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Bioactive flavonoids in edible horticultural produce: Health benefits and utilization challenges

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Abstract
Flavonoids are a diverse group of plant secondary metabolites widely distributed in edible horticultural produce such as fruits, vegetables, herbs and flowers. Renowned for their antioxidant, anti-inflammatory and anticancer properties, flavonoids play a pivotal role in promoting human health and preventing chronic diseases including cardiovascular disorders, cancer and neurodegenerative conditions. Classified into subclasses flavonols, flavones, flavanones, flavan-3-ols, anthocyanins and isoflavones, each exhibits distinct bioactivities that contribute to their therapeutic potential. However, their application in functional foods and nutraceuticals is often constrained by challenges such as low bioavailability, instability during food processing and formulation limitations.

This review highlights key horticultural sources of flavonoids, including apples, onions, berries, parsley, edible flowers and certain seeds and nuts. It also discusses the impact of food matrix, metabolism and processing techniques on flavonoid efficacy. To address utilization barriers, strategies like biofortification, encapsulation and advanced food technologies are being explored to enhance their nutritional and therapeutic potential. Ongoing research is crucial to improve flavonoid extraction, stability and targeted health outcomes. Collectively, integrating flavonoids into health-promoting products offers significant promise for advancing functional food development and improving public health.

Keywords: Flavonoids, horticultural crops, bioactives, functional foods, health benefits, food processing

1. Introduction

Flavonoids, a prominent class of phytochemicals, are increasingly recognized for their critical role in promoting human health. These polyphenolic compounds are abundantly found in edible plants, particularly in horticultural produce such as fruits, vegetables, herbs, and flowers. Their wide range of biological activities including antioxidant, anti-inflammatory, and anticancer effects, has led to growing interest in their inclusion in daily diets and health-promoting products (Priya *et al*., 2025) [1]; (Abhinav *et al*., 2024) [2]. As modern nutrition shifts toward preventive strategies, the integration of plant-derived bioactives like flavonoids into public health guidelines becomes increasingly relevant.

Flavonoids function primarily as antioxidants by neutralizing free radicals and reducing oxidative stress, a major factor contributing to cellular aging, inflammation, and chronic diseases such as cardiovascular disorders and cancer (Goswami *et al*., 2024) [3]; (Priya *et al*., 2025) [1]. Beyond their antioxidant capacity, flavonoids also demonstrate anti-mutagenic and anti-carcinogenic actions, contributing to their value in both nutraceutical and pharmaceutical applications (Abhinav *et al*., 2024) [2].

The relevance of plant-based diets in reducing the incidence of chronic illnesses has been widely documented. These diets, rich in phytochemicals derived from fruits, vegetables, legumes, nuts, and whole grains, are associated with improved lipid profiles, reduced inflammation, and enhanced immune response (Goswami *et al*., 2024) [3]. Flavonoids, as key bioactives in these diets, play a critical role in maintaining cellular homeostasis and protecting against metabolic dysfunction.

Horticultural crops are especially important in this context, offering a diverse range of bioactive compounds including flavonoids, carotenoids, phenolics, and essential vitamins. Their consumption contributes not only to the intake of vital nutrients like vitamins A, C, and E and dietary fiber but also to the prevention of non-communicable diseases

(Krishnamoorthi *et al*., 2023) [4]; (Thayalan *et al*., 2024) [5]; (Dias, 2023) [6]. As a result, horticultural produce has emerged as a critical component of functional foods and natural health products, with implications for both human well-being and economic development.

This review aims to consolidate the current understanding of flavonoid biosynthesis, distribution, and health-promoting mechanisms, while also addressing their applications in food, pharmaceutical, and agricultural systems (Galatro *et al*., 2024) [7]; (Krishnamoorthi *et al*., 2023) [4]. It highlights the molecular and physiological pathways through which flavonoids exert their bioactivities, thereby providing a foundation for future innovations in functional product development (Priya *et al*., 2025) [1]. Furthermore, the review emphasizes the need for continued research to explore the bioavailability, safety, and formulation challenges associated with flavonoids, supporting efforts toward sustainable agriculture and improved public health outcomes (El-Ramady *et al*., 2022) [8].

Despite the well-established benefits of flavonoids, their efficacy can vary based on dosage, dietary context, and individual health status. The complexity of flavonoid interactions within the human body underscores the necessity for a deeper understanding of their metabolic pathways and safety profiles. High concentrations or chronic use in sensitive populations may pose risks, thus warranting careful scientific evaluation to inform evidence-based dietary recommendations (Goswami *et al*., 2024) [3]; (Abhinav *et al*., 2024) [2].

2. Classification and Types of Flavonoids

Flavonoids are a diverse class of plant-derived compounds distinguished by their polyphenolic structures. These compounds are categorized into six major subclasses based on variations in the C-ring structure, oxidation level, and pattern of substitution (Table 1). Each class possesses unique biological properties and distribution in plants (Carpena Rodriguez *et al*., 2021) [9].

Table 1: Major Flavonoid Subclasses, Sources, and Health Functions

Flavonoid Class	Key Compounds	Common Sources	Primary Bioactivities	References
Flavonols	Quercetin, Kaempferol	Apples, onions, kale	Antioxidant, cardioprotective	Bagwe-Parab *et al*., 2019 [10]
Flavones	Apigenin, Luteolin	Parsley, celery	Anti-inflammatory, anticancer	Hosseinzadeh *et al*., 2020 [11]
Flavanones	Naringenin, Hesperidin	Citrus fruits	Glucose metabolism regulation, vascular health	Khan *et al*., 2021 [12]
Anthocyanins	Cyanidin, Delphinidin	Berries, grapes	Antioxidant, anti-cancer, neuroprotective	Ku *et al*., 2020 [13]
Isoflavones	Genistein	Soy	Estrogenic effects, menopausal symptom relief	Wang *et al*., 2023 [14]
Flavan-3-ols	Catechins	Green tea	Heart health, weight regulation	Liga *et al*., 2023 [15]

3. Edible Horticultural Sources of Flavonoids

Flavonoids are widely distributed in edible horticultural crops, playing a vital role in both human health and plant defense. These compounds contribute to colour, flavour, and nutritional value in plant-based foods (Đorđević, 2023) [16]; (Krishnamoorthi *et al*., 2023) [4].

Table 2: Distribution of Flavonoid Classes in Horticultural Produce

Fruits	Vegetables	Herbs	Edible Flowers
Berries (Anthocyanins)	Kale (Flavonols)	Parsley (Flavones)	Hibiscus (Anthocyanins)
Apples (Flavonols)	Onions (Flavonols)	Thyme (Flavones)	Marigold, Rose (Mixed)
Grapes (Flavanols)	Amaranth (Flavonoids)	Mint (Flavones)	
Citrus (Flavanones)	Spinach (Mixed)		

These foods not only enhance dietary quality but also contribute to chronic disease prevention by delivering various subclasses of flavonoids (Barreca *et al*., 2020; Sebghatollahi *et al*., 2022; Galatro *et al*., 2024; Ku *et al*., 2020; Singh & Semwal, 2024; Thayalan *et al*., 2024) [17], [18], [7], [13], [19], [5].

4. Health Benefits of Flavonoids

Flavonoids confer a range of physiological benefits due to their antioxidant, anti-inflammatory, and metabolic modulatory activities as shown in Table 2.

- **Antioxidant Effects:** Flavonoids neutralize reactive oxygen species (ROS), preventing oxidative stress-induced cellular damage (Pyo *et al*., 2024) [20].
- **Anti-inflammatory and Anti-cancer Activity:** Apigenin and quercetin reduce expression of NF-κB and COX-2, mediating inflammation and tumor suppression (Barreca *et al*., 2023) [21]; (Deepak, 2022) [22].
- **Cardiovascular Protection:** Flavonoids lower LDL cholesterol, enhance nitric oxide bioavailability, and reduce blood pressure (Singh *et al*., 2023) [23].
- **Neuroprotection and Metabolic Regulation:** Catechins and anthocyanins protect neuronal structures and improve insulin sensitivity (Hasnat *et al*., 2024) [24].
- **Gut and Hormonal Balance:** Isoflavones from soy exert phytoestrogenic effects, while flavonoids support gut microbial diversity (Hasnat *et al*., 2024) [24].

Table 3: Summary of Key Health Benefits of Flavonoids

Health Benefit	Mechanism of Action	Representative Compounds	References
Antioxidant	Neutralization of free radicals, prevention of oxidative damage	Quercetin, Catechins	(Pyo *et al*., 2024) [20]
Anti-inflammatory & Anti-cancer	Downregulation of NF-κB, COX-2, induction of apoptosis	Apigenin, Luteolin	(Barreca *et al*., 2023) [21]; (Deepak, 2022) [22]
Cardiovascular Protection	LDL reduction, NO enhancement, anti-atherosclerotic effects	Hesperidin, Kaempferol	(Singh *et al*., 2023) [23]
Neuroprotection	Inhibition of neuroinflammation, protection against oxidative neuronal damage	Anthocyanins, Catechins	(Hasnat *et al*., 2024) [24]
Metabolic & Hormonal Balance	Estrogenic activity, improved insulin sensitivity, gut microbiota modulation	Genistein, Isoflavones	(Hasnat *et al*., 2024) [24]

NF-κB = Nuclear Factor kappa-light-chain-enhancer of activated B cells; COX-2 = Cyclooxygenase-2; LDL = Low-Density Lipoprotein; NO = Nitric Oxide.

5. Factors Affecting Stability and Bioavailability

Flavonoids, though bioactive and beneficial, often demonstrate limited efficacy when consumed due to issues related to their chemical stability and bioavailability the extent to which they are absorbed and utilized in the body (Fu *et al*., 2021) [25].

- **Processing Effects:** Thermal processing methods such as boiling, roasting, and frying can degrade flavonoids significantly. For example, quercetin and anthocyanins are highly heat-sensitive. Conversely, fermentation can sometimes improve flavonoid bioavailability by breaking down glycosidic bonds and producing aglycones, which are more easily absorbed (Fu *et al*., 2021) [25].
- **Environmental Conditions:** Factors like pH, temperature and light can destabilize flavonoids during storage. For instance, anthocyanins degrade rapidly under high pH or when exposed to light, leading to a reduction in colour and antioxidant efficacy (Jia *et al*., 2025) [26].
- **Food Matrix Interactions:** The bioavailability of flavonoids depends on how they interact with dietary macronutrients. Proteins may bind to flavonoids and prevent absorption, while fats can enhance solubility and uptake, especially for lipophilic compounds like flavanones (Debelo *et al*., 2020) [27].
- **Gut Microbiota:** In the colon, certain gut bacteria possess enzymes that transform flavonoids into more bioavailable or bioactive forms. For example, daidzein (an isoflavone) is metabolized into equol, which has potent estrogenic activity (Kiriyama *et al*., 2024) [28].
- **Synergistic Nutrients:** Co-consumption with nutrients like vitamin C, piperine or other polyphenols can boost flavonoid bioavailability through enhanced absorption or reduced degradation (Shahidi & Peng, 2018) [29].

6. Challenges in Functional Food Development

Despite the promise of flavonoids in human health, incorporating them effectively into functional food products is difficult due to several challenges:

- **Stability and Storage Limitations:** Flavonoids degrade under light, air, and high temperatures, reducing their shelf life and bioactivity. To address this, antioxidant packaging, edible films, and low-oxygen processing technologies are being developed (Cieplý, 2022) [30].
- **Low Bioavailability:** Many flavonoids, particularly glycosides, are poorly absorbed in the gastrointestinal tract. Techniques such as nanoencapsulation, liposomal delivery, and micelle formation can help protect the active compound until absorption (Rashidinejad *et al*., 2024) [31].
- **Lack of Regulatory Standardization:** Global variation in how nutraceuticals and functional foods are regulated creates inconsistencies in product quality, safety, and efficacy. The absence of harmonized testing and labelling standards hinders international trade and consumer trust (Birch *et al*., 2019) [32].
- **Industrial Scale-Up Issues:** Extracting and stabilizing flavonoids at an industrial scale remains expensive. Additionally, maintaining uniform flavonoid concentrations in processed foods is a technical challenge, affecting product consistency and commercial feasibility (Simões *et al*., 2021) [33].
- **Consumer Acceptance:** Flavonoids can impart bitter or astringent flavours. Without proper formulation, this can negatively impact taste. Moreover, lack of consumer awareness about health benefits limits market demand (Sadohara *et al*., 2022) [34]. Hence, sensory optimization and education are vital.

7. Opportunities and Future Directions

Despite current limitations, ongoing research and technological innovation provide promising pathways for enhancing flavonoid use in foods and health applications:

- **Biofortification:** This strategy involves genetic selection, molecular breeding, or agronomic practices to increase flavonoid content in crops. For example, purple tomatoes enriched with anthocyanins have shown enhanced antioxidant capacity (Chen *et al*., 2024) [35].
- **Encapsulation Technologies:** Innovations like nanoparticles, emulsions, hydrogels, and liposomes allow better protection of flavonoids from digestive degradation and environmental factors. This improves targeted delivery and controlled release in the body (Dadwal *et al*., 2021) [36]; Zhang *et al*., 2022) [37].
- **Public Health Campaigns:** Raising awareness about flavonoid-rich diets through nutrition education, school programs, and social media outreach can improve consumption patterns. Integration of these bioactives into daily meals may support preventive healthcare, especially in populations at risk of chronic diseases (Palai & Rudrapal, 2023) [38].
- **Sustainable Agriculture:** Cultivating flavonoid-rich crops not only enhances dietary quality but also supports biodiversity, climate resilience, and soil health. This aligns with goals of sustainable

development and planetary health (Yuan *et al*., 2023) [39].

8. Conclusion

Flavonoids are crucial in linking horticultural crops to public health through their diverse health benefits. However, bioavailability, extraction efficiency, and consumer-centric product development remain major bottlenecks. A transdisciplinary approach, combining horticultural science, nutrition, and food technology, is essential to overcome these barriers and leverage flavonoids for human health and sustainable food systems. Flavonoids are emerging as essential bioactive components in the intersection of agriculture, nutrition, and public health. Their integration into daily diets via horticultural produce presents a natural, food-based approach to health promotion and disease prevention. With extensive antioxidant, anti-inflammatory, and metabolic benefits, flavonoids can significantly contribute to reducing the burden of NCDs.

However, their real-world application is hampered by low stability, poor absorption, and formulation challenges. Addressing these issues requires a transdisciplinary strategy involving plant scientists, nutritionists, biochemists, and food technologists. Innovations like biofortification, encapsulation and public health education can help bridge the gap between flavonoid-rich foods and functional health outcomes.

Furthermore, as global health systems aim to shift toward preventive and sustainable nutrition, flavonoid research offers promising solutions—combining natural plant-based health interventions with scalable, environmentally friendly food systems.

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