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Polyphenols in Agriculture and Human Health: A Comprehensive Review of Their Biological Functions and Benefits

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ABSTRACT

Polyphenols are a diverse group of naturally occurring secondary metabolites widely distributed in plants, where they play critical roles in growth, development, and defense against biotic and abiotic stresses. In recent decades, polyphenols have attracted considerable scientific interest due to their multifunctional properties and their significance in both agriculture and human health. In agriculture, polyphenols contribute to plant resilience by enhancing tolerance to environmental stresses such as drought, salinity, temperature extremes, heavy metal toxicity, and pathogen attack through antioxidant activity, signaling regulation, and antimicrobial effects. These properties improve crop productivity, quality, and sustainability while reducing reliance on synthetic agrochemicals. In human health, dietary polyphenols exhibit potent antioxidant, anti-inflammatory, cardio protective, antidiabetic, neuroprotective, and anticancer activities. Their beneficial effects are mediated through modulation of cellular signaling pathways, regulation of oxidative stress and inflammation, improvement of endothelial and metabolic functions, and interactions with the gut microbiota. Despite growing evidence supporting their health-promoting properties, challenges related to bioavailability, metabolism, and variability among polyphenol sources remain important areas for future research. Overall, polyphenols represent a crucial link between sustainable agriculture and human well-being, offering promising opportunities for improving crop performance, food quality, and disease prevention. This review summarizes current knowledge and discusses future perspectives regarding the utilization of polyphenols in agricultural and biomedical applications.

Keywords: Antioxidants, biochemical composition, disease, functional foods, horticultural crops.

Introduction

Phenols are found as secondary metabolites in many fruits, vegetables, and plant products and play an important role in the human diet (13). Main classes of polyphenols related to simple phenols, phenolic acids, acetophenones, phenylacetic acids, coumarins, anthraquinones, xanthones, stilbenes, lignans, and flavonoids. The second group are the most complicated and the most widely spread out in plants. Flavonoids account for approximately two-thirds of dietary polyphenols and the remaining one-third are phenolic acids, being the second most important group of phenolic present in foods (27). Flavonoids are an indispensable part of the diet of animals and humans, plants being the only source, as animals cannot synthesize them (14). The most common class of flavonoids in foods are flavanols, which are usually present in the form of different glycosides in various fruits (43). Phenolic compounds had large diversity of composition obtained from the aromatic amino acids phenylalanine and tyrosine. Phenolic composition can contribute to the astringency and bitter taste of some products. They are generally present in low concentrations, but in certain cases, such as in blueberry, they can reach levels of more than 0.1% (16). Phenolic extracts containing strong anthocyanin can also be prepared using an acidified organic solvent, such as ethanol or methanol. Due to their ease of use, shortened extraction times, and reduced use of organic solvents, a number of simple and contemporary extraction techniques, including ultrasound-assisted extraction, ultrasound-microwave-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, and subcritical water extraction, have recently attracted much attention (36).

The results of researches showed that Pre-treatments such as enzymatic hydrolysis, pulsed electric fields and high-pressure processing can be applied to fruit-based products to improve polyphenol extraction efficiency. There is high potential for the use of environmentally friendly processes for enrichment of polyphenols from fruit-based products using membrane filtration. Polyphenol enrichment technologies need to be cost-effective and rapid and facilitate retention of the biological activities of the polyphenols (13). Bio fortification of food can be done to improve human health and prevent diseases by increasing the absorption of minerals, vitamins or antioxidants. In this regard, the study of plant secondary metabolites such as polyphenols plays a very important role in the development of a new generation of plant products that can compensate for the low nutritional quality of diets. Researchers investigated the antioxidant and anti-inflammatory properties of different types of polyphenols in the prevention of intestinal diseases (32). Melatonin and polyphenols are important antioxidants, and melatonin is also a potential plant growth regulator. The role of melatonin in regulating polyphenol metabolism is unclear.

Although previous reviews have examined polyphenols in agriculture, food, or human health separately, this review provides an integrated agriculture-to-human-health perspective, highlighting how agricultural practices and polyphenol-rich resources can support sustainable crop production, health-promoting foods, and human well-being.

Role of polyphenols in agriculture

Antioxidant activity of phenolic acids is mainly related to the number of hydroxyl groups, and HCAs are often more effective antioxidants than HBAs (31). Agricultural residues like sugarcane bagasse (SCB), corn husk (CH), peanut husk (PNH), coffee cherry husk (CCH), rice bran (RB) and wheat bran (WB) are low-value byproducts of agriculture. The results of Vijayalaxmi et al. (41) showed that the potential of agricultural residues to be an abundant source of natural antioxidants suitable for further development into dietary supplements and various food additives. The role of some polyphenol wrote in table 1.

Table 1: Major classes of polyphenols, their principal molecular mechanisms, and potential health effects.

Type of polyphenol	Major molecular mechanisms	Potential health/clinical effects
Phenolic acids	Scavenging of reactive oxygen species (ROS), metal chelation, modulation of oxidative-stress-related pathways, and regulation of inflammatory signaling	Antioxidant, anti-inflammatory, cardioprotective, and potential metabolic protective effects
Flavonoids	Regulation of cellular signaling pathways, modulation of oxidative stress and inflammation, inhibition of selected enzymes, and regulation of apoptosis and cell proliferation	Antioxidant, anti-inflammatory, cardioprotective, antidiabetic, neuroprotective, and anticancer effects
Anthocyanins	ROS scavenging, modulation of oxidative and inflammatory signaling, protection of cellular components, and regulation of endothelial and metabolic functions	Cardiovascular protection, antioxidant activity, anti-inflammatory effects, and potential metabolic and neuroprotective benefits
Stilbenes (e.g., resveratrol)	Modulation of cellular signaling, oxidative-stress pathways, inflammatory responses, apoptosis, and metabolic signaling	Cardioprotective, neuroprotective, anti-inflammatory, metabolic, and potential anticancer effects
Lignans	Antioxidant activity, modulation of cellular signaling and inflammatory pathways, and interactions with metabolic pathways	Antioxidant, cardioprotective, anti-inflammatory, and potential chronic-disease-preventive effects
Tannins	Free-radical scavenging, metal chelation, protein interactions, antimicrobial activity, and modulation of oxidative processes	Antioxidant, antimicrobial, anti-inflammatory, and potential gastrointestinal protective effects
Coumarins	Modulation of oxidative stress and inflammatory signaling and interactions with enzymes and cellular pathways	Antioxidant, anti-inflammatory, antimicrobial, and potential protective effects against chronic diseases
Xanthones	Regulation of oxidative stress, inflammatory signaling, apoptosis, and cellular defense mechanisms	Antioxidant, anti-inflammatory, neuroprotective, and potential anticancer effects

Advantages of polyphenols in agriculture

1. Polyphenols as plant defense compounds

Polyphenols play a major role in plant protection against pathogens, herbivores, and environmental stresses through antioxidant activity and signaling functions (44). Certain polyphenols, particularly lignin precursors, contribute to cell wall reinforcement. Stronger cell walls improve mechanical support and create physical barriers against pathogen invasion and pest attack. This structural protection enhances overall plant health and resistance (20).

2- Improvement of stress tolerance

Polyphenols accumulate in response to drought, salinity, UV radiation, temperature extremes, and heavy metal stress, helping plants neutralize reactive oxygen species (ROS) and maintain cellular integrity (35).

3- Important role in growing process in plants

Phenolic are caused under favorable and unfavorable conditions in plants and had key roles in developmental processes like cell division, hormonal regulation, photosynthetic activity, nutrient mineralization, and reproduction. Plants showed increased synthesis of polyphenols such as phenolic acids and flavonoids under abiotic stress conditions, which help the plant to cope with environmental constraints (35).

4- Contribution to crop quality

Phenolic compounds influence fruit and vegetable color, taste, aroma, and nutritional quality. Anthocyanins, flavonoids, and tannins are major contributors to sensory and quality traits (44).

5- Antioxidant and postharvest benefits

Polyphenols act as natural antioxidants, reducing oxidative deterioration and helping maintain product quality during storage and processing (44).

6- Sustainable agriculture and reduced agrochemical use

Recent reviews suggest that polyphenol-based bio-stimulants and formulations can enhance crop resilience and may provide sustainable alternatives or complements to synthetic agrochemicals (18).

7- Value addition from agricultural by-products

Polyphenols recovered from grape pomace (15), and other agricultural wastes can be utilized in food, nutraceutical, pharmaceutical, and cosmetic industries, increasing the value of agricultural products (9).

8- Use of polyphenols in the cosmetic industry

Researchers reported that polyphenols extracted from citrus peel, lemon peel, grapefruit peel, olive leaf, pomegranate peel, peach pomace, and grape pomace can be used for high-value applications in cosmetics and other industries (23).

9- Increasing shelf life of agricultural products

Applying polyphenols, whether in isolated form or as extracts, to fruits can prolong their shelf life. The use of polyphenols led to advantageous outcomes, including color retention, delayed softening, and a significant reduction in the loss of total phenolics, titratable acidity, betacyanin, and soluble solids in fruits (24). Polyphenols have strong antioxidant and antimicrobial properties that may act to inhibit the growth of spoilage microorganisms, which are the main cause of fruit spoilage. The application of polyphenols leads to beneficial effects such as betacyanin, total phenolics, titratable acidity, color retention, and delay in softening and loss of soluble solid content in fruits. They increase the shelf life of fruits and preserve their freshness by reducing enzymatic browning (34).

Role of polyphenols in human health

primary metabolites (proteins, carbohydrates, and vitamins) are crucial components of a healthy diet, whereas secondary metabolites are not essential for survival. Within the plant, these metabolites help a "survival" role, that is, they take action as a protection mechanism in response to environmental stresses or when competing with other plants, for example, some plants exhibit bright colors or smell to become greater pollination (9, 33). Plant secondary metabolites, including polyphenols, flavonoids, carotenoids, alkaloids, and terpenoids play important ecological and physiological roles in plants and possess diverse biological activities that may be relevant to human health [5,6]. In plants, these compounds contribute to adaptation to biotic and abiotic stresses by participating in defense mechanisms, signaling, protection against herbivores and pathogens, and interactions with the surrounding environment [6,44]. In addition, polyphenols are important dietary bioactive compounds and have been associated with antioxidant, anti-inflammatory, immunomodulatory, cardioprotective, and neuroprotective activities in humans [6,11,29]. Therefore, although secondary metabolites are not generally classified as essential nutrients required for basic human survival, their biological activities may contribute to the health-promoting effects of plant-based foods and may play a role in disease prevention [6,11]. Moreover, plant pigments and volatile secondary metabolites can contribute to visual and olfactory cues that attract pollinators, thereby facilitating plant reproduction [6,44].

Ployphenols has one or more phenolic ring and one hydroxyl group, that has been linked to the potential ability of these compounds to mitigate against degenerative diseases in humans (29). After extraction, polyphenols can be used to the harvested fruits by spraying or coating them on their surface. Another way of applying polyphenols can be by immersing the fruits in a polyphenol solution (24, 45, 25). Verhulst et al. (40) reported that *Lolium perenne* L, *Cichorium intybus* L, *Plantago lanceolata* L. and *Trifolium pratense* L, which have been recognized for their polyphenolic composition, had antioxidant, anti-cancer, and anti-diabetic properties. Polyphenols supply health benefits by a number of mechanisms, containing the removal of free radicals, the preseravation and regeneration of other dietary antioxidants (e.g. vitamin E) and the chelation of pro-oxidant metals (28).

Advantages of polyphenols in human health

Studies showed that regular consumption of polyphenol-rich foods is associated with improved health outcomes and a lower risk of chronic diseases. Polyphenols influence normal and abnormal cell function, and thus influence cellular processes involved in the initiation and progression of cancer, cardiovascular disease, and neurodegeneration. For example, their ability to activate ERK in neurons leads to increased neuronal survival and cognitive improvement, both of which influence the progression of Alzheimer's disease, while ERK activation by polyphenols in vascular endothelial cells influences nitric oxide production, blood pressure, and ultimately cardiovascular disease risk. (39). Some studies showed that these phyto-chemicals heal wound (26). In addition to antioxidant activity, flavonoids have other properties such as anti-mutagenic effects, reducing the risk of cardiovascular diseases, inhibiting tumor proliferation, protecting against atherosclerosis, protecting against radiation, strengthening hair, storing hormones in naturally menopausal women, and antimicrobial properties (43). Some of the importance of polyphenols in various fields of medical science are as follows:

1. **Cardiovascular Protection:** Polyphenols contribute to cardiovascular health by: Improving endothelial function, increasing nitric oxide production, lowering blood pressure, Reducing LDL oxidation, decreasing platelet aggregation and reducing inflammation. These mechanisms may help lower the risk of atherosclerosis, coronary heart disease, and stroke (4).
2. **Antioxidant Activity:** Polyphenols act as antioxidants by: Scavenging reactive oxygen species (ROS), protecting cellular components from oxidative damage, reducing oxidative stress associated with aging and chronic diseases. Oxidative stress is implicated in cardiovascular disease, diabetes, cancer, and neurodegenerative disorders (5).
3. **Anti-Inflammatory Effects:** Polyphenols regulate inflammatory pathways by inhibiting pro-inflammatory mediators and cytokines. Benefits are reduced chronic inflammation, lower risk of inflammatory diseases, improved immune regulation. Chronic inflammation is a major contributor to obesity, diabetes, cardiovascular disease, and cancer (30).
4. **Prevention and Management of Type 2 Diabetes:** Research indicates that polyphenols may: improve insulin sensitivity, protect pancreatic β-cells, reduce postprandial blood glucose spikes, enhance glucose metabolism. These effects may reduce the risk of insulin resistance and type 2 diabetes (2, 19).
5. **Neuroprotective Effects:** Polyphenols may help maintain cognitive function by: Reducing neuro inflammation, protecting neurons from oxidative damage, enhancing cerebral blood flow, modulating signaling pathways involved in memory and learning. Evidence suggests potential protective effects against Alzheimer's disease and other neurodegenerative disorders

(39, 10). polyphenols play a pivotal role due to their ability to exert neuroprotective, immunomodulatory and microbiota-remodeling activities (1).

6. **Anticancer Potential:** Polyphenols may contribute to cancer prevention through: Inhibition of tumor cell proliferation, promotion of apoptosis (programmed cell death), reduction of DNA damage, modulation of cell-signaling pathways involved in carcinogenesis. Although more human clinical studies are needed, substantial experimental evidence supports these mechanisms (21, 37, 9). Flavonoids such as quercetin and genistein inhibit the enzyme tyrosine kinase, the increased expression of which may cause various proliferative diseases such as cancer and psoriasis (38).
7. **Improved Gut Health:** Polyphenols interact closely with the gut microbiota by: stimulate beneficial bacteria, suppress harmful microorganisms, increase microbial diversity, support intestinal barrier integrity. These effects contribute to digestive health and immune regulation (42, 17). They are powerful antioxidants that protect our tissues from toxins. Polyphenols may help prevent blood clots and lower blood sugar levels. Some polyphenols protect cells from potentially harmful free radicals. Some polyphenols increase the growth of beneficial gut bacteria and aid in digestion. Some polyphenols may enhance healthy brain function, thereby aiding concentration, learning, and memory (33).
8. **Healthy Aging and Longevity:** Recent studies suggest that diets rich in polyphenols may be associated with: Slower biological aging, better immune function, reduced cellular aging markers, increased health span. These benefits are likely mediated through antioxidant, anti-inflammatory, and microbiome-related mechanisms (22).

Conclusion

Polyphenols are naturally occurring plant compounds that provide significant benefits in both agriculture and human health. In agriculture, they enhance plant growth and productivity by protecting crops against pathogens, insects, and environmental stresses such as drought, salinity, extreme temperatures, and ultraviolet radiation. Their antioxidant properties help reduces oxidative damage, improve crop quality, and contribute to sustainable farming by reducing dependence on synthetic pesticides. In human health, polyphenols act as powerful antioxidants and anti-inflammatory agents, helping to protect cells from oxidative stress and chronic inflammation. Regular consumption of polyphenol-rich foods has been associated with improved cardiovascular health, better blood glucose regulation, enhanced gut microbiota balance, neuroprotection, and a reduced risk of chronic diseases such as diabetes, cardiovascular disorders, and certain cancers. Therefore, polyphenols play a crucial role in linking sustainable agriculture with improved nutrition, disease prevention, and overall well-being.

Future Perspectives and Challenges

Despite the promising applications of polyphenols in agriculture, food science, and human health, challenges remain regarding their variability, bioavailability, metabolism, and standardization. Future research should focus on optimizing agricultural practices to enhance beneficial polyphenol accumulation, valorizing agricultural by-products, and developing safe and effective extraction, encapsulation, and delivery technologies. Stronger clinical evidence is also needed to establish their effective doses, safety, and health outcomes. A multidisciplinary approach integrating agriculture, food science, chemistry, nutrition, microbiology, and clinical research will be essential to establish a stronger link between agricultural production, food quality, and human health and to support the sustainable application of polyphenols.

Author′s contribution

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Data Availability

The article is a review, so it lacks research data.

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Corresponding author fully consent to the publication of the article in the journal.

Conflict of interests

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Artificial intelligence (AI)-assisted technology

In this article, artificial intelligence has only been used to provide general information about the benefits of polyphenols, approximately 20%.

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