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Nutritional composition, bioactive compounds, and health benefits of banana

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Abstract
Bananas (*Musa spp.*) are widely consumed fruits known for their nutritional richness and health-promoting properties. This review summarizes recent findings on their nutritional composition, bioactive compounds, and therapeutic potential. Bananas are rich in carbohydrates, dietary fiber, essential minerals such as potassium and magnesium, vitamins (notably vitamin C and B6), and phenolic compounds including catechins and dopamine. Both pulp and by-products such as peel and pseudostem exhibit significant antioxidant, anti-inflammatory, and antimicrobial activities. These bioactive components contribute to metabolic regulation, cardiovascular protection, gastrointestinal health, and neuroprotection. Emerging applications in functional foods, nutraceuticals, and biodegradable materials highlight the industrial relevance of banana biomass. Despite promising findings, further clinical validation and standardization are required. Overall, bananas represent a valuable functional food with significant potential in promoting human health and sustainable food systems.

Keywords: Banana (*Musa spp.*), bioactive compounds, antioxidants, resistant starch, functional foods, health benefits

1. Introduction
The banana (*Musa spp.*), a member of the *Musa*ceae family, is a globally significant fruit both economically and nutritionally. It is cultivated in over 135 countries and ranks among the top five most traded fruits worldwide [1]. Oxidative stress and lipid peroxidation are major contributors to food deterioration and various chronic diseases, driving the need for natural antioxidant-rich foods [2]. Beyond its culinary appeal, bananas have attracted increasing scientific interest for their diverse nutritional and therapeutic properties [3]. The fruit's unique composition—rich in carbohydrates, dietary fiber, vitamins, minerals, and phytochemicals make it a valuable functional food in both developed and developing nations [4].
In the context of global nutrition, bananas are a key dietary staple for millions, particularly in tropical and subtropical regions [5]. Recent research has explored the potential of banana and its by-products (such as peel and pseudostem) as cost-effective sources of bioactive compounds with antioxidant, antimicrobial, and anti-inflammatory properties [6-7]. The shift toward plant-based diets and the functional food movement has further emphasized banana's potential as a health-promoting fruit [8].
This review aims to compile recent evidence on banana's nutritional composition, phytochemical profile, and associated health benefits. It also explores emerging applications in food technology and the nutraceutical industry, identifying key knowledge gaps and future research directions.

2. Nutritional Composition of Banana
Bananas are rich in essential nutrients that contribute to their classification as an energy-dense yet health-promoting food. Their composition varies with ripening stage, variety, and processing conditions [9].

2.1 Macronutrients
Carbohydrates form the major component of banana pulp, constituting 22–32% of its fresh weight, predominantly as starch in unripe bananas and sugars (glucose, fructose, sucrose) in

ripe fruit [10]. The transition from starch to sugar during ripening contributes to the fruit's sweetness and digestibility. Bananas also contain 2–3% dietary fiber, composed mainly of resistant starch and non-starch polysaccharides, both of which support gastrointestinal health [4].

The protein content of banana pulp is relatively low (about 1.0–1.5%), but the amino acid profile includes essential amino acids such as leucine, isoleucine, and valine [11]. The lipid content is also minimal, typically ranging from 0.3% to 0.5% [12]. Although limited in quantity, the lipid fraction is predominantly composed of unsaturated fatty acids, including oleic and linoleic acids, which contribute negligibly to total caloric intake while maintaining the fruit's overall healthy metabolic profile [13].

2.2 Micronutrients

Bananas are recognized as an excellent source of potassium, providing 350–400 mg per 100 g of fruit, which supports cardiovascular and muscular function [14]. They are also rich in magnesium, phosphorus, and trace elements like zinc and manganese [15].

Vitamin content includes vitamin C (8–12 mg/100 g), vitamin B6 (pyridoxine), niacin, and folate, contributing to antioxidant defense and energy metabolism. The peel and pseudostem, often discarded, also contain high levels of these micronutrients and are being investigated as nutritional supplements [16].

2.3 Resistant Starch and Fiber

Unripe bananas contain significant quantities of resistant starch (up to 70–80% of total starch), which escapes digestion and acts as a prebiotic substrate in the colon. This component has been linked to improved glycemic control, weight management, and gut microbiome health [17]. Incorporation of banana pseudostem flour into food products such as biscuits significantly enhances dietary fiber, mineral content, and overall nutritional value [18].

3. Bioactive Compounds and Phytochemicals

Bananas are abundant in phytochemicals, including polyphenols, carotenoids, amines, and flavonoids, which play essential roles in antioxidant and anti-inflammatory defense.

3.1 Phenolic Compounds

The phenolic profile includes catechin, epicatechin, gallic acid, ferulic acid, and caffeic acid [7]. These compounds exhibit potent radical-scavenging activity, which contributes to reduced oxidative stress in biological systems. The peel generally contains higher total phenolic content than the pulp, making it an underutilized resource for functional ingredient extraction [19]. Fatty acid-derived bioactive compounds, such as ascorbyl esters, have been reported to exhibit enhanced antioxidant activity compared to their parent compounds, highlighting the importance of lipid–bioactive interactions in food systems [20].

3.2 Dopamine and Serotonin

Banana pulp and peel are rich in biogenic amines, notably dopamine and serotonin, which have antioxidant and neuromodulatory functions. Dopamine levels are particularly high in banana peel, with concentrations exceeding 40 mg/100 g in some cultivars. These compounds may contribute to mood regulation and neuroprotection [21]. Banana pseudostem sap has also been reported to contain flavonoids, dopamine, and glycosides with significant antioxidant and antibacterial properties [22].

3.3 Carotenoids and Tannins

Yellow- and orange-fleshed banana varieties are sources of carotenoids such as β-carotene, α-carotene, and lutein, which act as provitamin A and support eye health [23]. Tannins, abundant in unripe bananas, provide astringent properties and may exert antimicrobial and antidiarrheal effects [24].

3.4 Antioxidant Activity

The antioxidant potential of banana has been extensively documented, particularly in extracts from peel, pulp, and flour [19]. In vitro studies demonstrate significant DPPH and ABTS radical-scavenging activity, linked to phenolic and flavonoid content [25]. Antioxidants function by scavenging free radicals and interrupting oxidative chain reactions, thereby protecting biological systems from damage [2].

4. Phytochemical Profile and Therapeutic Potential of *Musa spp.*

The phytochemical composition described in Section 3 underpins the biological mechanisms discussed below.

The nutritional and therapeutic value of the banana is a direct result of its complex secondary metabolite profile. Unlike many tropical fruits, both the pulp and the peel of the banana (genus *Musa*) serve as rich reservoirs of bioactive molecules, including phenolics, biogenic amines, and specialized polysaccharides. The major bioactive compounds present in banana and their associated health benefits are summarized in Figure 1.

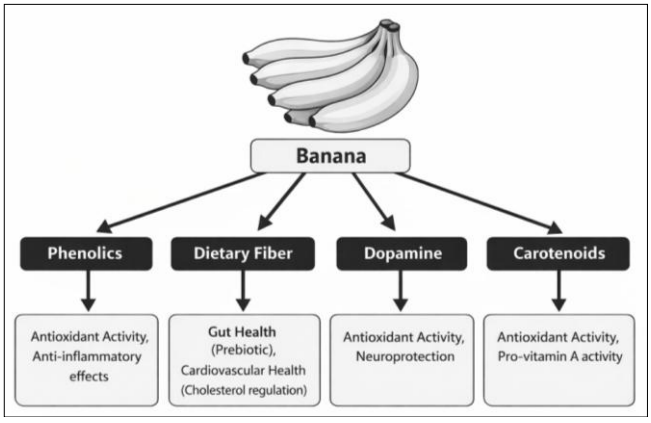

Fig 1: Schematic representation of major bioactive compounds in banana (*Musa spp.*) and their associated physiological and health-promoting effects.

4.1. Bioactive Composition and Distribution

As summarized in Table 1, the distribution of these compounds is tissue-specific. While the pulp is widely recognized for its high content of carotenoids—specifically β-carotene and lutein—the peel frequently exhibits significantly higher concentrations of phenolic acids and flavonoids, such as quercetin and catechin. Notably, bananas are among the richest dietary sources of biogenic amines like dopamine and serotonin. These compounds are present in both the peel and pulp, though the peel typically contains higher concentrations to assist in the plant's defense mechanisms against oxidative stress and pathogens.

Table 1: Profile and Biological Functions of Major Bioactive Compounds in *Musa spp.*

Compound Class	Key Representative Compounds	Primary Source	Principal Biological Functions	References
Phenolic Acids	Gallic acid, Ferulic acid, Syringic acid	Peel > Pulp	Antioxidant, Anti-inflammatory, Hepatoprotective	[3, 26]
Flavonoids	Catechin, Quercetin, Epicatechin	Peel	Free radical scavenging, Cardioprotective, Anti-ulcerogenic	[3, 19]
Biogenic Amines	Dopamine, Serotonin, Norepinephrine	Peel & Pulp	Neuroprotection, Antioxidant stress response, Glycemic regulation	[27]
Carotenoids	β-carotene, α-carotene, Lutein	Pulp	Provitamin A activity, Macular (eye) health, Immune enhancement	[3, 28]
Polysaccharides	Pectin, Resistant starch, Cellulose	Pulp & Peel	Prebiotic (Gut microbiota modulation), Anti-diabetic, Gastroprotective	[6, 26]
Phytosterols	β-sitosterol, Stigmasterol	Peel & Pulp	Cholesterol-lowering, Anti-carcinogenic	[3, 27]

4.2. Mechanisms of Action and Health Promotion

The clinical relevance of these phytochemicals lies in their diverse mechanisms of action within the human body. The health-promoting properties of banana (*Musa* spp.) extend beyond basic caloric nutrition to involve complex biochemical interactions, as detailed in Table 2.

For instance, the antioxidant activity of bananas is not merely a result of Vitamin C content but is driven primarily by the synergistic action of phenolics and flavonoids which directly scavenge reactive oxygen species (ROS). Furthermore, the high concentration of resistant starch and pectin provides a dual benefit for metabolic and gastrointestinal health. These polysaccharides escape digestion in the small intestine, acting as prebiotics that modulate the gut microbiota and improve insulin sensitivity through the production of short-chain fatty acids (SCFAs).

Table 2: Health Benefits of Banana and Associated Mechanisms.

Health Benefit	Key Component(s)	Mechanism of Action	References
Metabolic Regulation	Resistant starch, Dietary fiber	Improves insulin sensitivity and slows postprandial glucose absorption	[3, 29]
Cardiovascular Health	Potassium, Phenolic compounds	Regulates osmotic pressure and inhibits LDL cholesterol oxidation	[30]
Gastrointestinal Health	Pectin, Resistant starch	Acts as a prebiotic substrate for beneficial gut bacteria (e.g., *Bifidobacterium*)	[3, 6]
Neurological Health	Dopamine, Vitamin B6, Magnesium	Facilitates neurotransmitter biosynthesis and provides neuroprotective antioxidants	[8]
Antioxidant Activity	Flavonoids (Quercetin, Catechin)	Direct scavenging of Reactive Oxygen Species (ROS) and metal chelation	[7]

In the neurological domain, the presence of dopamine and vitamin B6 provides a unique neuroprotective framework. These constituents support neurotransmitter biosynthesis and help mitigate oxidative damage in the brain, suggesting a potential role for banana consumption in supporting long-term cognitive and neurological health.

5. Health Benefits of Banana Consumption

5.1 Metabolic Health

Banana consumption has been linked to improved metabolic parameters. The high fiber and resistant starch content help modulate postprandial glycemia, making bananas beneficial for individuals with type 2 diabetes [31]. Studies in rodent models have demonstrated that resistant starch from unripe bananas significantly improves insulin sensitivity and lipid metabolism in obesity [32]. Furthermore, human and clinical trials suggest that banana flour supplementation can reduce fasting glucose and reinforce gut barrier integrity by modulating the gut microbiome [33].

5.2 Cardiovascular Health

The potassium content of bananas plays a crucial role in maintaining electrolyte balance and blood pressure regulation. Epidemiological studies have consistently shown an inverse relationship between potassium intake and hypertension, with evidence suggesting that increased intake significantly lowers cardiovascular risk factors [34]. Furthermore, the fiber and phenolic antioxidants present in bananas contribute to reducing LDL oxidation and improving endothelial function, largely through the radical-scavenging capacity of their bioactive phytochemical profile [4].

Banana polyphenols may enhance nitric oxide bioavailability, promoting vasodilation and cardiovascular protection [35]. Regular intake of fruits has been associated with a decreased risk of ischemic heart disease (IHD) in large-scale cohort studies, such as the EPIC-Heart investigation [36]. Although these findings are based on overall fruit consumption, bananas contribute to this protective effect due to their high potassium content, which plays a key role in blood pressure regulation and cardiovascular risk reduction [34].

5.3 Gastrointestinal Health

Bananas have long been traditionally used as part of the "BRAT" diet (Banana, Rice, Applesauce, Toast) to manage gastrointestinal disorders. Beyond traditional use, the fruit's soluble fiber and prebiotic properties are scientifically recognized for supporting gut microbiota diversity and colonic health. Specifically, supplementation with green banana flour, rich in resistant starch, has been demonstrated to increase populations of beneficial gut bacteria, notably *Bifidobacterium* and *Lactobacillus* species [37]. Furthermore, the synergy between pectin and resistant starch provides a protective effect against diarrhea and helps maintain mucosal integrity in ulcerative conditions by improving small intestinal permeability and reducing fluid loss [38].

5.4 Neurological and Psychological Health: Emerging evidence highlights the potential neuroprotective and mood-

modulating effects of banana consumption, largely attributed to its bioactive profile including dopamine, serotonin, and high levels of vitamin B6 [8]. While dietary dopamine and serotonin act primarily as peripheral antioxidants, bananas supply tryptophan—a critical amino acid precursor for endogenous serotonin synthesis [4]. Furthermore, the high concentration of vitamin B6 serves as an essential cofactor for the enzymatic conversion of 5-hydroxytryptophan to serotonin, thereby supporting mood regulation and the mitigation of mild depressive symptoms.

5.5 Antioxidant and Anti-Inflammatory Properties

Banana extracts exhibit significant antioxidant activity, effectively reducing lipid peroxidation and modulating inflammatory pathways [8, 39]. Aqueous banana peel extracts, in particular, have demonstrated the ability to downregulate pro-inflammatory cytokines such as TNF-α and IL-6 in experimental cell models [40]. These properties suggest a therapeutic potential for the prevention of chronic diseases linked to oxidative stress, including diabetes, atherosclerosis, and various neurodegenerative disorders [8].

5.6 Anticancer Potential

Recent studies suggest that banana peel and pulp extracts possess anticancer properties against several human cancer cell lines, notably MCF-7 and HCT-116 [41]. Polyphenols such as ferulic and gallic acid contribute to this cytotoxic activity by modulating inflammatory pathways and inhibiting cellular proliferation [42]. However, these promising findings remain largely preclinical, having been demonstrated in vitro and in animal models; therefore, further human clinical studies are required to validate these therapeutic effects [43].

6. Industrial and Functional Food Applications

Beyond nutritional benefits, banana biomass has emerged as a versatile resource for industrial and environmental applications. Banana and its by-products are increasingly being integrated into the food and nutraceutical industries, driven by a growing demand for functional ingredients. Banana pseudostem can be utilized in textiles, paper production, biofertilizers, and composite materials, contributing to sustainable waste valorization [44]. Banana flour and banana pulp are currently utilized in bakery products, beverages, and infant foods, serving as vehicles for dietary fiber and prebiotic compounds that contribute to enhanced colonic health and overall nutritional quality. Banana peel, often treated as waste, is increasingly being valorized as a rich source of dietary fiber, phenolics, and pectin, which are essential for functional food development [6].

Beyond food, innovative industrial applications include the development of biodegradable packaging and edible films, which leverage the peel's natural polysaccharide content to offer a sustainable alternative to synthetic plastics [45]. Furthermore, banana peel biomass is being explored as a viable fermentation substrate for the production of bio-based products and microbial growth media [46]. Banana pseudostem-derived charcoal exhibits high adsorption capacity due to its dual-porosity structure, making it an effective low-cost adsorbent for wastewater treatment [47]. Moreover, banana pseudostem fibers possess high tensile strength and biodegradability, enabling their use in eco-friendly paper production and packaging materials [48].

Furthermore, banana starch is increasingly utilized in gluten-free formulations and as a functional fat replacer in low-calorie products, leveraging its high viscosity and resistant starch content [49]. This approach aligns with circular economy principles by transforming agricultural waste such as rejected or overripe bananas into value-added food ingredients, thereby minimizing food loss and promoting sustainable production chains [50].

7. Limitations and Future Perspectives

While banana's nutritional and therapeutic potentials are well documented, several limitations persist. Most studies remain preclinical, with limited randomized clinical trials confirming long-term health effects; furthermore, the bioavailability and metabolism of banana-derived polyphenols in humans remain areas requiring further elucidation [51]. Moreover, the extensive varietal diversity across *Musa* species leads to significant compositional variation, complicating standardization for research and industrial applications [52-53]. Future studies must transition toward exploring the molecular mechanisms underlying banana's bioactive effects and integrating 'omics' technologies such as metabolomics and nutrigenomics to provide a high-resolution understanding of banana's functional potential in precision nutrition [54].

8. Conclusion

Bananas are not only a widely consumed and nutritious fruit but also a rich source of bioactive compounds with diverse health-promoting properties. Their unique blend of carbohydrates, fiber, minerals, vitamins, and phytochemicals supports metabolic, cardiovascular, gastrointestinal, and neurological health. Emerging research on banana by-products highlights their potential as sustainable functional food ingredients.

Despite existing gaps in human clinical validation, the evidence strongly positions bananas as an essential component of a balanced, health-promoting diet and a promising natural resource for the nutraceutical and functional food industries.

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