Review Article

Biological activities and health-related potential of plant phenolic compounds

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Abstract

lant-derived foods and medicinal resources contain a wide diversity of bioactive compounds that may contribute to biological functions in plants and potential health effects in humans. Among these compounds, phenolic compounds constitute an important group of plant secondary metabolites and include phenolic acids, flavonoids, lignans, stilbenes, tannins, coumarins, and related structures. Their chemical diversity contributes to a broad range of biological activities, including antioxidant, anti-inflammatory, antimicrobial, enzyme-modulating, and cell-signaling effects.

Phenolic compounds have attracted considerable scientific interest because many of them can interact with reactive oxygen species, inflammatory mediators, enzymes, receptors, and intracellular signaling pathways. Experimental studies have also reported antimicrobial, antiviral, antiproliferative, cardiometabolic, and neuroprotective effects for selected compounds. However, these activities vary substantially according to molecular structure, concentration, chemical form, metabolism, and experimental conditions. In particular, findings obtained from in vitro and animal studies cannot necessarily be extrapolated to therapeutic effects in humans.

This narrative review summarizes the structural diversity, biological activities, mechanisms of action, bioavailability, and metabolism of plant phenolic compounds, with particular attention to the factors that influence their biological relevance. Current evidence indicates that digestion, absorption, phase I and phase II metabolism, and transformation by the gut microbiota can substantially modify the forms and concentrations of phenolic compounds available to tissues. Inter-individual differences in metabolism and microbiota may further contribute to variability in biological responses. Future research should therefore focus on structure–activity relationships, physiologically relevant concentrations, bioactive metabolites, long-term safety, and well-designed human intervention studies. Such evidence will be important for determining the realistic potential of phenolic compounds in functional foods, nutraceuticals, and pharmaceutical development.

Keywords: Phenolic compounds, plant resources, flavonoids, biological activity, secondary metabolites, polyphenols

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Introduction

Plant secondary metabolites are chemically diverse compounds synthesized through specialized metabolic pathways and are involved in plant defense, adaptation, signaling, pigmentation, structural development, and interactions with the surrounding environment. Among these metabolites, phenolic compounds represent one of the major groups and are widely distributed in fruits, vegetables, cereals, beverages, and medicinal plants. Phenolic compounds are characterized by the presence of at least one aromatic ring bearing one or more hydroxyl groups, although their structures range from relatively simple phenolic acids to complex polymers. Polyphenols constitute an important subgroup of phenolic compounds rather than a complete synonym for all phenolics. Flavonoids, phenolic acids, lignans, stilbenes, tannins, and related compounds account for much of the structural diversity observed in plant phenolics (Rudrapal *et al*., 2024; El-Saadony *et al*., 2024).

The biological importance of phenolic compounds has received increasing attention because of their potential antioxidant and other bioactive properties. Dietary exposure to phenolic-rich foods has been associated with favorable health outcomes in observational studies, including associations with cardiovascular, metabolic, and neurodegenerative health. However, the strength of evidence differs according to the specific compound, dietary source, outcome, and study design, and epidemiological associations do not establish causality (Vivarelli *et al*., 2023; Rathod *et al*., 2023; Zupo *et al*., 2024).

The biological effects of phenolic compounds extend beyond direct radical scavenging. Depending on their structure and concentration, they may influence inflammatory pathways, enzyme activity, cellular signaling, microbial growth, and metabolic processes (Pisoschi *et al*., 2024; Sun *et al*., 2024; Li *et al*., 2024; Wang *et al*., 2026). Some phenolic compounds have also shown antibacterial activity against drug-resistant microorganisms in experimental models, although the translation of such findings into clinical applications remains uncertain (Sun *et al*., 2024).

An important challenge in evaluating phenolic compounds is their variable bioavailability. The compounds consumed in foods may undergo digestion, absorption, conjugation, microbial transformation, and other metabolic processes that substantially modify their chemical forms. Consequently, the compounds detected in circulation or tissues may differ from those originally present in the food (Quesada-Vázquez *et al*., 2024; Favari *et al*., 2024; Williamson, 2025).

This review provides a narrative overview of the structural diversity, biological activities, mechanisms of action, bioavailability, and metabolism of plant phenolic compounds. Particular attention is given to the distinction between experimental evidence and clinically established effects, as well as to current limitations and research priorities.

Plant phenolic compounds and their biological relevance

Plant secondary metabolites are ecologically and biologically important compounds produced through specialized biochemical pathways. Although they are generally distinguished from primary metabolites, their functions may be highly important for plant survival and adaptation. They contribute to defense against herbivores and pathogens, protection against environmental stress, pigmentation, signaling, and interactions with other organisms (El-Saadony *et al*., 2024; Rudrapal *et al*., 2024).

Plant secondary metabolites can broadly be grouped into phenolic compounds, terpenoid compounds, and nitrogen-containing compounds (Table 1). Phenolic compounds include phenolic acids, flavonoids, lignans, stilbenes, tannins, coumarins, and lignin-related structures. Terpenoid compounds include carotenoids, sterols, cardiac glycosides, and volatile constituents, whereas nitrogen-containing compounds include alkaloids and glucosinolates (Rathod *et al*., 2023; El-Saadony *et al*., 2024; Rudrapal *et al*., 2024).

Table 1: Summarizes the main classes of phenolic compounds, their representative examples, sources, and biological activities

Class of phenolic compounds	Representative examples	Major natural sources	Biological activity
Phenolic acids	Gallic acid, caffeic acid, ferulic acid, vanillic acid	Coffee, tea, fruits, vegetables, cereals	Antioxidant, anti-inflammatory, antimicrobial
Flavonoids	Quercetin, kaempferol, myricetin, catechins, anthocyanins	Citrus fruits, berries, grapes, green tea	Antioxidant, cardioprotective, anticancer
ignans	Secoisolariciresinol, matairesinol	Flax seeds, whole grains, legumes	Phytoestrogenic, antitumor, antioxidant
Stilbenes	Resveratrol, pterostilbene	Red wine, grapes, peanuts	Antioxidant, neuroprotective, anti-aging
Tannins	Condensed and hydrolyzable tannins	a, bark, nuts, pomegranate	Astringent, antimicrobial, anti-diarrheal
Coumarins	Umbelliferone, esculetin	Parsley, celery, citrus fruits	Anti-inflammatory, anticoagulant, photoprotective

Phenolic compounds perform diverse functions in plants. Anthocyanins, for example, contribute to pigmentation and may participate in interactions with pollinators and seed dispersers, whereas lignin provides structural support. Other phenolics contribute to plant defense and protection against environmental stresses (El-Saadony *et al*., 2024’ Rudrapal *et al*., 2024).

The occurrence of phenolic compounds in edible plants has also contributed to their extensive investigation as dietary bioactive constituents. Fruits, vegetables, cereals, tea, coffee, and other plant-derived foods can provide different classes and quantities of phenolic compounds. Their concentrations may vary according to plant species, cultivar, growing conditions, maturity, processing, and storage (Lippolis *et al*., 2023; Rudrapal *et al*., 2024).

Structural classification and biological relevance

Flavonoids are one of the largest and most extensively studied groups of plant polyphenols. They include several structural subclasses, such as flavones, flavonols, flavanones, flavanols, isoflavones, and anthocyanidins. Quercetin, kaempferol, myricetin, catechins, and anthocyanin derivatives are among the commonly investigated representatives (Fig.1).

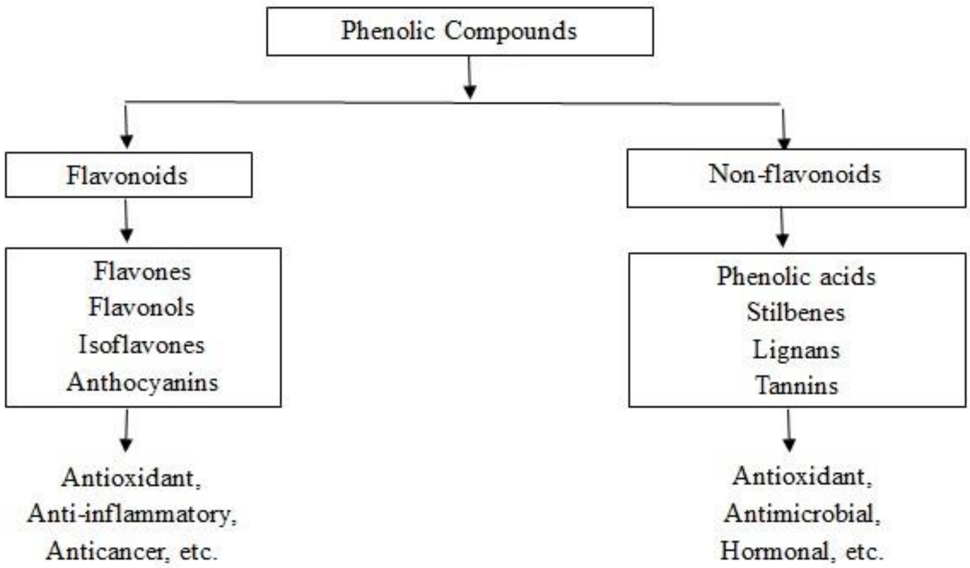

Figure 1: Classification and functional roles of phenolic compounds in plants.

Phenolic compounds exhibit considerable structural diversity. Simple phenolic compounds may contain a single aromatic ring, whereas more complex compounds contain additional carbon skeletons, multiple hydroxyl groups, glycosyl groups, or polymeric structures. These structural differences are important because antioxidant capacity, enzyme interaction, cellular uptake, metabolism, and biological activity can vary markedly among individual phenolics.

The position and number of hydroxyl groups, degree of methoxylation, glycosylation, polymerization, and other structural characteristics can influence the reactivity and biological behavior of phenolic compounds. Recent evidence emphasizes the importance of structure–activity relationships when comparing the biological effects of different flavonoids and related compounds (Li *et al*., 2024; Tang *et al*., 2025; Wang *et al*., 2026).

Phenolic compounds are also investigated for their technological applications. Their antioxidant properties may contribute to the stabilization of foods and inhibition of lipid oxidation, making selected phenolics potentially useful as natural food preservatives. However, their effectiveness depends on the food matrix, concentration, chemical stability, and processing conditions (Sun *et al*., 2024; Wang *et al*., 2026).

Selected phenolic compounds may interact with enzymes, receptors, transcription factors, and other molecular targets. These interactions may occur through hydrogen bonding, hydrophobic interactions, ionic interactions, or other forms of molecular recognition. Such interactions provide possible mechanistic explanations for some of the biological activities reported in experimental studies (Li *et al*., 2024; Pisoschi *et al*., 2024).

Isoflavones are of particular interest because some members can interact with estrogen receptors and are therefore commonly described as phytoestrogens. Their effects depend on chemical structure, receptor subtype, dose, metabolism, and individual physiological characteristics. They should therefore not be assumed to have uniform estrogenic or therapeutic effects.

Tannins comprise structurally diverse high-molecular-weight phenolic compounds. Experimental studies have reported antioxidant, antimicrobial, antiparasitic, and other biological effects for different tannins. However, these activities vary according to tannin structure, degree of polymerization, concentration, and experimental model (Tang *et al*., 2025; Yu *et al*., 2025).

Biological activities and mechanisms of action

Antioxidant activity

Antioxidant activity is among the most extensively studied properties of phenolic compounds. Many phenolics can donate hydrogen atoms or electrons and interact with reactive oxygen and nitrogen species. Their antioxidant behavior is influenced by the number and position of hydroxyl groups, molecular conformation, conjugation, and other structural features (Rudrapal *et al*., 2024; Pisoschi *et al*., 2024).

However, antioxidant activity measured in chemical assays should not automatically be interpreted as antioxidant activity in humans. The concentrations used in laboratory experiments may differ substantially from those achievable in tissues following dietary consumption. In addition, phenolic compounds undergo extensive metabolism after ingestion, and the metabolites present in vivo may differ from the parent compounds

(Quesada-Vázquez *et al*., 2024; Williamson, 2025).

Phenolic compounds may also influence oxidative stress indirectly by modulating cellular antioxidant systems and signaling pathways. Such effects may be more biologically relevant than direct radical scavenging under physiological conditions.

Anti-inflammatory activity

Inflammatory signaling represents another important area of phenolic research. Selected phenolic compounds have been reported to influence inflammatory mediators, transcription factors, cytokine production, and oxidative stress-related pathways. These effects have been observed in cell-based and animal models and may contribute to the biological effects attributed to phenolic-rich foods (Pisoschi *et al*., 2024). Nevertheless, experimental anti-inflammatory activity does not establish clinical efficacy. Differences in experimental concentrations, compound purity, exposure time, and biological model make direct comparison between studies difficult. Human intervention studies are therefore required to determine whether specific phenolics or phenolic-rich foods produce clinically meaningful effects.

Antimicrobial and antiviral activities

Several phenolic compounds exhibit antimicrobial activity against Gram-positive and Gram-negative bacteria and, in some experimental systems, against fungi and viruses. Proposed mechanisms include disruption of microbial membranes, interference with enzymes, alteration of cellular signaling, and effects on microbial adhesion or biofilm formation (Pisoschi *et al*., 2024; Sun *et al*., 2024). Some studies have reported activity against drug-resistant microorganisms. Such findings are scientifically relevant because antimicrobial resistance represents an important global challenge. However, most available evidence remains experimental, and questions concerning effective concentrations, pharmacokinetics, toxicity, and clinical applicability remain unresolved.

Antiproliferative and anticancer-related effects

Flavonoids and other phenolic compounds have been investigated for their effects on cellular proliferation, apoptosis, oxidative stress, inflammation, angiogenesis, and signaling pathways associated with cancer development. These effects have mainly been demonstrated in cell culture and animal models. The interpretation of these findings requires caution. Concentrations producing antiproliferative effects in vitro may not be achievable through ordinary dietary consumption, and the metabolism of phenolic compounds may substantially alter their biological activity. Therefore, experimental anticancer activity should not be interpreted as established anticancer efficacy in humans (Vivarelli *et al*., 2023; Tang *et al*., 2025; Yu *et al*., 2025).

Cardiometabolic and enzyme-modulating effects

Phenolic compounds have also been investigated in relation to cardiovascular and metabolic processes. Epidemiological studies have reported associations between higher consumption of polyphenol-rich foods and favorable health outcomes, although the magnitude and consistency of these associations vary (Rathod *et al*., 2023; Vivarelli *et al*., 2023; Zupo *et al*., 2024). At the molecular level, selected phenolics may affect enzymes involved in oxidative stress and metabolism. For example, some flavonoids can inhibit xanthine oxidase, while others have been investigated for their effects on carbohydrate-digesting enzymes, glucose uptake, insulin-related signaling, and lipid metabolism (Li *et al*., 2024; Wang *et al*., 2026). These observations provide plausible mechanisms but do not by themselves demonstrate therapeutic efficacy. The physiological relevance of enzyme inhibition depends on the concentration of the compound or its metabolites at the relevant biological site.

Cellular signaling and molecular interactions

The biological effects of phenolic compounds may involve multiple cellular targets rather than a single mechanism. Phenolics can interact with enzymes, receptors, transcription factors, ion channels, and signaling proteins. They may also influence pathways involved in oxidative stress, inflammation, apoptosis, and cellular metabolism (Li *et al*., 2024; Pisoschi *et al*., 2024; Wang *et al*., 2026). The multiplicity of molecular targets may partly explain why phenolic-rich foods and extracts can produce complex biological effects. At the same time, it makes it difficult to attribute a specific physiological outcome to a single compound.

Bioavailability, metabolism, and the gut microbiota

A major limitation in the interpretation of phenolic research is the relatively low and variable bioavailability of many compounds. After ingestion, phenolics may be released from the food matrix during digestion, absorbed in the gastrointestinal tract, metabolized in intestinal cells and the liver, and transformed by the gut microbiota (Lippolis *et al*., 2023; Williamson, 2025).

Phase I and phase II metabolic reactions can produce glucuronidated, sulfated, methylated, or otherwise modified metabolites. These metabolites may differ from the parent compounds in terms of absorption, circulation time, biological activity, and tissue distribution (Quesada-Vázquez *et al*., 2024; Williamson, 2025).

The gut microbiota plays an important role in the metabolism of many phenolic compounds. Microbial enzymes can cleave glycosidic bonds and transform complex phenolics into smaller metabolites that may be absorbed and exert biological effects. Conversely, phenolic compounds may also influence microbial composition and microbial metabolic functions (Cheng *et al*., 2023; Alqudah and Claesen, 2024; Sejbuk *et al*., 2024).

Recent research has emphasized the considerable inter-individual variability in phenolic metabolism. Differences in dietary habits, age, health status, genetic factors, gut microbiota composition, and metabolic phenotype may contribute to differences in the concentrations of circulating phenolic metabolites and their biological responses (Favari *et al*., 2024; Quesada-Vázquez *et al*., 2024).

The interaction between phenolics and the gut microbiota is therefore potentially bidirectional. Polyphenols can influence microbial communities, while microorganisms can transform dietary phenolics into metabolites with distinct biological properties. This interaction may contribute to some of the health effects associated with polyphenol-rich diets (Sejbuk *et al*., 2024; Liu *et al*., 2025; Petersen and Mansell, 2025).

Strategies to improve phenolic bioavailability include formulation approaches, encapsulation, delivery systems, and other technological interventions. Such approaches may increase solubility, stability, absorption, or controlled delivery, but their practical application requires evaluation of safety, stability, scalability, and clinical benefit (Aatif, 2023; Taldaev *et al*., 2025).

Health-related evidence and research limitations

The potential health benefits of phenolic-rich foods have been investigated in observational, experimental, and clinical studies. Epidemiological research generally provides evidence of associations rather than direct proof of causality. For example, systematic reviews have reported associations between dietary polyphenol intake and mortality outcomes, but such findings can be influenced by overall dietary patterns, lifestyle, socioeconomic factors, and other confounding variables (Zupo *et al*., 2024).

Experimental studies provide important mechanistic information, but they also have limitations. Cell culture experiments may employ concentrations that are substantially higher than physiological levels, whereas animal studies may differ from humans in metabolism and pharmacokinetics. Consequently, a biological effect demonstrated experimentally should be considered a hypothesis-generating observation until supported by appropriate human evidence.

Another challenge is the use of complex plant extracts. The biological effects of an extract may reflect the combined actions of multiple constituents, but apparent synergy cannot be assumed without appropriate experimental evidence. Interactions among compounds may be additive, synergistic, or even antagonistic depending on their concentrations and the biological system.

Standardization is also important. Differences in plant species, cultivar, cultivation conditions, extraction procedures, processing, storage, and analytical methods can result in substantial differences in phenolic composition. This variability can make it difficult to compare studies and reproduce biological findings.

Current evidence therefore supports continued investigation of phenolic compounds but does not justify generalized claims that all phenolics are beneficial or that phenolic-rich foods can substitute for established medical interventions.

Future research perspectives

Future research should increasingly focus on the relationship between chemical structure and biological activity. Rather than evaluating phenolic compounds solely according to broad categories, studies should consider individual molecular structures, metabolites, concentrations, and relevant biological targets.

Improved characterization of bioavailability is also essential. Researchers should distinguish between the concentration of a compound in a food and the concentration of the parent compound or its metabolites that actually reaches biological tissues. This distinction is particularly important when interpreting antioxidant, anti-inflammatory, or anticancer mechanisms (Favari *et al*., 2024; Williamson, 2025).

The gut microbiota represents another important research area. Identification of microbial metabolites and determination of their biological functions may provide a better understanding of why individuals respond differently to similar dietary exposures (Alqudah and Claesen, 2024; Liu *et al*., 2025).

Future clinical studies should use well-characterized interventions, appropriate controls, standardized phenolic exposure, and validated biomarkers. Long-term safety and potential interactions with medications should also receive greater attention.

Finally, technological approaches designed to improve bioavailability should be evaluated not only for their ability to increase absorption but also for whether increased exposure produces a meaningful and safe biological benefit (Aatif, 2023; Taldaev *et al*., 2025).

Conclusion

Plant phenolic compounds constitute a chemically diverse group of bioactive molecules with important ecological functions in plants and considerable scientific interest because of their potential biological activities. Current evidence indicates that selected phenolic compounds can exert antioxidant, anti-inflammatory, antimicrobial, enzyme-modulating, and signaling-related effects through multiple molecular mechanisms.

However, the magnitude and biological relevance of these effects vary substantially among individual compounds and depend on molecular structure, dose, chemical form, bioavailability, metabolism, and experimental context. Findings obtained from chemical assays, cell culture systems, and animal models should therefore not be directly interpreted as evidence of established therapeutic efficacy in humans.

A major limitation in the field is the variable bioavailability of many phenolic compounds. Digestion, absorption, phase I and phase II metabolism, gut microbial transformation, and inter-individual differences can substantially modify the forms and concentrations of phenolic metabolites available to tissues (Cheng *et al*., 2023; Pop *et al*., 2023; Alqudah and Claesen, 2024; Sejbuk *et al*., 2024; Liu *et al*., 2025; Mahdi *et al*., 2025).

Epidemiological evidence suggests associations between consumption of phenolic-rich foods and several favorable health outcomes, while experimental studies provide plausible mechanisms involving oxidative stress, inflammation, cellular signaling, and metabolic pathways. Nevertheless, these lines of evidence should be interpreted according to their respective limitations.

Further research should address dose–response relationships, structure–activity relationships, long-term safety, bioavailability, microbial metabolism, and individual variability. Well-designed human intervention studies are particularly important for determining whether promising experimental mechanisms translate into clinically meaningful effects.

Overall, phenolic compounds represent a promising group of plant-derived bioactive molecules with potential applications in functional foods, nutraceuticals, and pharmaceutical research. Their future development should, however, be guided by the quality of available evidence, realistic assessment of bioavailability and metabolism, and appropriate evaluation of efficacy and safety (Alqudah and Claesen, 2024; Liu *et al*., 2025; Petersen and Mansell, 2025).

References

Aatif, M., 2023. Current understanding of polyphenols to enhance bioavailability for better therapies. *Biomedicines*, 11(**7**), 2078. https://doi.org/10.3390/biomedicines11072078

Alqudah, S. and Claesen, J., 2024. Mechanisms of gut bacterial metabolism of dietary polyphenols into bioactive compounds. *Gut Microbes*, 16(**1**), 2426614. https://doi.org/10.1080/19490976.2024.2426614

Cheng, H., Zhang, D., Wu, J., Liu, J., Zhou, Y., Tan, Y., Feng, W. and Peng, C., 2023. Interactions between gut microbiota and polyphenols: A mechanistic and metabolomic review. *Phytomedicine*, 119, 154979. https://doi.org/10.1016/j.phymed.2023.154979

El-Saadony, M.T., Yang, T., Saad, A.M., Alkafaas, S.S., Elkafas, S.S., Eldeeb, G.S., Mohammed, D.M., Salem, H.M., Korma, S.A., Loutfy, S.A., Alshahran, M.Y., Ahmed, A.E., Mosa, W.F.A., Abd El-Mageed, T.A., Ahmed, A.F., Fahmy, M.A., El-Tarabily, M.K., Mahmoud, R.M., AbuQamar, S.F., El-Tarabily, K.A. and Lorenzo, J.M., 2024. Polyphenols: Chemistry, bioavailability, bioactivity, nutritional aspects and human health benefits: A review. *International Journal of Biological Macromolecules*, 277(**Pt 3**), 134223. https://doi.org/10.1016/j.ijbiomac.2024.134223

Favari, C., Rinaldi de Alvarenga, J.F., Sánchez-Martínez, L., Tosi, N., Mignogna, C., Cremonini, E., Manach, C., Bresciani, L., Del Rio, D. and Mena, P., 2024. Factors driving the inter-individual variability in the metabolism and bioavailability of (poly)phenolic metabolites: A systematic review of human studies. *Redox Biology*, 71, 103095. https://doi.org/10.1016/j.redox.2024.103095

Li, K., Wang, Y., Liu, W., Zhang, C., Xi, Y., Zhou, Y., Li, H. and Liu, X., 2024. Structure-activity relationships and changes in the inhibition of xanthine oxidase by polyphenols: A review. *Foods*, 13(**15**), 2365. https://doi.org/10.3390/foods13152365

Lippolis, T., Cofano, M., Caponio, G.R., De Nunzio, V. and Notarnicola, M., 2023. Bioaccessibility and bioavailability of diet polyphenols and their modulation of gut microbiota. *International Journal of Molecular Sciences*, 24(**4**), 3813. https://doi.org/10.3390/ijms24043813

Liu, X., Alharbi, A., Gibson, R. and Rodriguez-Mateos, A., 2025. (Poly)phenol-gut microbiota interactions and their impact on human health. *Current Opinion in Clinical Nutrition and Metabolic Care*, 28(**4**), 316–322. https://doi.org/10.1097/MCO.0000000000001132

Mahdi, L., Graziani, A., Baffy, G., Mitten, E.K., Portincasa, P. and Khalil, M., 2025. Unlocking polyphenol efficacy: The role of gut microbiota in modulating bioavailability and health effects. *Nutrients*, 17(**17**), 2793. https://doi.org/10.3390/nu17172793

Petersen, K. and Mansell, T.J., 2025. Unveiling the prebiotic potential of polyphenols in gut health and metabolism. *Current Opinion in Biotechnology*, 95, 103338. https://doi.org/10.1016/j.copbio.2025.103338

Pisoschi, A.M., Iordache, F., Stanca, L., Cimpeanu, C., Furnaris, F., Geicu, O.I., Bilteanu, L. and Serban, A.I., 2024. Comprehensive and critical view on the anti-inflammatory and immunomodulatory role of natural phenolic antioxidants. *European Journal of Medicinal Chemistry*, 265, 116075. https://doi.org/10.1016/j.ejmech.2023.116075

Pop, O.L., Suharoschi, R., Socaci, S.A., Berger Ceresino, E., Weber, A., Gruber-Traub, C., Vodnar, D.C., Fărcaş, A.C. and Johansson, E., 2023. Polyphenols—Ensured accessibility from food to the human metabolism by chemical and biotechnological treatments.

Antioxidants, 12(**4**), 865. https://doi.org/10.3390/antiox12040865

Quesada-Vázquez, S., Eseberri, I., Les, F., Pérez-Matute, P., Herranz-López, M., Atgié, C., Lopez-Yus, M., Aranaz, P., Oteo, J.A., Escoté, X., Lorente-Cebrian, S., Roche, E., Courtois, A., López, V., Portillo, M.P., Milagro, F.I. and Carpéné, C., 2024. Polyphenols and metabolism: From present knowledge to future challenges. *Journal of Physiology and Biochemistry*, 80(**3**), 603–625. https://doi.org/10.1007/s13105-024-01046-7

Rathod, N.B., Elabed, N., Punia, S., Ozogul, F., Kim, S.K. and Rocha, J.M., 2023. Recent developments in polyphenol applications on human health: A review with current knowledge. *Plants*, 12(**6**), 1217. https://doi.org/10.3390/plants12061217

Rudrapal, M., Rakshit, G., Singh, R.P., Garse, S., Khan, J. and Chakraborty, S., 2024. Dietary polyphenols: Review on chemistry/sources, bioavailability/metabolism, antioxidant effects, and their role in disease management. *Antioxidants*, 13(**4**), 429. https://doi.org/10.3390/antiox13040429

Sejbuk, M., Mirończuk-Chodakowska, I., Karav, S. and Witkowska, A.M., 2024. Dietary polyphenols, food processing and gut microbiome: Recent findings on bioavailability, bioactivity, and gut microbiome interplay. *Antioxidants*, 13(**10**), 1220. https://doi.org/10.3390/antiox13101220

Sun, S., Liu, Z., Lin, M., Gao, N. and Wang, X., 2024. Polyphenols in health and food processing: Antibacterial, anti-inflammatory, and antioxidant insights. *Frontiers in Nutrition*, 11, 1456730. https://doi.org/10.3389/fnut.2024.1456730

Taldaev, A., Svotin, A.A., Obukhov, S.I., Terekhov, R.P. and Selivanova, I.A., 2025. Modification of biopharmaceutical parameters of flavonoids: A review. *Frontiers in Chemistry*, 13, 1602967. https://doi.org/10.3389/fchem.2025.1602967

Tang, S., Wang, B., Liu, X., Xi, W., Yue, Y., Tan, X., Bai, J. and Huang, L., 2025. Structural insights and biological activities of flavonoids: Implications for novel applications. *Food Frontiers*, 6, 218–247. https://doi.org/10.1002/fft2.494

Vivarelli, S., Costa, C., Teodoro, M., Giambò, F., Tsatsakis, A.M. and Fenga, C., 2023. Polyphenols: A route from bioavailability to bioactivity addressing potential health benefits to tackle human chronic diseases. *Archives of Toxicology*, 97(**1**), 3–38. https://doi.org/10.1007/s00204-022-03391-2

Wang, X., Li, Y., Zhao, X. and Fu, D., 2026. Flavonoids in medicine and food homology substances:

Structure–activity relationship, application challenges, and cutting-edge technological breakthroughs. *Foods*, 15(**4**), 658. https://doi.org/10.3390/foods15040658

Williamson, G., 2025. Bioavailability of food polyphenols: Current state of knowledge. *Annual Review of Food Science and Technology*, 16, 315–332. https://doi.org/10.1146/annurev-food-060721-023817

Yu, B., Zhang, J., Zhu, M., Li, Z., Ren, L., Zhang, F., Liu, C. and Zhang, L., 2025. Flavonoids: A natural remedy in the prevention and management of diverse diseases. *Frontiers in Medicine*, 12, 1713869. https://doi.org/10.3389/fmed.2025.1713869

Zupo, R., Castellana, F., Lisco, G., Corbo, F., Crupi, P., Sardone, R., Panza, F., Lozupone, M., Rondanelli, M. and Clodoveo, M.L., 2024. Dietary intake of polyphenols and all-cause mortality: A systematic review with meta-analysis. *Metabolites*, 14(**8**), 404. https://doi.org/10.3390/metabo14080404