stress in neuronal cells. Some phenolics can also regulate inflammatory responses and protect neurons from oxidative and mitochondrial damage (Rana *et al.*, 2022; Sun and Shahrajabian, 2023).

Flavonoids and phenolic acids have been investigated in experimental models of neurodegenerative disorders. Their reported actions include modulation of inflammatory signalling, protection against neuronal apoptosis, and maintenance of cellular antioxidant defenses. Some phenolics may also influence pathways related to amyloid processing and neuronal signalling.

However, the therapeutic potential of phenolic compounds in neurological disorders is influenced by their absorption, metabolism, and ability to cross the blood-brain barrier. Most available evidence is still based on *in vitro* and animal

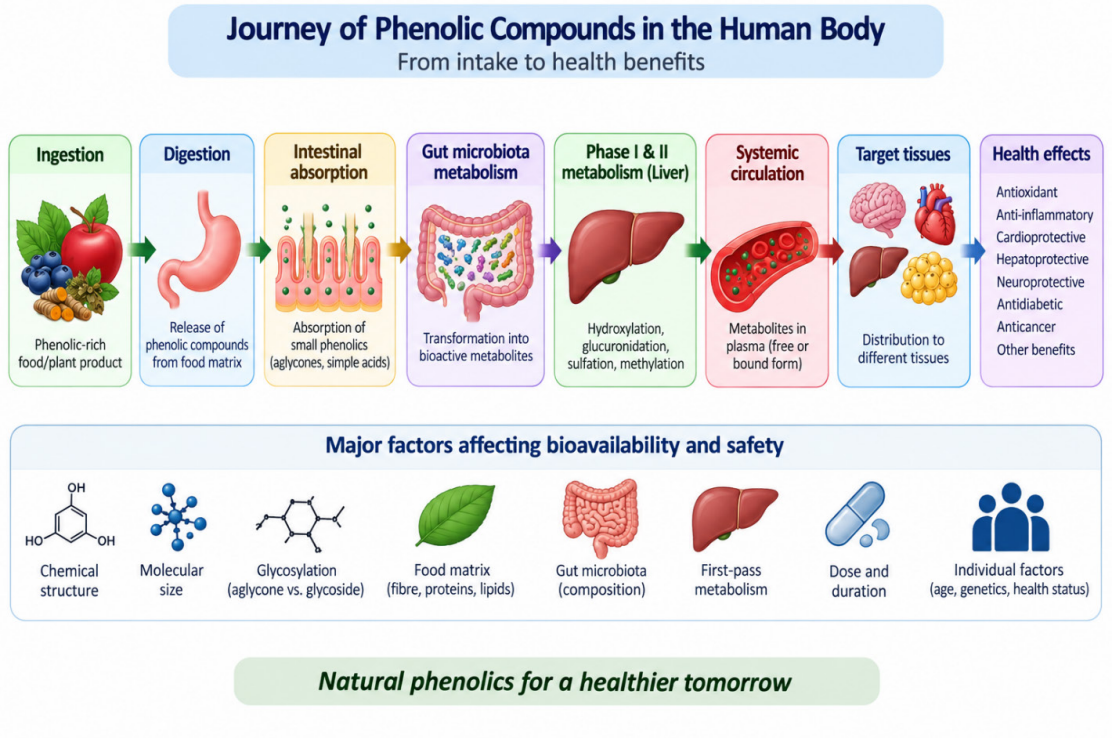


Figure 9: Journey of Phenolic Compounds in the Human Body: Absorption, Metabolism, Bioavailability and Health Effects.

Table 12: Major hepatoprotective actions of phenolic compounds.

Mechanism	Protective effect
Antioxidant activity	Reduces oxidative damage
Inhibition of lipid peroxidation	Preserves hepatocyte membranes
Anti-inflammatory action	Reduces inflammatory signalling
Enhancement of endogenous antioxidants	Supports cellular defense
Antifibrotic activity	May limit excessive collagen deposition

Table 13: Major cardioprotective actions of phenolic compounds.

Mechanism	Potential benefit
Antioxidant activity	Reduces oxidative vascular damage
Anti-inflammatory action	Limits vascular inflammation
LDL oxidation inhibition	May reduce atherosclerotic risk
Lipid regulation	Supports healthy lipid levels
Endothelial protection	Supports vascular function

Table 14: Major neuroprotective actions of phenolic compounds.

Mechanism	Potential benefit
Antioxidant activity	Reduces neuronal oxidative stress
Anti-inflammatory action	Limits neuroinflammation
Anti-apoptotic effects	Supports neuronal survival
Mitochondrial protection	Maintains neuronal energy function
Modulation of neuronal signalling	Supports cognitive and neuronal functions

studies. Clinical studies are therefore needed to confirm their neuroprotective effects in humans (Table 14).

Anticancer Activity

Phenolic compounds have been widely studied for their potential anticancer effects. Their activity may involve antioxidant and anti-inflammatory actions, as well as direct effects on cancer cell growth. Flavonoids, phenolic acids, tannins, and other polyphenols have shown inhibitory effects on cancer cells in experimental models (Oluwole *et al.*, 2022; Sun and Shahrajabian, 2023).

Several phenolics can influence important cellular processes, including cell-cycle regulation, apoptosis, and intracellular signalling. They may also reduce angiogenesis and cancer cell migration. These effects suggest that phenolic compounds may act on multiple targets involved in cancer development and progression.

However, anticancer activity observed in laboratory studies cannot be directly translated into clinical efficacy. Factors such as dose, metabolism, bioavailability, and tissue distribution can strongly influence their effects. Further *in vivo* and clinical studies are required to determine their therapeutic value (Table 15).

Other Pharmacological Activities

In addition to the major activities discussed above, phenolic compounds have been investigated for several other pharmacological effects. These include wound healing, gastrointestinal protection, antimicrobial protection, and effects on metabolic health. Tannins and flavonoids are of particular interest because of their astringent, antioxidant, and anti-inflammatory properties.

Some phenolic compounds may support tissue repair by reducing oxidative damage and inflammation. Tannins can also interact with proteins and form protective layers over damaged tissues. These properties have contributed to their traditional use in conditions such as diarrhoea, minor wounds, and inflammatory disorders.

Phenolic compounds have also been investigated for antiparasitic, antiviral, and antibacterial effects. However, the strength of evidence varies considerably between individual compounds and plant extracts. Most reported activities are based on experimental studies and should not be considered proof of clinical efficacy (Table 16 and Figure 8).

Mechanisms of Action

The pharmacological effects of phenolic compounds are mediated through several interconnected biological mechanisms. Their activity is not limited to direct antioxidant effects. Phenolics can regulate oxidative stress, inflammatory pathways, cellular signalling, and programmed cell death. The exact mechanism depends on the chemical structure, concentration, metabolism, and biological target of the compound (Del Bo' *et al.*, 2019; Fraga *et al.*, 2019).

Regulation of Oxidative Stress

Phenolic compounds can regulate oxidative stress through direct and indirect mechanisms. Their hydroxyl groups allow them to donate hydrogen atoms or electrons to Reactive Oxygen Species (ROS). This can reduce the formation of highly reactive free radicals and limit oxidative damage to cellular components (Rice-Evans *et al.*, 1996; Heim *et al.*, 2002).

Phenolics may also support endogenous antioxidant defenses. They can influence cellular systems involved in maintaining redox balance. These effects may increase the activity or expression of antioxidant enzymes and improve the cellular response to oxidative stress. Therefore, their antioxidant action involves both direct radical scavenging and regulation of cellular

defense mechanisms (Table 17) (Albuquerque *et al.*, 2021; Sun and Shahrajabian, 2023).

Modulation of Inflammatory Pathways

Phenolic compounds can influence several signalling pathways involved in inflammation. They may reduce the activation of inflammatory mediators and transcription factors. The Nuclear Factor-Kappa B (NF-κB) pathway is one important target associated with the regulation of inflammatory responses. Phenolics may also influence cytokines such as Tumour Necrosis Factor-alpha (TNF-α) and Interleukin-6 (IL-6).

The anti-inflammatory effects of phenolics are closely related to their antioxidant properties. Reduction of oxidative stress may decrease the activation of redox-sensitive inflammatory pathways. Thus, antioxidant and anti-inflammatory actions can occur together and contribute to cellular protection (Del Bo' *et al.*, 2019; Sun and Shahrajabian, 2023).

Regulation of Cellular Signaling and Apoptosis

Phenolic compounds can affect cellular signalling pathways that control cell survival, proliferation, differentiation, and apoptosis. Flavonoids and other phenolics have been reported to interact with signalling networks involved in cellular stress responses. These effects may contribute to their antioxidant, anti-inflammatory, and anticancer activities (Chen *et al.*, 2023; Teka *et al.*, 2022).

Phenolics may also influence apoptosis, a controlled process involved in the removal of damaged or abnormal cells. Depending on the compound and cellular condition, they may promote apoptosis in cancer cells while protecting normal cells from excessive cell death. Such effects are associated with changes in pro-apoptotic and anti-apoptotic signalling pathways.

Phenolic Compounds and Human Health

Phenolic compounds are important dietary and plant-derived bioactive compounds with potential benefits for human health. Their reported effects include antioxidant, anti-inflammatory, cardiovascular, metabolic, and neuroprotective actions. These effects are related to their ability to influence oxidative stress, inflammatory responses, and cellular processes (Del Bo' *et al.*, 2019; Fraga *et al.*, 2019).

Regular intake of phenolic-rich foods and plant products has been associated with several positive health outcomes. Flavonoids, phenolic acids, stilbenes, and other phenolics may contribute to cardiovascular and metabolic health. However, the effects can vary according to the type and number of phenolic compounds consumed (Del Bo' *et al.*, 2019).

The health effects of phenolics are not determined only by their content in a plant or food. Chemical structure, absorption, metabolism, and interaction with the gut microbiota can influence their biological activity. Therefore, high phenolic content does not always indicate greater health benefits (Fraga *et al.*, 2019).

Phenolic compounds may therefore contribute to a healthy diet and support the development of plant-based health products. However, most evidence does not justify considering phenolic compounds as substitutes for established medical treatments. More human studies are required to determine effective doses, long-term effects, and clinically relevant benefits (Table 18).

Bioavailability, Metabolism and Safety

The biological effects of phenolic compounds depend not only on their concentration but also on their absorption and metabolism in the human body. Many phenolics have limited bioavailability because of poor absorption, rapid metabolism, and extensive transformation in the gastrointestinal tract. Their chemical structure and glycosylation can also influence their absorption and biological activity (Del Bo' *et al.*, 2019; Fraga *et al.*, 2019).

After ingestion, phenolic compounds may undergo several metabolic processes. These include hydrolysis, conjugation, and transformation by intestinal microorganisms. The resulting metabolites can differ from the original compounds in their biological activity. Gut microbiota therefore plays an important role in determining the fate and effects of dietary phenolics (Fraga *et al.*, 2019).

Table 15: Major anticancer actions of phenolic compounds.

Mechanism	Potential effect
Cell-cycle regulation	Inhibits uncontrolled cell proliferation
Apoptosis induction	Promotes cancer cell death
Anti-inflammatory activity	Reduces tumour-promoting inflammation
Anti-angiogenic activity	May limit tumour blood supply
Inhibition of cell migration	May reduce metastatic potential

Table 16: Selected other pharmacological activities of phenolic compounds.

Activity	Major proposed action
Wound healing	Antioxidant and tissue-protective effects
Gastroprotective	Reduction of oxidative and inflammatory damage
Antidiarrheal	Astringent and antimicrobial effects
Antiparasitic	Interaction with microbial or parasitic targets
Antiviral	Interference with viral activity

Table 17: **Major mechanisms involved in the regulation of oxidative stress.**

Mechanism	Biological effect
Free-radical scavenging	Reduces reactive species
Hydrogen/electron donation	Stabilizes free radicals
Metal chelation	Limits radical-generating reactions
Lipid peroxidation inhibition	Protects cellular membranes
Antioxidant defense regulation	Supports endogenous cellular protection

Table 18: **Major health benefits associated with phenolic compounds.**

Health area	Potential benefit
Cardiovascular health	Supports vascular and lipid health
Metabolic health	May support glucose regulation
Brain health	May protect against oxidative and inflammatory damage
Cellular protection	Reduces oxidative stress
Inflammation	Helps regulate inflammatory responses

Table 19: **Potential applications of phenolic compounds.**

Application	Examples	Major consideration
Pharmaceutical	Standardized extracts, phenolic-based formulations	Purity, dose and safety
Nutraceutical	Capsules, tablets, powders, extracts	Bioavailability and stability
Functional food	Beverages, cereals, fortified foods	Sensory quality and processing stability

Safety is another important consideration. Phenolic compounds are generally associated with beneficial biological effects, but their activity can depend on dose and duration of exposure. High concentrations of some phenolics may produce undesirable effects or interfere with nutrient absorption. Therefore, safety evaluation is essential before their use in concentrated pharmaceutical or nutraceutical preparations.

The bioavailability and safety of phenolic compounds remain important challenges for their therapeutic development. Improving absorption, identifying active metabolites, and establishing appropriate doses may help translate experimental findings into practical health applications (Figure 9).

Pharmaceutical, Nutraceutical and Functional Food Applications

Phenolic compounds have considerable potential in pharmaceutical, nutraceutical, and functional food products. Their diverse biological activities make them attractive for developing plant-based products with antioxidant, anti-inflammatory, cardioprotective, metabolic, and other health-related benefits. However, their practical use requires proper characterization, standardization, stability assessment, and safety evaluation (Kumar *et al.*, 2021; Albuquerque *et al.*, 2021).

Pharmaceutical applications

Phenolic-rich extracts and purified phenolic compounds can be investigated as active or supportive ingredients in pharmaceutical formulations. Their potential applications include products targeting oxidative stress, inflammation, metabolic disorders, and other chronic conditions. Standardized extracts are particularly important because the phenolic profile can vary with plant species, plant part, cultivation conditions, and extraction method.

Nutraceutical applications

Phenolics are widely considered for nutraceutical formulations such as capsules, tablets, powders, and concentrated plant extracts. Such products may provide a convenient source of selected phenolic compounds. However, low bioavailability remains a major limitation. Formulation approaches that improve solubility, stability, and absorption may increase their practical value.

Functional food applications

Phenolic compounds can also be incorporated into functional foods and beverages. Fruits, vegetables, cereals, herbs, spices, teas, and other plant materials naturally provide phenolic compounds. Their incorporation into food products may enhance the functional value of the product. Food applications, however, require attention to taste, stability, processing conditions, and consumer acceptability (Table 19).

CURRENT CHALLENGES AND FUTURE PERSPECTIVES

Despite the growing interest in phenolic compounds, several challenges limit their translation into pharmaceutical and health applications. The major concerns include variation in phenolic composition, low bioavailability, limited clinical evidence, difficulties in standardization, and differences in extraction and processing methods. Plant species, geographical origin, harvesting stage, and environmental conditions can also influence phenolic content.

Another important challenge is the gap between experimental and clinical evidence. Many reported pharmacological effects are based on *in vitro* and animal studies. Human studies are still

Table 20: Major Challenges and Future Directions for Phenolic Compounds.

Current challenge	Future direction
Variable phenolic composition	Standardized plant materials and extracts
Low bioavailability	Advanced delivery and formulation systems
Limited clinical evidence	Well-designed clinical trials
Difficult standardization	Validated analytical markers
Variation in extraction methods	Optimized and sustainable extraction
Limited pharmacokinetic data	Detailed ADME studies
Complex metabolism	Metabolomics and gut microbiota studies
Safety uncertainties	Long-term toxicological evaluation

limited for many individual phenolic compounds. Differences in absorption, metabolism, gut microbiota, and effective dose further complicate the interpretation of clinical outcomes.

Future research should focus on standardized extracts, improved delivery systems, pharmacokinetic studies, and well-designed clinical trials. Advanced analytical approaches can help identify active compounds and establish reliable quality markers. Sustainable extraction technologies may also support large-scale production while reducing solvent use and environmental impact.

Integration of metabolomics, genomics, and other omics approaches may improve understanding of phenolic biosynthesis and biological activity. Nanotechnology and advanced formulation strategies may further improve solubility, stability, and bioavailability. These approaches can support the development of more consistent and evidence-based phenolic products (Table 20).

CONCLUSION

Phenolic compounds are an important group of bioactive constituents found widely in medicinal plants. Their structural diversity contributes to a broad range of biological activities, including antioxidant, anti-inflammatory, antimicrobial, antidiabetic, hepatoprotective, cardioprotective, neuroprotective, and anticancer effects. Their activities are associated with regulation of oxidative stress, inflammatory pathways, cellular signalling, and apoptosis.

Advances in extraction and analytical techniques have improved the identification, characterization, and standardization of plant phenolics. However, low bioavailability, complex metabolism, variation in plant composition, and limited clinical evidence remain important challenges. Future research should therefore focus on standardized extracts, improved delivery systems, sustainable extraction, detailed pharmacokinetic studies, and well-designed clinical trials.

Overall, phenolic compounds have significant potential for pharmaceutical, nutraceutical, and functional food applications. Better understanding of their chemistry, biological mechanisms, bioavailability, and safety will help translate their promising pharmacological properties into reliable and evidence-based health products.

ABBREVIATIONS

ADME: Absorption, Distribution, Metabolism, and Excretion; **ALP:** Alkaline Phosphatase; **ALT:** Alanine Aminotransferase; **AST:** Aspartate Aminotransferase; **C4H:** Cinnamate 4-Hydroxylase; **4CL:** 4-Coumarate-CoA Ligase; **CHS:** Chalcone Synthase; **DES:** Deep Eutectic Solvents; **EAE:** Enzyme-Assisted Extraction; **FTIR:** Fourier Transform Infrared Spectroscopy; **GC-MS:** Gas Chromatography–Mass Spectrometry; **HPLC:** High-Performance Liquid Chromatography; **HPTLC:** High-Performance Thin-Layer Chromatography; **IL-6:** Interleukin-6; **LC-MS:** Liquid Chromatography–Mass Spectrometry; **LDL:** Low-Density Lipoprotein; **MAE:** Microwave-Assisted Extraction; **MS:** Mass Spectrometry; **NF-κB:** Nuclear Factor-kappa B; **NMR:** Nuclear Magnetic Resonance; **NO:** Nitric Oxide; **PAL:** Phenylalanine Ammonia-Lyase; **PLE:** Pressurized Liquid Extraction; **ROS:** Reactive Oxygen Species; **SFE:** Supercritical Fluid Extraction; **TNF-α:** Tumour Necrosis Factor-alpha; **UAE:** Ultrasound-Assisted Extraction.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Aktaş, H., and Kurek, M. A. (2024). Deep eutectic solvents for the extraction of polyphenols from food plants. Food Chemistry, 444, 138629. https://doi.org/10.1016/j.foodchem.2024.138629

Al Mamari, H. H. (2021). Phenolic compounds: Classification, chemistry, and updated techniques of analysis and synthesis. In Phenolic compounds. IntechOpen. https://doi.org/10.5772/intechopen.98958

Alara, O. R., Abdurahman, N. H., and Ukaegbu, C. I. (2021). Extraction of phenolic compounds: A review. Current Research in Food Science, 4, 200-214. https://doi.org/10.1016/j.crfs.2021.03.011

Albuquerque, B. R., Heleno, S. A., Oliveira, M. B. P. P., Barros, L., and Ferreira, I. C. F. R. (2021). Phenolic compounds: Current industrial applications, limitations and future challenges. Food and Function, 12(1), 14-29. https://doi.org/10.1039/D0FO02324H

Ameer, K., Shahbaz, H. M., and Kwon, J. H. (2017). Green extraction methods for polyphenols from plant matrices and their byproducts: A review. Comprehensive Reviews in Food Science and Food Safety, 16(2), 295-315. https://doi.org/10.1111/1541-4337.12253

Chen, S., Wang, X., Cheng, Y., Gao, H., and Chen, X. (2023). A review of classification, biosynthesis, biological activities and potential applications of flavonoids. International Journal of Molecular Sciences, 28(13), 4982. https://doi.org/10.3390/ijms28134982

Del Bo', C., Bernardi, S., Marino, M., Porrini, M., Tucci, M., *et al.* (2019). Systematic review on polyphenol intake and health outcomes: Is there sufficient evidence to define a health-promoting polyphenol-rich dietary pattern? Nutrients, 11(6), 1355. https://doi.org/10.3390/nu11061355

Fraga, C. G., Croft, K. D., Kennedy, D. O., and Tomás-Barberán, F. A. (2019). The effects of polyphenols and other bioactives on human health. Food and Function, 10(2), 514-528. https://doi.org/10.1039/C8FO01997E

Gligor, O., Mocan, A., Moldovan, C., Locatelli, M., Crișan, G., and Ferreira, I. C. F. R. (2019). Enzyme-assisted extractions of polyphenols-A comprehensive review. Trends in Food Science and Technology, 88, 302-315. https://doi.org/10.1016/j.tifs.2019.03.029

Heim, K. E., Tagliaferro, A. R., and Bobilya, D. J. (2002). Flavonoid antioxidants: Chemistry, metabolism and structure-activity relationships. The Journal of Nutritional Biochemistry, 13(10), 572-584. https://doi.org/10.1016/S0955-2863(02)00208-5

Jangpangi, D., Patni, B., Chandola, V., and Chandra, S. (2025). Medicinal plants in a changing climate: Understanding the links between environmental stress and secondary metabolite synthesis. Frontiers in Plant Science, 16, 1587337. https://doi.org/10.3389/fpls.2025.1587337

Kisiriko, M., Anastasiadi, M., Terry, L. A., Yasri, A., Beale, M. H., and Ward, J. L. (2021). Phenolics from medicinal and aromatic plants: Characterisation and potential as biostimulants and bioprotectants. Molecules, 26(21), 6343. https://doi.org/10.3390/molecules26216343

Kumar, B., Misra, A., and Srivastava, S. (2021). Bioactive phenolic compounds from Indian medicinal plants for pharmaceutical and medical aspects. In Phenolic compounds: Chemistry, synthesis, diversity, non-conventional industrial, pharmaceutical and therapeutic applications. IntechOpen. https://doi.org/10.5772/intechopen.99672

Kumar, N., and Goel, N. (2019). Phenolic acids: Natural versatile molecules with promising therapeutic applications. Biotechnology Reports, 24, e00370. https://doi.org/10.1016/j.btre.2019.e00370

Maeda, H., and Dudareva, N. (2012). The shikimate pathway and aromatic amino acid biosynthesis in plants. Annual Review of Plant Biology, 63, 73-105. https://doi.org/10.1146/annurev-arplant-042811-105439

Mustafa, A., and Turner, C. (2011). Pressurized liquid extraction as a green approach in food and herbal plants extraction: A review. Analytica Chimica Acta, 703(1), 8-18. https://doi.org/10.1016/j.aca.2011.07.018

Oluwole, O., Fernando, W. M. A. D. B., Lumanlan, J., Ademuyiwa, O., and Jayasena, V. (2022). Role of phenolic acid, tannins, stilbenes, lignans and flavonoids in human health: A review. International Journal of Food Science and Technology, 57(10), 6326-6335. https://doi.org/10.1111/ijfs.15936

Pant, P., Pandey, S., and Dall'Acqua, S. (2021). The influence of environmental conditions on secondary metabolites in medicinal plants: A literature review. Chemistry and Biodiversity, 18(11), e202100345. https://doi.org/10.1002/cbdv.202100345

Rana, A., Samtiya, M., Dhewa, T., Mishra, V., and Aluko, R. E. (2022). Health benefits of polyphenols: A concise review. Journal of Food Biochemistry, 46(10), e14264. https://doi.org/10.1111/jfbc.14264

Rice-Evans, C. A., Miller, N. J., and Paganga, G. (1996). Structure-antioxidant activity relationships of flavonoids and phenolic acids. Free Radical Biology and Medicine, 20(7), 933-956. https://doi.org/10.1016/0891-5849(95)02227-9

Salehi, B., Sharifi-Rad, J., Seca, A. M. L., Pinto, D. C. G. A., Michalak, I., Trincone, A., *et al.* (2019). Current evidence on medicinal plants in hepatoprotection. Biomolecules, 9(8), 356.

Serna-Vázquez, J., Ahmad, M. Z., Boczkaj, G., and Castro-Muñoz, R. (2021). Latest insights on novel deep eutectic solvents (DES) for sustainable extraction of phenolic compounds from natural sources. Molecules, 26(16), 5037. https://doi.org/10.3390/molecules26165037

Siddiqui, S. A., Redha, A. A., Salauddin, M., Harahap, I. A., and Rupasinghe, H. P. V. (2025). Factors affecting the extraction of (poly)phenols from natural resources using deep eutectic solvents combined with ultrasound-assisted extraction. Critical Reviews in Analytical Chemistry, 55(1), 139-160. https://doi.org/10.1080/10408347.2023.2266846

Sun, W., and Shahrajabian, M. H. (2023). Therapeutic potential of phenolic compounds in medicinal plants-Natural health products for human health. Molecules, 28(4), 1845. https://doi.org/10.3390/molecules28041845

Teka, T., Zhang, L., Ge, X., Li, Y., Han, L., and Yan, X. (2022). Stilbenes: Source plants, chemistry, biosynthesis, pharmacology, application and problems related to their clinical application-A comprehensive review. Phytochemistry, 197, 113128. https://doi.org/10.1016/j.phytochem.2022.113128

Tohge, T., and Fernie, A. R. (2017). An overview of compounds derived from the shikimate and phenylpropanoid pathways and their medicinal importance. Mini-Reviews in Medicinal Chemistry, 17(12), 1013-1027. https://doi.org/10.2174/1389557516666160624123425

Tungmunnithum, D., Thongboonyou, A., Pholboon, A., and Yangsabai, A. (2018). Flavonoids and other phenolic compounds from medicinal plants for pharmaceutical and medical aspects: An overview. Medicines, 5(3), 93. https://doi.org/10.3390/medicines5030093

Vinogradova, N., Vinogradova, E., Chaplygin, V., Mandzhieva, S., Kumar, P., *et al.* (2023). Phenolic compounds of the medicinal plants in an anthropogenically transformed environment. Molecules, 28(17), 6322. https://doi.org/10.3390/molecules28176322

Vogt, T. (2010). Phenylpropanoid biosynthesis. Molecular Plant, 3(1), 2-20. https://doi.org/10.1093/mp/ssp106

Wang, Z., Li, S., Ge, S., and Lin, S. (2020). Review of distribution, extraction methods, and health benefits of bound phenolics in food plants. Journal of Agricultural and Food Chemistry, 68(11), 3330-3343. https://doi.org/10.1021/acs.jafc.9b06574

Zagoskina, N. V., Zubova, M. Y., Nechaeva, T. L., Kazantseva, V. V., Goncharuk, E. N., *et al.* (2023). Polyphenols in plants: Structure, biosynthesis, abiotic stress regulation, and practical applications. International Journal of Molecular Sciences, 24(18), 13874. https://doi.org/10.3390/ijms241813874

Zhang, W., Zeng, Y., Jiao, M., Ye, C., Li, Y., Liu, C., and Wang, J. (2023). Integration of high-throughput omics technologies in medicinal plant research: The new era of natural drug discovery. Frontiers in Plant Science, 14, 1073848. https://doi.org/10.3389/fpls.2023.1073848

Zhang, Y., Cai, P., Cheng, G., and Zhang, Y. (2022). A brief review of phenolic compounds identified from plants: Their extraction, analysis, and biological activity. Natural Product Communications, 17(1), 1-14. https://doi.org/10.1177/1934578X211069721

Cite this article: Ashok PK, Babita, Lohani V, Gupta R, Samanta J, Upadhyaya K. Phenolic Compounds in Medicinal Plants: Chemistry, Pharmacological Activities and Health Benefits. Life Sci Res Commn. 2026;2(3):222-43.