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Anthocyanins and Polyphenols in Fruits and Beverages: Comparative Stability, Bioavailability, and Antioxidant Mechanisms

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Abstract

Anthocyanins and polyphenols are among the most extensively studied phytochemicals in fruits and beverages, recognized for their sensory contributions and remarkable biological activities. They play crucial roles in human health by reducing oxidative stress, modulating inflammatory pathways, and lowering the risk of chronic diseases. However, their functional efficacy is influenced by several factors including chemical stability, food processing methods, gastrointestinal transformation, and systemic bioavailability. This review consolidates current knowledge on the structural diversity of anthocyanins and polyphenols, their distribution in fruits and beverages, stability during processing and storage, absorption and metabolism, and antioxidant mechanisms. A comparative analysis highlights the challenges and opportunities in enhancing their functional properties through novel delivery systems, biotechnological interventions, and dietary strategies. The review also outlines future directions for translating preclinical findings into clinical outcomes, underscoring their potential in nutraceutical and functional food applications.

Keywords: *Anthocyanins, polyphenols, fruits, beverages, stability, bioavailability, antioxidant mechanisms, nutraceuticals, functional foods.*

1. Introduction

The growing interest in dietary bioactive compounds has placed fruits and beverages at the center of nutritional and biomedical research. Among the diverse phytochemicals present in plant-derived foods, anthocyanins and polyphenols have received significant attention owing to their dual role in enhancing food quality and delivering potential health benefits. Their contribution extends beyond sensory appeal, such as color, aroma, and taste, to profound biological activities that may reduce the risk of numerous chronic diseases [1]. Over the past two decades, the consumption of polyphenol-rich foods and beverages has been consistently associated with lower incidences of cardiovascular diseases, obesity, type 2 diabetes, certain cancers, and neurodegenerative conditions. As a result, anthocyanins and polyphenols have emerged as promising candidates for functional food formulations and nutraceutical applications [2]. Anthocyanins, a subclass of flavonoids, are water-soluble pigments responsible for the red, purple, and blue hues observed in many fruits, flowers, and vegetables. They are most abundant in berries such as blueberries, blackberries, and strawberries, as well as in red grapes, cherries, and pomegranates. Structurally, anthocyanins are glycosylated derivatives of anthocyanidins, and their stability and color expression are strongly influenced by pH, light, temperature, and co-pigmentation with other compounds. While their vivid pigmentation contributes to the visual appeal and marketability of fruits and beverages, their biological relevance lies in their antioxidant, anti-inflammatory, and cardioprotective properties. However, anthocyanins are known to be chemically unstable and exhibit poor bioavailability, with less than 1% of ingested anthocyanins reaching systemic circulation in intact form. This paradox between high in vitro activity and limited in vivo bioavailability continues to be a central theme in anthocyanin research, polyphenols constitute a larger and more diverse group of secondary metabolites found widely in plant-based foods and beverages [3]. They include flavonoids (such as flavonols, flavones, flavanones, catechins, and anthocyanins themselves) as well as non-flavonoid compounds like phenolic acids, stilbenes, and lignans. Green tea is rich in catechins, coffee provides chlorogenic acids, cocoa contains abundant procyanidins, and red wine delivers resveratrol and flavonols. The structural diversity of polyphenols underlies their broad spectrum of biological activities, ranging from antioxidant and anti-carcinogenic effects to modulation of gut microbiota. Compared to anthocyanins, polyphenols generally display greater chemical stability, though they too undergo extensive metabolic transformations that affect their functional efficacy.

The wealth of epidemiological and experimental evidence, a significant challenge in leveraging the benefits of anthocyanins and polyphenols lies in understanding their stability and bioavailability. Food processing and storage conditions, including pasteurization, fermentation, oxygen exposure, and temperature fluctuations, can degrade these compounds or transform them into less active derivatives [4]. Within the human body, factors such as digestive enzymes, gut microbiota composition, and genetic variability further influence their absorption, metabolism, and biological actions.

For example, anthocyanins may degrade in the stomach but produce bioactive metabolites via microbial fermentation in the colon. Similarly, polyphenols often undergo conjugation reactions (glucuronidation, sulfation, methylation) that modulate their systemic circulation and target tissue activity.

Another aspect is the antioxidant and biological mechanisms of anthocyanins and polyphenols. While their ability to scavenge free radicals and reactive oxygen species in vitro is well documented, their in vivo effects are often mediated by more complex pathways. These compounds can activate endogenous defense mechanisms, such as the nuclear factor erythroid 2–related factor 2 (Nrf2) signaling pathway, leading to upregulation of antioxidant enzymes. They also modulate inflammatory signaling cascades, inhibit lipid peroxidation, and regulate glucose and lipid metabolism. The synergistic interplay between anthocyanins, polyphenols, and other dietary components further enhances their biological relevance, anthocyanins and polyphenols serve not only as health-promoting agents but also as quality determinants that shape consumer preference [5]. The color stability of anthocyanins, for example, is a major concern in the wine and juice industries, while the bitterness and astringency associated with polyphenols affect the sensory profile of tea, coffee, and cocoa. Recent advances in food processing and biotechnology have focused on enhancing their stability and bioefficacy through encapsulation, fermentation, co-pigmentation, and controlled storage techniques. At the same time, growing research into personalized nutrition highlights the importance of inter-individual variability in response to these compounds, driven largely by differences in gut microbiota composition and host metabolism.

The multifaceted roles of anthocyanins and polyphenols, this review aims to provide a comprehensive synthesis of current knowledge on their comparative stability, bioavailability, and antioxidant mechanisms in fruits and beverages, their structural features, distribution, and interactions with processing and physiological factors, we highlight both the challenges and opportunities in maximizing their potential as dietary antioxidants [6]. The review further emphasizes the translational gap between preclinical findings and clinical outcomes, proposing strategies for improving functional efficacy and paving the way for future research in nutraceutical development, anthocyanins and polyphenols occupy a unique position at the intersection of food science, nutrition, and health. Their comparative evaluation offers valuable insights into how natural compounds can be preserved, delivered, and optimized to promote wellbeing in human populations, plant-based compounds for preventive and therapeutic applications in an era of rising chronic disease burdens.

Table 1. Major Food and Beverage Sources of Anthocyanins and Polyphenols

Compound Class	Key Sources (Fruits)	Key Sources (Beverages)	Representative Compounds
Anthocyanins	Blueberries, blackberries, cherries, pomegranate, grapes	– (primarily fruit-based juices & wines)	Cyanidin, Delphinidin, Malvidin, Pelargonidin
Polyphenols	Apples, citrus fruits, cocoa beans	Green tea, black tea, coffee, red wine, cocoa, citrus juices	Catechins (EGCG), Chlorogenic acids, Resveratrol, Quercetin

Table 2. Factors Affecting Stability of Anthocyanins and Polyphenols

Factor	Anthocyanins	Polyphenols
pH	Stable in acidic; degrade in neutral/alkaline	Generally stable; may oxidize in alkaline environments
Temperature	Heat-sensitive; degrade in pasteurization	Relatively stable; some loss at high heat
Light & Oxygen	Rapid degradation under light exposure	Oxidation and polymerization possible
Storage	Best under cool, dark conditions	Best under oxygen-limited packaging

Table 3. Bioavailability of Anthocyanins and Polyphenols

Compound	Absorption (%)	Major Metabolites	Role of Gut Microbiota
Anthocyanins	<1%	Glucuronides, sulfates, phenolic acids	Converts into bioactive metabolites
Polyphenols	Variable (5–30%)	Phenolic acids, urolithins, small flavonoid metabolites	Crucial in breakdown and transformation

Table 4. Biological Mechanisms and Health Benefits

Mechanism	Anthocyanins (Examples)	Polyphenols (Examples)
Direct antioxidant activity	Scavenging ROS, lipid protection	Free radical neutralization, metal chelation
Indirect antioxidant activity	Nrf2 activation, NF-κB suppression	Modulation of MAPK, antioxidant enzymes
Cardiometabolic effects	Improved endothelial function	Anti-diabetic, anti-obesity
Neurological benefits	Neuroprotection, anti-inflammatory	Cognitive support, anti-aging
Gut microbiota modulation	Prebiotic-like activity	Strong microbiota interactions

2. Structural Characteristics and Distribution

2.1 Anthocyanins

Anthocyanins belong to the flavonoid family and are widely recognized as natural pigments responsible for the vivid red, purple, and blue colors of many fruits, vegetables, and flowers. Structurally, they are glycosylated derivatives of anthocyanidins and are characterized by a flavylium cation as their central core. The diversity of anthocyanins arises through multiple structural modifications, including hydroxylation, methylation, acylation, and variations in sugar conjugation. These substitutions not only influence their stability and solubility but also affect their color expression and biological activities, more than 700 anthocyanin compounds have been identified in nature, reflecting the extensive diversity of these metabolites. Their distribution is particularly concentrated in deeply pigmented fruits such as blueberries, blackberries, strawberries, red grapes, cherries, and pomegranates [7]. Anthocyanins also occur in vegetables like red cabbage and purple sweet potatoes, and they are a defining component of red wines and certain fruit juices. The abundance and diversity of anthocyanins in fruits make them major contributors to both visual appeal and potential health benefits, anthocyanins function as protective agents in plants, offering defense against ultraviolet radiation, pathogens, and oxidative stress. Their distribution within the plant is often tissue-specific, with high concentrations in the skin or peel where protection is most needed. From a nutritional standpoint, the variety of anthocyanin structures consumed through different fruits and beverages translates into a wide spectrum of potential biological effects in humans.

2.2 Polyphenols

Polyphenols represent one of the most diverse and abundant groups of plant secondary metabolites, with thousands of individual compounds reported. Broadly, they are divided into two categories: flavonoids and non-flavonoids. Flavonoids encompass subclasses such as flavanols (catechins), flavonols (quercetin, kaempferol), flavones, isoflavones, and anthocyanins, whereas non-flavonoids include phenolic acids (caffeic acid, ferulic acid), stilbenes (resveratrol), and lignans [8].This structural diversity significantly influences their biological activity, antioxidant potential, and interactions with biomolecules. For example, the number and position of hydroxyl groups, degree of polymerization, and presence of glycosidic linkages determine solubility, stability, and reactivity toward free radicals.

Polyphenols are widely distributed across plant-based foods and beverages. Green tea is rich in catechins such as epigallocatechin gallate (EGCG), coffee provides chlorogenic acids, cocoa contains high levels of flavan-3-ols and procyanidins, while wine—especially red wine—is a notable source of resveratrol and flavonols. Citrus fruits, apples, onions, and legumes further expand the dietary spectrum of polyphenol intake, polyphenols serve ecological functions, including defense against herbivores, UV radiation, and microbial infections, while also contributing to pigmentation and flavor. In humans, their widespread consumption is linked to multiple health-promoting properties [9]. The structural complexity of polyphenols underlies their capacity to interact with proteins, lipids, and nucleic acids, mediating a variety of biochemical effects relevant to disease prevention.

3. Stability in Fruits and Beverages

3.1 Anthocyanins

The stability of anthocyanins in fruits and beverages is a critical factor influencing both product quality and health benefits. These pigments are highly sensitive to processing conditions, with significant degradation observed during thermal treatments such as pasteurization, boiling, and sterilization. Even mild heating can reduce anthocyanin concentrations, leading to diminished color intensity and antioxidant potential. Prolonged storage under ambient conditions further accelerates degradation, often resulting in browning and loss of visual appeal in juices and beverages.pH is the most influential determinant of anthocyanin stability [10]. Under acidic conditions (pH 1–3), the flavylium cation is the dominant and stable form, producing vivid red hues. As the pH increases toward neutral or alkaline levels, structural transformations occur, resulting in color loss and the formation of colorless or degraded products. This sensitivity to pH explains the variation in color intensity observed in fruit-based products and beverages over time, several stabilization strategies have been explored. Co-pigmentation, wherein anthocyanins interact with other polyphenols, organic acids, or metal ions, enhances color intensity and stability by creating more stable molecular complexes. Encapsulation technologies, including nanoemulsions, liposomes, and biopolymer matrices, provide a physical barrier that protects anthocyanins from heat, light, and oxygen exposure, optimized storage conditions, such as refrigeration, low-light environments, and oxygen-reduced packaging, are widely recommended to preserve anthocyanin integrity in commercial products.

3.2 Polyphenols

Polyphenols exhibit greater resilience compared to anthocyanins during common food and beverage processing methods such as juicing, brewing, and fermentation. Many polyphenols can withstand moderate heating without severe degradation, though prolonged high-temperature exposure can lead to partial losses. For example, catechins in green tea and chlorogenic acids in coffee are relatively stable during brewing, while certain flavonoids in wine remain intact throughout fermentation, polyphenols are still subject to degradation pathways over time. The most common include oxidation (initiated by exposure to oxygen, enzymes, or light) and polymerization, where smaller molecules combine to form larger complexes with altered bioactivity. Such transformations can reduce antioxidant capacity and modify sensory attributes such as bitterness or astringency. Storage duration, oxygen permeability of packaging, and exposure to light and humidity are key factors influencing these changes, preservation strategies are employed across the food industry [11]. The addition of natural antioxidants such as ascorbic acid, rosemary extract, or tocopherols can reduce oxidative losses. Packaging innovations, including oxygen-impermeable films, vacuum sealing, and modified atmosphere systems, limit oxygen exposure during storage. Furthermore, embedding polyphenols within protective matrices such as proteins, polysaccharides, or encapsulation systems helps maintain their stability, solubility, and bioactivity during processing and shelf life.

4. Bioavailability and Metabolism

4.1 Anthocyanins

Anthocyanins, despite their abundance in fruits and beverages, demonstrate remarkably low bioavailability in humans. Less than 1% of ingested anthocyanins appear in systemic circulation as intact molecules, highlighting the challenges of harnessing their full biological potential. Their absorption in the gastrointestinal tract is limited by their hydrophilic nature and instability under varying pH conditions.Once absorbed, anthocyanins undergo extensive metabolism in the small intestine and liver. Phase II conjugation reactions such as glucuronidation, sulfation, and methylation generate more hydrophilic derivatives that circulate in plasma and are eventually excreted in urine. However, intact anthocyanins are rarely detected in significant amounts, suggesting that their bioactivity may rely more on their metabolites than on the parent compounds.The gut microbiota plays a pivotal role in anthocyanin metabolism. Non-absorbed anthocyanins reaching the colon are subject to microbial catabolism, leading to the formation of smaller phenolic acids, including protocatechuic acid and vanillic acid [12]. These microbial metabolites exhibit higher stability and potentially stronger biological activities, particularly in terms of antioxidant, anti-inflammatory, and cardioprotective effects. The contribution of these secondary metabolites underscores the importance of the gut microbiome in modulating anthocyanin bioefficacy.

4.2 Polyphenols

The bioavailability of polyphenols is highly variable and strongly dependent on their structural class and complexity. For example, catechins, the predominant flavanols in green tea, are absorbed efficiently in the small intestine, with measurable concentrations detected in plasma within hours of consumption. In contrast, ellagitannins, abundant in pomegranates and some berries, are too large and complex for direct absorption. Instead, they undergo microbial hydrolysis in the colon to release urolithins, which have been shown to exert anti-inflammatory and anticancer effects.Similar to anthocyanins, polyphenols are subjected to extensive phase II metabolism (glucuronidation, sulfation, methylation) during absorption and hepatic processing. These transformations generate a diverse array of conjugated metabolites, many of which retain or even enhance bioactivity compared to their parent molecules, gut microbiota-mediated transformations provide an additional layer of metabolic diversity. Polyphenols serve as substrates for microbial enzymes, leading to the production of low-molecular-weight compounds such as phenylpropionic, phenylacetic, and benzoic acid derivatives [13]. These metabolites often exhibit distinct biological effects, including modulation of vascular health, glucose metabolism, and immune function.A crucial consideration in polyphenol bioavailability is inter-individual variability. Differences in gut microbiota composition, influenced by genetics, diet, lifestyle, and antibiotic use, result in significant variability in the types and amounts of metabolites produced. For instance, individuals classified as “urolithin producers” may derive greater health benefits from ellagitannin-rich foods compared to “non-producers.” This highlights the personalized nature of polyphenol metabolism and suggests opportunities for tailoring dietary recommendations based on microbial profiles.

5. Antioxidant and Biological Mechanisms

5.1 Direct Antioxidant Action

Anthocyanins and polyphenols exert potent direct antioxidant effects, which are largely attributable to their chemical structures rich in hydroxyl groups. These functional groups enable them to neutralize free radicals and reactive oxygen species (ROS), thereby reducing oxidative stress at the cellular level. By donating hydrogen atoms or electrons, anthocyanins and polyphenols stabilize radical species, preventing chain reactions that damage biomolecules. The protective action is the inhibition of lipid peroxidation in cell membranes. Oxidative degradation of lipids leads to the loss of membrane integrity and generates harmful by-products such as malondialdehyde, which contribute to tissue damage and disease progression [14]. Anthocyanins, particularly those in berries and red grapes, and polyphenols like catechins and resveratrol, have been shown to integrate into lipid bilayers, where they reduce peroxidation and preserve membrane stability.

5.2 Indirect Mechanisms

Beyond direct radical scavenging, anthocyanins and polyphenols activate a range of indirect defense pathways. A central mechanism is the Nrf2 (nuclear factor erythroid 2–related factor 2) pathway, which regulates the expression of endogenous antioxidant enzymes, including glutathione peroxidase, superoxide dismutase, and catalase. By enhancing cellular antioxidant defenses, these compounds provide longer-lasting protection compared to their immediate radical-neutralizing actions, polyphenols influence inflammatory signaling pathways, such as NF-κB (nuclear factor kappa B) and MAPK (mitogen-activated protein kinases) [11]. The suppressing NF-κB activation, they reduce the transcription of pro-inflammatory cytokines, chemokines, and adhesion molecules [15]. This mechanism is particularly relevant for mitigating chronic inflammation associated with cardiovascular diseases, obesity, and diabetes, the protection of endothelial function, which is critical for vascular health. Anthocyanins and polyphenols enhance nitric oxide bioavailability, reduce oxidative stress in vascular tissues, and improve vasodilation. Furthermore, they help regulate glucose metabolism by modulating insulin sensitivity and inhibiting carbohydrate-digesting enzymes such as α-amylase and α-glucosidase.

5.3 Health Implications

The diverse mechanisms of anthocyanins and polyphenols translate into wide-ranging health benefits supported by both experimental and clinical studies.Anthocyanins have been associated with cardioprotective effects, including reduced blood pressure and improved lipid profiles. Their anti-inflammatory properties help lower systemic inflammation, while their ability to modulate adipocyte function supports anti-obesity actions. Emerging evidence also highlights their role in neuroprotection, where they improve cognitive performance and reduce neurodegenerative processes linked to Alzheimer's and Parkinson's disease.Polyphenols, owing to their structural diversity, exhibit an even broader range of bioactivities [9-12]. They demonstrate anti-carcinogenic potential by modulating carcinogen metabolism, inducing apoptosis in tumor cells, and inhibiting angiogenesis. Their anti-diabetic properties include improving insulin sensitivity and glycemic control. Polyphenols are also recognized for their anti-aging effects, attributed to their ability to reduce oxidative damage and regulate cellular signaling pathways linked to longevity [16], they play a key role in gut microbiota modulation, fostering beneficial bacterial populations while suppressing pathogenic strains, thereby contributing to metabolic and immune health.

6. Applications in Fruits and Beverages

Fruits and beverages are the most significant dietary sources of anthocyanins and polyphenols, contributing to their widespread consumption and health-promoting potential. Among fruits, berries (such as blueberries, blackberries, strawberries, and raspberries), grapes, cherries, and pomegranates are particularly rich in anthocyanins. Their vivid coloration is a direct reflection of anthocyanin content, which often serves as a marker of antioxidant potency. Regular intake of these fruits has been associated with reduced risk of cardiovascular and neurodegenerative diseases due to their high antioxidant and anti-inflammatory properties.In the case of polyphenols, a wider range of beverages serve as primary contributors to dietary intake. Green tea provides catechins such as epigallocatechin gallate (EGCG), one of the most extensively studied compounds for its cardiovascular and metabolic benefits. Coffee is a major global source of polyphenols, primarily chlorogenic acids, which have been linked to improved glucose metabolism and liver function. Cocoa and dark chocolate contain flavanols such as epicatechin and procyanidins that support vascular health and cognitive performance [7], citrus fruits provide flavanones, while wine, particularly red wine, is enriched with resveratrol and other phenolic compounds that arise or increase in concentration during fermentation.Processing techniques also influence the polyphenolic content of beverages. For instance, fermentation not only preserves but also enhances bioavailability of certain compounds. In red wine, the fermentation process leads to the release and stabilization of resveratrol and related polyphenols, amplifying their biological activity. Similarly, fermentation of tea leaves during black tea production transforms catechins into theaflavins and thearubigins, which contribute to the beverage's antioxidant potential. These examples highlight how traditional food and beverage preparation methods may inadvertently maximize health benefits.

7. Strategies to Enhance Functional Efficacy

Despite their recognized health benefits, anthocyanins and polyphenols face challenges related to poor stability and low bioavailability. Several strategies have been developed to optimize their functional efficacy in human health.One of the most promising approaches is the use of encapsulation technologies. Liposomes, nanoemulsions, and biopolymer-based carriers protect these compounds from degradation during processing and digestion, while also enhancing their absorption in the gastrointestinal tract. For example, anthocyanins encapsulated in nanocarriers show significantly improved stability against pH fluctuations and light exposure, leading to higher bioactivity *in vivo*. Similarly, polyphenols such as curcumin and resveratrol exhibit enhanced solubility and bioavailability when delivered through nanoemulsions or lipid-based systems.Another strategy involves co-supplementation, where anthocyanins and polyphenols are consumed alongside complementary dietary components [5]. The presence of dietary fats can enhance the solubility and uptake of lipophilic polyphenols, while the inclusion of probiotics and prebiotics supports gut microbiota-mediated transformations into more bioactive metabolites. Such synergistic combinations are increasingly explored in functional foods and nutraceutical formulations to improve overall efficacy, the advent of personalized nutrition opens new opportunities to tailor polyphenol and anthocyanin intake according to individual variability. Genetic factors, metabolic capacity, and the composition of the gut microbiome strongly influence the bioavailability and effects of these compounds [4]. Personalized dietary interventions, supported by advances in nutrigenomics and microbiome profiling, may therefore maximize the therapeutic potential of anthocyanins and polyphenols for disease prevention and health promotion.

9. Conclusion

Anthocyanins and polyphenols represent two of the most important groups of bioactive compounds in fruits and beverages, serving as key contributors to both the sensory qualities of foods and their health-promoting potential.

These compounds exhibit a wide range of biological activities, from direct antioxidant actions such as free radical scavenging to indirect effects including modulation of inflammatory pathways, regulation of metabolic processes, and maintenance of vascular and neurological health. Regular dietary intake of anthocyanin- and polyphenol-rich foods has been consistently associated with reduced risk of chronic conditions such as cardiovascular disease, diabetes, obesity, and neurodegeneration, the practical application of anthocyanins and polyphenols faces limitations. Anthocyanins are highly unstable under environmental stressors such as pH, light, and temperature, while both anthocyanins and polyphenols exhibit variable and often limited bioavailability. Advances in food technology—including encapsulation methods, fermentation, and optimized food formulations—are providing effective solutions to enhance their stability and absorption. Moreover, the emerging field of personalized nutrition, which tailors interventions to individual metabolic and microbiome profiles, holds significant potential for improving outcomesthe gap between experimental evidence and clinical application requires continued research, well-designed human trials, and innovations in delivery systems to fully realize the preventive and therapeutic potential of these compounds.

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