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REVIEW ARTICLE

THE MULTIFUNCTIONAL ROLE OF PHENOLIC COMPOUNDS IN PLANTS AND HUMANS

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Abstract: Phenolic compounds constitute a structurally diverse group of plant secondary metabolites with significant ecological and biomedical relevance. This review provides an expanded and integrated classification into eleven groups, including both classical phenols and specialized derivatives with important biological activity. The objective is to present a framework that links chemical structure, plant function, and potential applications in human health and industry. The manuscript discusses their biosynthetic origins, and details their ecological roles in defense, stress tolerance, pigmentation, and signaling. A comprehensive description of tissue-specific distribution, environmental modulation, developmental variation, and genetic influence is provided, highlighting factors that determine phenolic profiles in different plant species. The review also examines their health-promoting properties, such as antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory effects, and explores how these functions contribute to chronic disease prevention, microbiome modulation, and pharmacological innovation. Emerging applications are discussed, including their use in green synthesis of nanoparticles, biopolymer modification, active food packaging, cosmetic formulations, and environmental remediation. Conclusion: phenolic compounds act as molecular bridges between plant biology and human well-being, with multifunctional properties that make them strategic in addressing challenges in health, sustainability, and industry.

Keywords: *Phenolic compounds, Secondary metabolites, Antioxidant activity, Phytochemistry, Human health applications*

INTRODUCTION

Phenolic compounds are a large and structurally diverse family of secondary metabolites synthesized by plants (Reyna-Margarita *et al*., 2019; Tomar, 2022a). Their common chemical feature is the presence of one or more hydroxyl groups attached to an aromatic ring (Irais *et al*., 2020). This simple structural motif gives rise to a wide array of molecules, ranging from low-molecular-weight phenolic acids to complex polyphenols such as flavonoids and tannins (Scott et al., 2022). These compounds play essential roles in plant physiology, development, and ecological interactions. They are widely recognized for their involvement in defense mechanisms against herbivores, pathogens, and environmental stresses (Erb & Kliebenstein, 2020). In addition, they participate in pigmentation, ultraviolet (UV) protection, lignification, and signaling between plants and their environment (Yang *et al*., 2018). In recent decades, phenolic compounds have gained increasing attention for their potential health benefits in humans (Crozier *et al*., 2009). Numerous studies have demonstrated their antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory properties (Tsao, 2010; Tomar, 2022b). As a result, they are considered bioactive components in functional foods, herbal medicines,

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and pharmacological formulations. Despite the broad interest in phenolic compounds, their classification remains fragmented. Many reviews focus only on specific families, such as flavonoids or tannins, without providing an integrated structural and functional overview (Xu e*t al*, 2020). This can limit the comparison among phenolic compounds and biological roles across plant species and human health contexts. Furthermore, there is a growing need to bridge the gap between phytochemistry and biomedical applications. A unified framework that relates chemical structure, ecological function, and bioactivity can facilitate interdisciplinary research and innovation. This article presents a comprehensive classification of phenolic compounds into eleven major groups. This system incorporates both classical and emerging phenolic structures, with emphasis on their functional relevance. The classification includes phenolic acids, flavonoids, tannins, lignans, stilbenes, phenylpropanoids, simple phenols, quinonoid phenolics, xanthones, anthraquinones, and a flexible category for special or mixed-function derivatives. This eleventh group includes compounds that do not strictly fit classical definitions of phenols but exhibit significant biological activity. Examples include aurones, furanocoumarins, capsaicinoids, and eugenol derivatives. Although structurally divergent, these compounds are included due to their phenol-like reactivity and effects on human health. The classification is complemented by examples of representative molecules and their distribution in plant species of nutritional, medicinal, or ecological interest. In addition to classification, the biosynthetic origins and functions of these compounds in plants are discussed. In human health, the antioxidant capacity of phenolics is the most studied feature. However, emerging evidence highlights their roles in modulating immune responses, cell signaling, and microbiome composition. Some phenolics interact with human enzymes, receptors, and transcription factors, contributing to therapeutic effects in chronic diseases. Finally, the emerging applications of phenolic compounds in green chemistry, nanotechnology, and the development of novel biomaterials, is explored.

CLASSIFICATION OF PHENOLIC COMPOUNDS

Phenolic compounds can be classified based on structural features, biosynthetic origin, and functional groups. Although their diversity is vast, they share a core structure of at least one hydroxyl group attached to an aromatic ring (Reyna-Margarita *et al.*, 2019). This simple feature enables a wide range of chemical modifications and polymerization patterns, resulting in a broad spectrum of phenolic types (Irais *et al.*, 2020). In this section, an expanded classification into eleven major groups each defined by shared structural motifs and biological relevance is proposed, as shown in Table 1. This system provides a practical framework to interpret phenolic diversity across plant systems and biomedical contexts.

Group 1: Phenolic acids

This group includes simple molecules such as hydroxybenzoic acids and hydroxycinnamic acids (Herrmann, 1989). Examples are gallic acid, protocatechuic acid, caffeic acid, ferulic acid, and p-coumaric acid. These compounds are widely distributed in fruits, grains, leaves, and bark. Their antioxidant capacity is closely linked to the number and position of hydroxyl groups on the aromatic ring. Phenolic acids also play important roles in lignin biosynthesis and pathogen defense (Tinikul *et al.*, 2018).

Group 2: Flavonoids

Flavonoids form one of the most studied groups of phenolic compounds. They are based on a C6–C3–C6 skeleton, with variations in oxidation, hydroxylation, and glycosylation (Liu *et al.*, 2021). Subclasses include flavones, flavonols, flavanones, isoflavones, anthocyanins, and catechins (Shen *et al.*, 2022). Flavonoids contribute to pigmentation, UV protection, pollen viability, and auxin transport. In human health, they are known for antioxidant, anti-inflammatory, and cardioprotective effects.

Group 3: Tannins

Tannins are high-molecular-weight polyphenols capable of precipitating proteins. They are classified into hydrolyzable tannins, which are based on gallic or ellagic acid esters, and condensed tannins (proanthocyanidins), which are polymers of flavonoid units (Maugeri *et al.*, 2022). Tannins occur in leaves, bark, unripe fruits, and seeds. In plants, they function as deterrents to herbivores and microbial pathogens. In humans, they have astringent, antioxidant, and antimicrobial properties (Chung *et al.*, 1998).

Group 4: Lignans and lignins

Lignans are dimeric phenylpropanoid compounds formed through oxidative coupling of coniferyl, sinapyl, or p-coumaryl alcohols (Berenshtein *et al.*, 2024). They exhibit antioxidant, estrogenic, and anticancer properties (Jang *et al.*, 2022). Lignins are complex polyphenolic polymers deposited in cell walls, providing mechanical strength and resistance to degradation. Both classes derive from phenylpropanoid metabolism and serve structural and defensive roles in vascular plants.

Group 5: Stilbenes

Stilbenes are characterized by a C6–C2–C6 structure. The best-known example is resveratrol, found in grapes, peanuts, and berries (Bo et al., 2023). Stilbenes act as phytoalexins in plants, accumulating in response to stress or infection. In humans, they show promise in cardiovascular protection, anti-aging, and anticancer therapies. Their biological activity is often linked to conjugated double bonds and hydroxylation patterns (Navarro-Orcajada *et al.*, 2023).

Group 6: Phenylpropanoids and coumarins

This group includes simple phenylpropanoids (such as cinnamic acid derivatives) and coumarins, which are lactones derived from o-hydroxycinnamic acids (Matern, 1991). Umbelliferone, scopoletin, and bergapten are typical members. These compounds contribute to allelopathy, UV filtration, and pathogen resistance (Stringlis *et al*., 2019). In pharmacology, they are used for anticoagulant, antimicrobial, and photosensitizing purposes.

Group 7: Simple phenols and polyphenols

This group includes low-complexity phenolic structures such as catechol, hydroquinone, resorcinol, and pyrogallol (Reyna-Margarita et al., 2019). These compounds are biosynthetic precursors for larger phenolics and serve important redox functions. Despite their simplicity, they exhibit antimicrobial and antioxidant properties (Irais et al., 2020). They are also involved in plant browning reactions and stress signaling.

Group 8: Quinonoid phenolics

Quinonoid phenolics contain oxidized aromatic rings bearing one or more hydroxyl groups. Examples include juglone, lawsone, and alkannin. These compounds often exhibit allelopathic or antimicrobial activities (Dos *et al*., 2021). Their redox cycling contributes to reactive oxygen species production in both plant and microbial systems (Nair *et al*., 2024). They are commonly found in roots, barks, and pigmented tissues (Kaur *et al*., 2022).

Group 9: Xanthones and xanthonoids

Xanthones are polycyclic phenolic compounds containing a tricyclic C6–C1–C6 core (Gul *et al*., 2022). Mangostin and norathyriol are representative examples (Shi *et al*., 2017). Found in tropical fruits such as mangosteen, these compounds display antioxidant, anti-inflammatory, and anticancer activities (Majdalawieh *et al*., 2024).

Group 10: Phenolic anthraquinones

These compounds possess a three-ring anthracene core with keto and hydroxyl substitutions. Found in species like Rheum, Senna, and Aloe, the most representative example is emodin (Wang *et al*., 2024). Anthraquinones often function as laxatives, antimicrobials, and anticancer agents (Khatoon *et al*., 2025). In plants, they contribute to defense and pigmentation.

Group 11: Special and mixed-function phenolics

This flexible group includes phenolic derivatives with additional functional groups or unique scaffolds. It covers aurones, furanocoumarins and capsaicinoids (Mazziotti *et al*., 2021; Ahmed *et al*., 2020; Naves *et al*., 2019). Although structurally diverse, these molecules share phenol-like bioactivity and relevance in plant defense or human pharmacology. Their inclusion acknowledges the need for an adaptable and functional classification.

Table 1. Classification of phenolic compounds, representative examples, and their main characteristics and biological activities. The classification includes eleven major groups covering both classical phenolic categories and special subgroups or mixed derivatives. Representative compounds are listed for each group, along with structural features, plant functions, and relevant biological activities related to human health and industrial applications.

Table 1.

Group	Representative examples	Characteristics and activity
1) Phenolic acids (hydroxybenzoic and hydroxycinnamic).	Gallic acid, protocatechuic acid, caffeic acid, ferulic acid, p-coumaric acid.	Simple structure (C6-C1 / C6-C3), high antioxidant capacity, metal chelation, common in foods and plants.
2) Flavonoids.	Quercetin, catechin, apigenin, luteolin, genistein.	C6-C3-C6 nucleus; potent antioxidant, anti-inflammatory, immunomodulatory, and vascular activity.
3) Tannins (hydrolyzable and condensed).	Ellagic acid, pentagalloylglucose, proanthocyanidins.	High molecular weight polyphenols; form complexes with proteins and metals; astringent and therapeutic effects.
4) Lignans and lignins.	Seco-isolariciresinol, matairesinol, sinapyl alcohol.	Derived from phenylpropanoid dimerization; estrogenic, antioxidant, and structural activity in plants.
5) Stilbenes.	Resveratrol, piceatannol.	C6-C2-C6 structure; cardiovascular, anticancer, and antioxidant effects.
6) Phenylpropanoids and coumarins.	Umbelliferone, scopoletin, sinapic acid.	Derived from phenylalanine; antimicrobial, anticoagulant, allelopathic properties.
7) Simple phenols and basic polyphenols.	Catechol, hydroquinone, resorcinol, pyrogallol.	Simple compounds, biosynthetic precursors, direct redox capacity.
8) Quinonoid phenolics.	Juglone, lawsone, alkannin.	Quinones with at least one phenolic -OH group; redox, allelopathic, and antimicrobial activity.

9) Xanthones and xanthonoids.	α-Mangostin, γ-Mangostin, norathyriol.	Tricyclic nucleus with -OH groups; antioxidant, anti-inflammatory, anticancer effects.
10) Phenolic anthraquinones.	Emodin, aloin, chrysophanol.	Fused aromatic rings with -OH and =O groups; laxative, antibacterial, immunomodulatory properties.
11) Special and mixed-function phenolics.	Auronas (leptosidin), furanocoumarins (psoralen), capsaicin.	Functional phenols with other active functions (amides, aldehydes, lactones); analgesic, photosensitizing, antimicrobial effects.

DISTRIBUTION AND ABUNDANCE OF PHENOLIC COMPOUNDS IN PLANTS

Phenolic compounds are present in the plants among a wide range of taxonomic groups, parts of the plant, and developmental stages (Erb & Kliebenstein, 2020). Their abundance and diversity are influenced by genetic, ecological, and environmental factors (Yang *et al*., 2018). Nearly all plants synthesize phenolic metabolites, although their concentrations and specific profiles vary substantially among species, parts of the plant, and environmental contexts (Crozier *et al*., 2009). Most phenolic compounds are synthesized in the cytoplasm of the cells and accumulate in the vacuole or are secreted into the apoplast. Their production is regulated by internal signals and external stimuli. Accumulation can be constitutive or inducible in response to stress, wounding, or pathogen attack. In terms of taxonomic distribution, phenolic compounds are abundant in angiosperms, especially in families such as Fabaceae, Lamiaceae, Rutaceae, Asteraceae, Rosaceae, Myrtaceae, and Poaceae. These families include many edible, medicinal, and aromatic plants with high phenolic content. Flavonoids are widely distributed in flowering plants and are abundant in Leguminosae, Apiaceae, and Solanaceae. In these families, flavonoids are involved in flower pigmentation, fertility, and UV protection (Veitch, 2007). Anthocyanins, a subclass of flavonoids, are responsible for red, blue, and purple coloration in petals, fruits, and leaves. Phenolic acids, such as gallic and caffeic acids, are common in both monocotyledons and dicotyledons (Bate-Smith, 1968). They are found in cereals like wheat and barley, and fruits like pomegranate and blueberries. These acids contribute to astringency and antioxidant defense. Tannins are found in woody plants such as oak, chestnut, and acacia. High levels of tannins are also found in grapes, persimmons, and tea leaves. In seeds and bark, tannins serve as defense compounds against herbivores and microbial invasion (Chung *et al*., 1998). Lignins are essential components of secondary cell walls in vascular plants. They are especially abundant in gymnosperms like conifers, where lignin content reaches up to 30% of wood dry weight. Lignification provides mechanical support and water impermeability in xylem vessels and fibers (Silva *et al*., 2023). Stilbenes, although less widespread, are notable in species such as Vitis vinifera, Arachis hypogaea, and Pinus spp. Resveratrol accumulation is often stress-induced, acting as a phytoalexin in response to pathogen attack or UV exposure (Dubrovina & Kiselev, 2017). Coumarins and furanocoumarins occur primarily in Apiaceae and Rutaceae, with species like Citrus, Petroselinum, and Ammi. These compounds can accumulate in roots, leaves, and peels, exhibiting allelopathic or phototoxic effects (Zhao *et al*., 2021). Xanthones, such as α-mangostin, are less common but are characteristic of tropical species like Garcinia mangostana. These compounds concentrate in the fruit pericarp and are implicated in defense and pigmentation (Majdalawieh *et al*., 2024). Anthraquinones are frequently found in the Polygonaceae, Rhamnaceae, and Fabaceae families. Important sources include Rheum, Cassia, and Aloe. These compounds are synthesized in leaves, roots, and latex, and serve as chemical defenses or laxative agents (Wang *et al*., 2024). In summary, phenolic compounds have a tissue-specific distribution that matches their functions. For instance, flavonoids occur in epidermal tissues for UV protection, tannins and lignins are found in structural tissues, and phenolic acids in vacuoles or exudates. Their levels change in response to environmental stress, cultivation practices, developmental stage, and genetic variation, affecting plant defense, crop quality, and breeding potential.

FUNCTIONS OF PHENOLIC COMPOUNDS IN PLANTS

Phenolic compounds perform a wide range of physiological and ecological functions in plants. These functions are closely related to their structural diversity, redox activity, and ability to interact with proteins, membranes, and signaling pathways (Corso *et al*., 2020). Although traditionally associated with defense, phenolics are now recognized as multifunctional agents involved in growth, development, and adaptation. One of the most well-characterized roles of phenolics is chemical defense against herbivores and pathogens. Tannins, for example, form insoluble complexes with dietary proteins, reducing digestibility and deterring feeding. Flavonoids and phenolic acids can inhibit bacterial and fungal enzymes or disrupt microbial membranes. Lignified tissues, rich in phenolic polymers, serve as physical and chemical barriers to infection and wounding (Erb & Kliebenstein, 2020). Phenolic compounds also contribute to plant-plant interactions, notably through allelopathy. Certain phenolics are released into the soil via root exudates or leaf litter, where they affect germination, growth, or nutrient uptake of neighboring species. Juglone, a quinonoid phenol produced by Juglans species, is a classic example of an allelopathic agent that inhibits root elongation in surrounding vegetation (Zhao *et al.*, 2021). In addition to their defensive roles, phenolics play a central role in protection against abiotic stress. Under ultraviolet (UV) radiation, drought, salinity, or heavy metal exposure, plants upregulate phenolic biosynthesis. Flavonoids, especially in the epidermis, absorb UV-B light and protect underlying tissues from damage. Phenolic antioxidants also scavenge reactive oxygen species (ROS) generated during oxidative stress, helping to maintain cellular redox homeostasis (Takshak & Agrawal, 2019). Another major function is structural support, particularly through the formation of lignin in secondary cell walls. Lignin deposition strengthens vascular tissues, enabling water transport and upright growth. It also reinforces mechanical resistance against environmental pressures such as wind, bending, and compression (Pesquet *et al.*, 2019).

Phenolics are intimately involved in pollinator attraction and reproductive success. Flavonoids and anthocyanins are responsible for a wide range of floral and fruit colors that attract insects, birds, and mammals. In some cases, phenolic volatiles contribute to floral scent profiles, further enhancing pollination efficiency. Certain phenolics act as signaling molecules in plant-microbe interactions. For example, isoflavonoids secreted by legume roots function as nodulation signals for Rhizobium bacteria. These molecules induce the expression of bacterial genes, initiating the formation of nitrogen-fixing root nodules. Similarly, coumarins and other low-molecular-weight phenolics modulate microbial communities, shaping beneficial plant–microbe associations (Bosse *et al.*, 2021). During developmental transitions, such as fruit ripening or senescence, phenolics accumulate or degrade in a coordinated manner. This contributes to changes in color, taste, texture, and resistance to pathogens. The browning observed in wounded tissues or cut fruits is often due to enzymatic oxidation of phenolics by polyphenol oxidases. The localization of phenolics also reflects their function. External cells of the plants often store UV-absorbing flavonoids. Phenolic-rich exudates in resin ducts act as first-line defense mechanisms against insects and microbes.

BIOLOGICAL ACTIVITY AND HEALTH EFFECTS OF PHENOLIC COMPOUNDS IN HUMANS

Phenolic compounds from plants have been widely studied for their health-promoting effects in humans. Their biological activity is primarily attributed to their redox properties, structural diversity, and ability to interact with biomolecules (Crozier *et al.*, 2009). These interactions affect cellular signaling, gene expression, and inflammatory responses, making phenolics important agents in preventive nutrition and therapeutic research. One of the most prominent features of phenolic compounds is their antioxidant capacity. Their hydroxyl groups can donate hydrogen atoms or electrons to neutralize ROS (Singh *et al.*, 2020). This helps reduce oxidative stress, which is implicated in the pathogenesis of cardiovascular disease, neurodegenerative disorders, diabetes, and cancer. Some phenolics can also chelate transition metals, further limiting ROS production through Fenton-type reactions. Beyond antioxidant activity, many phenolic compounds exhibit potent anti-inflammatory effects. They inhibit enzymes such as cyclooxygenase (COX), lipoxygenase (LOX), and inducible nitric oxide synthase (iNOS) (Murakami & Ohigashi, 2007). Inhibition of these enzymes reduces the production of pro-inflammatory mediators like prostaglandins, leukotrienes, and nitric oxide. Flavonoids such as quercetin and apigenin are among the most studied phenolics for these effects.

Phenolic compounds also modulate immune function. Certain flavonoids and phenolic acids regulate cytokine production, influence lymphocyte proliferation, and alter macrophage activity (Yahfoufi *et al.*, 2018). Some compounds, like resveratrol and curcumin, have been shown to shift immune responses from pro-inflammatory to regulatory profiles. These effects suggest potential applications in autoimmune conditions and chronic inflammation (Gupta *et al.*, 2013). Another area of interest is their anticancer potential. Phenolics can interfere with multiple stages of carcinogenesis, including initiation, promotion, and progression. They induce apoptosis, inhibit angiogenesis, block tumor cell proliferation, and modulate oncogene expression. For instance, resveratrol has demonstrated anticancer activity in models of colon, breast, and prostate cancer (Ren *et al.*, 2021).

Phenolic compounds also influence cardiovascular health. Their intake is associated with reduced blood pressure, improved endothelial function, and decreased platelet aggregation. These effects are partly mediated by nitric oxide availability and inhibition of LDL oxidation. Epidemiological studies link high dietary polyphenol intake with lower incidence of cardiovascular events (Ibrahim *et al.*, 2020). In metabolic health, phenolics regulate enzymes involved in glucose metabolism and lipid homeostasis. Some inhibit α-glucosidase and α-amylase, enzymes that break down carbohydrates into glucose. Others improve insulin sensitivity or inhibit lipogenesis in adipose tissue and liver. Green tea catechins and chlorogenic acid are examples with proven metabolic benefits (Wang *et al.*, 2014). Recent research also points to the role of phenolics in gut microbiome modulation. Many phenolic compounds are poorly absorbed in the small intestine and reach the colon, where they interact with gut bacteria. These interactions can promote the growth of beneficial microbial taxa and inhibit pathogens. The microbial metabolism of phenolics also produces bioactive metabolites with local and systemic effects (Wan *et al.,* 2021). Phenolic compounds show neuroprotective properties, partly through antioxidant mechanisms but also by modulating signaling pathways in the brain. Flavonoids such as epicatechin and luteolin improve memory, reduce neuroinflammation, and protect against excitotoxicity. Their potential roles in the prevention of Alzheimer's and Parkinson's diseases are under active investigation (Kim, 2010). Some phenolic-rich plant extracts are used in traditional medicine, and several isolated compounds have inspired pharmaceutical development. For example, salicylic acid—originally derived from willow bark—is the precursor of aspirin (Paterson & Lawrence, 2001). Similarly, anthraquinones from Senna and Aloe species are used as laxatives, and coumarins serve as anticoagulants (Suarez-Kurtz & Botton, 2015). Phenolic compounds offer a wide range of health benefits through mechanisms that go beyond simple antioxidant action. Their ability to modulate inflammation, metabolism, immunity, and microbiota makes them promising candidates for functional foods and therapeutic agents. Continued research is essential to clarify their bioavailability, safety, and clinical applications.

EMERGING APPLICATIONS OF PHENOLIC COMPOUNDS

Phenolic compounds, traditionally valued for their nutritional and medicinal properties, are now gaining attention in emerging fields such as biotechnology, green chemistry, nanotechnology, and biomaterial development (Tomar, 2021). Their unique redox behavior, structural versatility, and natural abundance make them attractive for sustainable and multifunctional applications (Wan *et al.*, 2021). In green chemistry, phenolic compounds are increasingly used as natural reducing agents and stabilizers for the synthesis of metal nanoparticles. For example, flavonoids and tannins can reduce silver or gold ions to form stable nanoparticles without the need for toxic chemicals. These green-synthesized nanoparticles have shown antibacterial, antioxidant, and anticancer properties, offering potential for biomedical use and eco-friendly production methods (Suhag *et al.,* 2023). Phenolics are also applied in biopolymer modification and coating technologies. Tannic acid, for instance, forms stable complexes with metal ions and proteins, enabling the creation of thin bioadhesive films. Such coatings are used for drug delivery systems, wound dressings, or as protective layers in packaging (Moghaddam *et al.,* 2023). Their biocompatibility and biodegradability offer advantages over synthetic polymers. In agricultural biotechnology, phenolic compounds are being explored as natural plant growth regulators, biopesticides, and allelochemicals. Their antimicrobial and insect-repelling activities help reduce the need for synthetic agrochemicals. Phenolic-rich extracts from Eucalyptus, Neem, or Citrus species have shown promise in integrated pest management strategies (Panzella *et al.,* 2020). Another emerging application is in food packaging and preservation. Phenolic compounds from grape seeds, tea leaves, or olive waste are incorporated into active packaging films to prevent microbial growth and oxidation. These natural additives help extend shelf life while reducing reliance on synthetic preservatives (Zhang *et al.,* 2023). Biodegradable films enriched with phenolics also meet growing consumer demand for sustainable food packaging. In the cosmetic industry, phenolics are valued for their anti-aging, skin-protective, and pigmentation-regulating properties. Flavonoids such as rutin, kaempferol, and apigenin are incorporated into creams, serums, and sunscreens for their ability to neutralize ROS and reduce UV-induced skin damage (Liu *et al.,* 2024). Plant extracts rich in phenolics also serve as natural colorants and anti-inflammatory agents.

Phenolic compounds are also used in environmental remediation, particularly in the design of bioadsorbents for heavy metal removal. Tannins and gallic acid-based polymers have high affinities for arsenic, lead, and mercury. Their hydroxyl and carboxyl groups form chelates with metal ions, enabling efficient and selective adsorption. Such systems provide cost-effective and environmentally friendly alternatives for water treatment (Jańczak-Pieniążek *et al.,* 2022). Some researchers are exploring phenolic–drug conjugates to improve pharmacological properties. By linking phenolic compounds to therapeutic agents, they aim to enhance solubility, stability, and bioavailability. These conjugates may also exhibit synergistic effects, combining antioxidant activity with targeted delivery or anti-inflammatory action (Irais *et al.,* 2020). Finally, phenolic compounds are increasingly studied in synergistic formulations with probiotics, vitamins, or other phytochemicals. These combinations may offer improved efficacy in managing inflammation, oxidative stress, or metabolic disorders. The interactions between phenolics and other bioactive molecules are a promising frontier in functional food design and precision nutrition.

CONCLUSIONS AND PERSPECTIVES

Phenolic compounds represent one of the most functionally versatile and structurally diverse classes of secondary metabolites in the plants. Their distribution across taxa, tissues, and ecological contexts reflects their importance in plant survival, communication, and adaptation. From defense against pathogens to the regulation of growth and reproduction, phenolic compounds are deeply integrated into plant life processes. At the same time, phenolic compounds have a great impact in human health and biotechnology. The antioxidant, anti-inflammatory, immunomodulatory, antimicrobial, and anticancer properties of phenolics position them as central players in the development of functional foods, nutraceuticals, and pharmacological agents. Their involvement in gut microbiome modulation and chronic disease prevention makes them relevant in precision nutrition and public health strategies. In this review, it was proposed an expanded classification of phenolic compounds into eleven functional groups, encompassing both classical and non-traditional phenols. This inclusive framework incorporates a wide range of structures, including flavonoids, tannins, lignans, stilbenes, xanthones, anthraquinones, and phenol-based conjugates with mixed biological functions. By recognizing both structural and functional criteria, this system offers a clearer understanding of phenolic diversity and potential. It was also highlighted the distribution of phenolics in plant species of nutritional, medicinal, and ecological relevance. Their accumulation is influenced by developmental stages, environmental stressors, and genetic factors, offering opportunities for selective breeding and crop improvement.

Beyond biology and health, phenolic compounds are emerging as key tools in green chemistry, nanotechnology, agriculture, and environmental remediation. Their redox activity and chemical reactivity enable applications in nanoparticle synthesis, smart coatings, bioadsorbents, and sustainable materials. This multifunctionality makes phenolics unique among natural product classes, with impact across scientific and industrial disciplines. Despite their promise, important challenges remain. Many phenolic compounds have low bioavailability, limiting their systemic effects in vivo. Metabolism, conjugation, and gut microbial transformation alter their activity and pharmacokinetics. Future research must focus on improving delivery systems, optimizing extraction methods, and understanding synergistic effects with other nutrients or drugs. Another challenge lies in the standardization of phenolic-rich extracts for clinical and industrial use. Variability in plant source, growth conditions, and processing can affect compound profiles. Advances in metabolomics, chemometrics, and quality control are essential to ensure reproducibility and efficacy. In conclusion, phenolic compounds are not merely secondary plant products but central molecular bridges between plant biology and human well-being. Their multifunctionality, natural origin, and bioactive potential support their continued exploration as key agents in science, medicine, and industry.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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