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Nutritional and bioactive potential of banana peel: A sustainable functional food resource

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Abstract
Banana peel, traditionally considered an agricultural by-product, is emerging as a functional material with significant therapeutic potentials. It contains carbohydrates, proteins, and dietary fiber, along with micronutrients including potassium, magnesium, and vitamins. The peel is also a rich source of bioactive compounds, including phenolics, flavonoids, tannins, and catecholamines, which confer antioxidant, anti-inflammatory, and antimicrobial activities. These compounds have been linked to health-promoting effects such as improved cardiovascular function, enhanced gut health, and mitigation of oxidative stress. The utilization of banana peel in functional foods, nutraceuticals, and value-added products presents a sustainable approach to waste management and nutritional enhancement. This review summarizes the nutritional composition, bioactive profile, and therapeutic properties of banana peel, highlighting its potential as a functional ingredient for health and food security applications.

Keywords: Antioxidant activity, banana peel, bioactive compounds, functional foods, sustainability, waste valorization

Introduction
The banana *(Musa spp.)* is a big perennial plant, a member of the *Musaceae* family. It is one of the most widely cultivated and consumed fruits worldwide, particularly in tropical and subtropical regions. India is the largest producer of bananas, contributing a significant share to global production (Ansari *et al*., 2023) [1]. Fruit peels constitute 30-40% of total fruit weight, results in a significant amount of waste. These peels are typically thrown away due to their abrasive texture and astringent flavor, which results in large post-harvest losses and environmental harm. The rapid perishability of bananas exacerbates these losses, highlighting the urgent need for sustainable waste management strategies (Martins *et al*., 2019) [14].

Traditionally, banana peels have been utilized in low-value applications, including animal feed, composting, or as biosorbents for water treatment (Vu *et al*., 2018) [27]. However, mounting data suggests that banana peel has significant potential for higher-value uses, especially in the creation of nutraceuticals, functional meals, and health-promoting goods (Vu *et al*., 2019) [28]. The valorization of banana peel not only enhances resource efficiency but also contributes to sustainable food systems by transforming agricultural waste into value-added products.

Banana peels are rich in dietary fiber, resistant starch, phenolic compounds, carotenoids, and essential minerals such as potassium, magnesium, and calcium (Barman *et al*., 2015; Kraithong & Issara, 2011) [4, 12]. Furthermore, a variety of phytochemicals, such as phenolic acids, flavonoids, tannins, carotenoids, and biogenic amines, provide a broad range of pharmacological activities, including antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and anticancer effects (Someya *et al*., 2002; Naksing *et al*., 2021; Santos *et al*., 2019) [16, 21, 23]. These bioactive components promote the possible use of banana peel in functional food formulations targeted at enhancing human health and contribute to a number of health advantages. In this context, the present review aims to provide a holistic overview of banana peel as a value-added resource. The review highlights its bioactive components, and related pharmacological actions. Despite this potential, further study is required to investigate its functional qualities and uses in value-added goods while encouraging waste valorization and sustainability (Vu *et al*., 2018) [27].

Nutritional Composition of Banana Peel
Banana pulp is primarily consumed for its energy-providing carbohydrates, pleasant taste, and digestibility, whereas banana peel, often discarded as waste. Although, it is nutritionally denser in dietary fiber, minerals, and bioactive compounds than pulp. The compositional profile of banana peel varies depending on cultivar, stage of ripening, and processing conditions. Nutritional composition of banana peel is shown in table 1 and mainly composed of carbohydrates (50–60%), with dietary fiber (35–50%) as the major component, followed by moderate protein content (6–9%) and low fat levels (1.5–3.5%), making it a low-fat, fiber-rich ingredient (Barman *et al*., 2015; Vu *et al*., 2018) [4, 27].

The ash content (8–12%) reflects its substantial mineral composition, including potassium, calcium, magnesium, phosphorus, iron, and zinc, which support electrolyte balance, bone health, and enzymatic functions (Kraithong & Issara, 2011; Martins *et al*., 2019) [12, 14]. Banana peel also contains appreciable amounts of vitamin C (15–35 mg/100 g), niacin, vitamin B6, and β-carotene (Someya *et al*., 2002; Emaga *et al*., 2007) [7, 23]. The fiber fraction mainly comprises cellulose, hemicellulose, lignin, and pectin, which are associated with improved digestive health, glycemic regulation, and cholesterol reduction (Mohapatra *et al*., 2010) [15]. In addition to essential nutrients, banana peel is rich in polyphenols, flavonoids, tannins, and dopamine, with total phenolic content reported to range between 300 and 500 mg GAE/100 g dry weight (Someya *et al*., 2002 [23]; Vu *et al*., 2019) [28]. These bioactive constituents contribute to strong antioxidant and antimicrobial properties, enhancing the potential of banana peel for application in functional foods and nutraceutical formulations. Overall, the nutritional composition of banana peel emphasizes its value as a fiber and mineral-rich by-product with significant antioxidant capacity, supporting its utilization in sustainable food systems and value-added product development.

Table 1: Proximate and Mineral Composition of Banana Pulp and Banana Peel (per 100 g dry weight)

Component	Banana Pulp	Banana Peel	References
Moisture (%)	70–75	60–70	Barman *et al*.(2015) [4]; Vu *et al*.(2018) [27]
Energy (kcal)	85–95	70–80	USDA, (2023) [26]; Martins *et al*.(2019) [14]
Total Carbohydrates (g)	22–25	50–60	Barman *et al*.(2015) [4]; Vu *et al*. (2018) [27]
Total Sugars (g)	12–15	5–10	Someya *et al*.(2002) [23]
Dietary Fiber (g)	2–3	35–50	Kraithong & Issara, (2011) [12]; Vu *et al*. (2019) [28]
Protein (g)	1.0–1.3	6–9	Barman *et al*.(2015) [4]
Fat (g)	0.2–0.5	1.5–3.5	Martins *et al*.(2019) [14]
Ash (g)	0.8–1.0	8–12	Kraithong & Issara, (2011) [12]
Potassium (mg)	350–400	800–1200	USDA, (2023) [26]; Vu *et al*.(2018) [27]
Calcium (mg)	5–10	60–120	Barman *et al*.(2015) [4]
Magnesium (mg)	25–30	70–100	Martins *et al*.(2019) [14]
Iron (mg)	0.3–0.6	2–4	Kraithong & Issara, (2011) [12]
Vitamin C (mg)	8–10	15–30	Someya *et al*.(2002) [23]
Total Phenolics (mg GAE)	30–60	300–500	Someya *et al*.(2002) [23]; Vu *et al*.(2019) [28]
Total Flavonoids (mg QE)	5–15	80–150	Vu *et al*.(2019) [28]
Antioxidant Activity	Moderate	High	Someya *et al*.(2002) [23]

Bioactive Compounds in Banana Peel

Banana peel is a rich reservoir of diverse bioactive compounds, including polyphenols, flavonoids, phenolic acids, catechins, epicatechins, etc. which exhibit outstanding therapeutic qualities, such as antioxidant, antibacterial, antifungal, and anti-inflammatory effects (Viana *et al*., 2024). These bioactives are essential substances may be classified as primary and secondary metabolites which vary with cultivar, maturity stage, and processing conditions. The bioactive substances found in banana peel are essential to human health and help prevent chronic disorders (Shankar, 2020) [22].

Phenolic Compounds and Flavonoids

Phenolic compounds are secondary metabolities play a crucial role in defense against abiotic stressors, including UV radiation and biotic stress like predators. Phenolic compounds are the most extensively studied bioactives in banana peel. They include phenolic acids such as gallic acid, caffeic acid, ferulic acid, chlorogenic acid, catechin, epicatechin, gallocatechin, tannins, and anthocyanins (Emaga *et al*., 2007; Jamilah *et al*., 2011; Someya *et al*., 2002) [7, 10, 23] and flavonoids such rutin, myricetin, kaempferol, and quercetin . Furthermore, phenolic compounds may scavenge reactive oxygen species (ROS) and stimulate antioxidant enzymes,are primarily responsible for the strong antioxidant activity of banana peel through free radical scavenging, metal chelation, and inhibition of lipid peroxidation (Zaini *et al*., 2020) [32]. According to Emaga *et al*. (2007) [7, 32] and Oliveira *et al*. (2009) [18], cultivar, ripening stage, and extraction technique all affect total phenolic content, which is commonly reported in the range of 400–1,000 mg gallic acid equivalents (GAE)/100 g dry weight.

These phenolics and flavonoids compounds are the predominant substances are which are found in the peel at significantly greater concentrations than in the edible pulp (Tsamo *et al*., 2015; Zaini *et al*., 2022) [25, 33] and have been associated with cardioprotective, antidiabetic, antiobesity and anticancer properties (Banerjee *et al*., 2018; Barman *et al*., 2015; Hikal *et al*., 2022) [3, 4, 9]. Gallic, ferulic, and catechic acids are the predominent phenolic compounds in banana peels possess phenolic structure with one or more hydroxyl (–OH) groups attached to an aromatic ring as shown in figure 1. The structure–activity connection of banana peel phenolics is intimately linked to their potent antioxidant activity. Aromatic rings with conjugated double bonds and multiple hydroxyl (–OH) groups enable molecules to donate hydrogen atoms or electrons to neutralize free radicals and stabilize the resulting phenoxyl radicals by resonance (Rasool *et al*., 2010; Williamson & Manach, 2005) [20, 29].

Flavonoids are polyphenolic compounds consisting of two aromatic rings linked by a heterocyclic ring as shown in figure1.The major flavonoids reported in banana peel include catechin, epicatechin (flavan-3-ols) and quercetin and rutin (flavonols). The number and position of hydroxyl (–OH) groups, particularly the *ortho-dihydroxy (catechol) structure* on the B-ring, are critical for strong antioxidant and metal-chelating activity. Additionally, glycosylation (as in rutin) enhances solubility and stability, while the degree of saturation in the C-ring (catechin vs quercetin) influences bioavailability and biological function. These structural features collectively govern the antioxidant, anti-inflammatory, antimicrobial, and antidiabetic properties of predominant flavonoids, explaining their functional significance in food and health applications. Additionally, quercetin has an ortho-dihydroxyl bond and a C2=C3 double bond conjugated with a 4-oxo group, which improve its ability to chelate metals and scavenge radicals and account for its potent anti-inflammatory and antioxidant properties (Perez Vizcaino & Duarte, 2010; Williamson & Manach, 2005) [19, 29]. In addition to supporting antioxidant and antimicrobial activity, condensed tannins (proanthocyanidins) have multiple flavanol units that provide numerous active sites for radical scavenging and protein or metal binding. However, when intake is extremely high, it may also decrease protein digestibility and mineral bioavailability (Emaga *et al*., 2007; Hikal *et al*., 2022) [7, 9]. The cultivar and ripening stage have a significant impact on the phenolic content and composition of banana peels. According to studies, ripe peels have a higher antioxidant capacity than unripe ones due to an increase in total phenolic content, gallocatechin, and some flavonoids; however, overripe peels may exhibit partial degradation of specific compounds (Emaga *et al*., 2007 [7]; Vu, Scarletti, & Golding, 2018) [27]. Differences among cultivars such as Grand Nain, Nendran and red banana have also been observed, with some varieties showing particularly high levels of gallocatechin and rutin (Tsamo *et al*., 2015; Zaini *et al*., 2022) [25, 33]. This variability underscores the importance of cultivar selection and maturity stage when targeting peel for functional ingredient development (Hikal *et al*., 2022) [9].

Carotenoids

Numerous carotenoids, including lutein, α-carotene, β-carotene, β-cryptoxanthin, and lycopene, are found in banana peels and provide both color and biological activity (Arancón *et al*., 2009; Jamilah *et al*., 2011; Zaini *et al*., 2022) [2, 10, 33]. Depending on cultivar and maturity, reported carotenoid concentrations vary from around 160 µg to over 2,500 µg per 100 g dry weight; lutein frequently predominates, particularly in unripe peels (Arancón *et al*., 2009; Emaga *et al*., 2007) [2, 7]. These carotenoids, especially β-carotene and α-carotene, which the human body enzymatically cleaves to retinal, can function as provitamin A sources and add to the peel's overall antioxidant capacity (Krinsky & Johnson, 2005; Zaini *et al*., 2022) [13, 33]. Carotenoids' long polyene chain with several conjugated double bonds controls their action by effectively scavenging peroxyl radicals and quenching singlet oxygen (Krinsky & Johnson, 2005; Santos *et al*., 2019) [13, 21]. The hydroxylated xanthophylls lutein and β-cryptoxanthin have a strong ability to shield cell membranes and ocular tissues from photo oxidative damage, while the β-ionone rings of β-carotene and α-carotene enable them to function as provitamin A, supporting visual function and epithelial integrity (Krinsky & Johnson, 2005) [13]. When ingested as part of the diet, carotenoids from banana peels are linked to a lower risk of cardiovascular disease, several types of cancer, and age-related macular degeneration due to their structural characteristics (Krinsky & Johnson, 2005; Santos *et al*., 2019) [13, 21].

Biogenic Amines and Catecholamines

Biogenic amines, including serotonin, norepinephrine, and catecholamines like dopamine and L-DOPA, are present in both banana peel and pulp (Gonzalez Montelongo *et al*., 2010; Yin *et al*., 2008) [15, 31]. Banana peel is one of the most abundant natural sources of dopamine, with concentrations frequently higher than those in the pulp (Kanazawa & Sakakibara, 2000; Someya *et al*., 2002) [11, 23]. These amines have strong antioxidant activities and play a major role in peel extracts' ability to scavenge radicals (Gonzalez Montelongo *et al*., 2010; Hikal *et al*., 2022) [8, 9]. The structural basis of catecholamines consist of an ethylamine side chain joined to a catechol ring (benzene with two adjacent hydroxyl groups), which underlies their neuroactive and antioxidant properties (Kanazawa & Sakakakibara, 2000; Yin *et al*., 2008) [11, 31]. The catechol moiety contributes strong radical scavenging activity, in some assays surpassing conventional antioxidants such as glutathione or butylated hydroxytoluene (BHT), through facile electron donation and formation of resonance-stabilized semiquinone radicals (Kanazawa & Sakakibara, 2000 [11]; Gonzalez Montelongo *et al*., 2010) [8]. The amine side chain facilitates binding to specific receptors and transporters, explaining their role in neurotransmission, mood regulation, cognition, and cardiovascular health (Yin *et al*., 2008) [31]. Nevertheless, the concentration and stability of these biogenic amines in peel-derived products must be carefully controlled, as excessive accumulation has been linked to adverse effects such as headaches and blood pressure fluctuations in sensitive individuals (Yin *et al*., 2008; Hikal *et al*., 2022) [9, 31].

Phytosterols and Triterpenes

Phytosterols and triterpenes, such as β-sitosterol, campesterol, stigmasterol, cycloartenol, and 24-methylenecycloartanol, are also found in banana peel and are mostly found in the unsaponifiable lipid fraction (Mohapatra *et al*., 2010; Zaini *et al*., 2022) [15, 33]. The potential of these substances as functional elements that target lipid metabolism and prevent chronic diseases is becoming more widely acknowledged (Choudhary & Tran, 2016; Hikal *et al*., 2022) [6, 9]. Because they include extra methyl or ethyl groups on the side chain, phytosterols can compete with cholesterol for absorption into mixed micelles in the intestinal lumen despite having a steroid nucleus that is extremely similar to that of cholesterol (Choudhary & Tran, 2016) [6]. Therefore, when routinely ingested in sufficient proportions, dietary phytosterols lower intestinal cholesterol absorption and increase its excretion, which helps lower blood LDL cholesterol (Wilt *et al*., 1999; Choudhary & Tran, 2016) [6, 30]. Sterol and triterpene structures allow interaction with cell membranes and signaling pathways involved in immunity and inflammation in addition to their hypocholesterolemic effect, which may account for the anti-inflammatory and possibly anticancer properties reported for β-sitosterol and related compounds (Hikal *et al*., 2022; Santos *et al*., 2019) [9, 21].

Synergy, Bioaccessability and Dual Roles

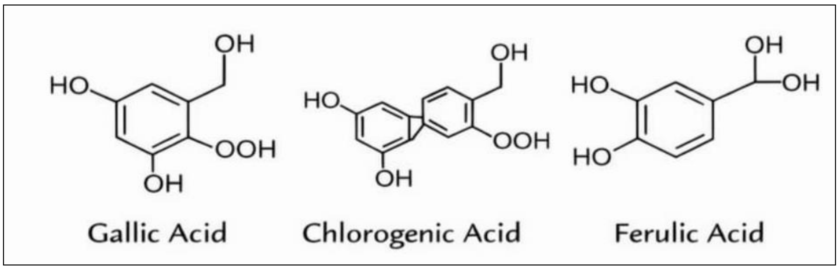
According to Thai *et al*. (2021) [24] phenolics, carotenoids, catecholamines, and phytosterols within the peel matrix work synergistically to provide the health benefits of banana peel. Several complementary mechanisms of antioxidant protection, antimicrobial activity, and metabolic pathway modulation are provided by overlapping structural features, such as phenolic hydroxyl groups, carotenoid polyenes, catechol rings, and sterol skeletons (Hikal *et al*., 2022) [9]. Stronger antioxidant and antibacterial effects for the whole extract are frequently reported in studies comparing crude peel extracts with isolated components, highlighting the significance of synergy (Thai *et al*., 2021 [24]; Gonzalez Montelongo *et al*., 2010) [8].

Additionally, these chemicals' metabolism and bioaccessibility have a significant impact on their effectiveness *in vivo*. Numerous phenolic compounds from peel enter the colon, where they are converted by the gut bacteria into smaller phenolic acids and other metabolites that may be absorbed and may have cardioprotective, anti-inflammatory, and systemic antioxidant effects (Santos *et al*., 2019; Oliveira *et al*., 2009) [18, 21]. For effective absorption, carotenoids must be incorporated into mixed micelles in the presence of dietary fat and bile salts, and depending on gastrointestinal circumstances, biogenic amines may be enzymatically degraded or absorbed

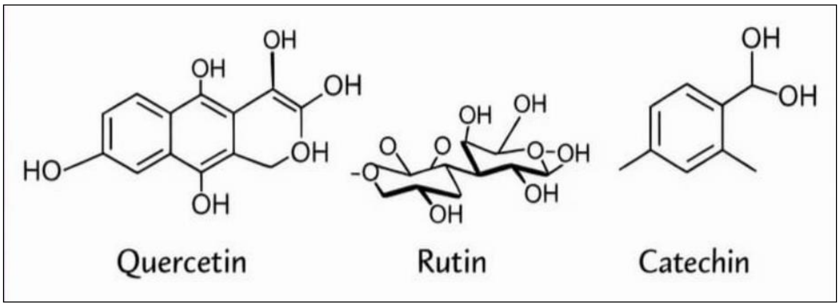
(Krinsky & Johnson, 2005; Yin *et al*., 2008) [13, 31]. Certain bioactives, such as tannins, oxalates, and some biogenic amines, have two functions: at moderate concentrations, they can have antioxidant, antimicrobial, or cholesterol-lowering effects; at high concentrations, they can affect the bioavailability of proteins and minerals or cause intolerance in those who are sensitive (Hikal *et al*., 2022; Barman *et al*., 2015) [4, 9]. In order to maximize health benefits while maintaining safety and sensory acceptability, processing conditions and inclusion levels must be optimized when using banana peel as a functional ingredient (Hikal *et al*., 2022; Zaini *et al*., 2022) [9, 33].

Chemical Structure of Key Bioactive Compounds in Banana Peel

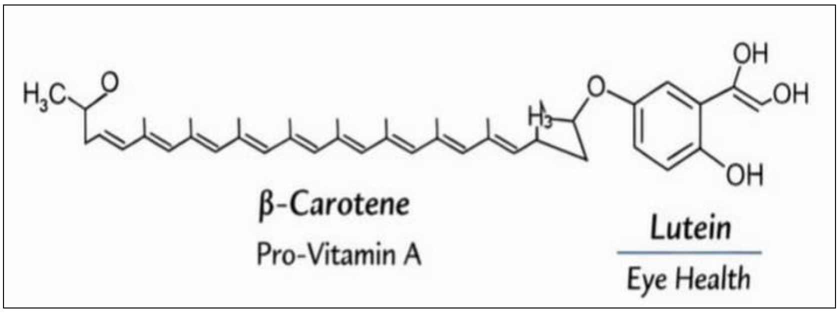
Phenolic Compounds



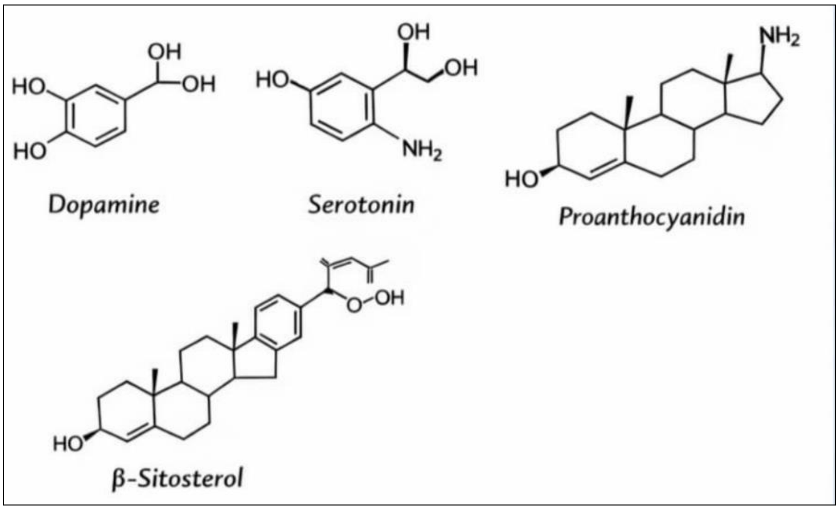
Flavonoids



Carotenoids



Biogenic Amines and Others



Source: PubChem Database (National Centre for Biotechnology Information, (NCBI), USA.

Fig 1: Chemical Structure of Selected Phenolics acids, Flavonoids, Carotenoids and Biogenic Amines Present in Banana Peel

Table 3: Bioactive compounds of banana Peel and their extraction/processing methods

Bioactive compound group	Major compounds reported	Functional/health properties	Extraction / processing methods	References
Phenolic acids	Gallic acid, ferulic acid, caffeic acid, chlorogenic acid	Antioxidant, anti-inflammatory, antimicrobial, antidiabetic	Solvent extraction (ethanol, methanol, aqueous ethanol), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE)	Someya *et al*. (2002); Santos *et al*, (2019); Naksing *et al*. (2021) [16, 21, 23]
Flavonoids	Catechin, epicatechin, quercetin, rutin	Antioxidant, cardioprotective, anti-inflammatory, anticancer	Hydroalcoholic extraction, UAE, enzymatic-assisted extraction	Someya *et al*. (2002) [23]; Vu *et al*. (2018) [27]; Santos *et al*. (2019) [21]
Tannins	Condensed tannins, hydrolysable tannins	Antimicrobial, antioxidant, astringent	Hot water extraction, aqueous ethanol extraction, fermentation	Barman *et al*.(2015) [4]; Naksing *et al*.(2021) [16]
Carotenoids	β-carotene, α-carotene, lutein	Provitamin A activity, antioxidant, immune support	Organic solvent extraction (acetone, hexane–ethanol), supercritical CO_2 extraction	Kraithong & Issara, (2011); Santos *et al*. (2019) [12, 21]
Biogenic amines	Dopamine, serotonin derivatives	Strong antioxidant, neuroprotective	Acidified solvent extraction, aqueous extraction	Someya *et al*. (2002) [23]; Vu *et al*. (2018) [27]
Dietary fiber & polysaccharides	Cellulose, hemicellulose, pectin, resistant starch	Prebiotic effect, glycemic control, cholesterol lowering	Hot water extraction, acid/alkali treatment, enzymatic hydrolysis	Barman *et al*. (2015) [4]; Vu *et al*., (2018) [27]
Phytosterols	β-sitosterol, campesterol	Hypocholesterolemic, anti-inflammatory	Soxhlet extraction, supercritical fluid extraction	Santos *et al*. (2019) [21]
Minor phytochemicals	Alkaloids, saponins, glycosides	Antimicrobial, synergistic bioactivity	Aqueous / hydroalcoholic extraction	Naksing *et al*. (2021) [16]

Pharmacological Activities of Banana Peel

Pharmacological Activity	Major Bioactive Compounds	Mechanism of Action	Potential Applications	References
Antioxidant	Phenolic acids (gallic, ferulic), flavonoids (quercetin, catechin), carotenoids and dopamine	Free radical scavenging, metal ion chelation and inhibition of lipid peroxidation	Functional foods, natural antioxidants, nutraceuticals	Someya *et al*. (2002) [23]; Vu *et al*. (2018) [27]
Antimicrobial	Tannins, flavonoids, phenolic acids	Disruption of microbial cell membrane, protein precipitation, enzyme inhibition	Natural food preservatives, pharmaceutical formulations	Barman *et al*. (2015) [4]; Vu *et al*. (2019) [28]
Antifungal	Tannins, flavonoids, saponins, alkaloids	Inhibition of fungal cell wall synthesis and membrane integrity	Food preservation, antifungal agents	Chabuck *et al*. (2013) [5]; Hikal *et al*. (2022) [9]
Antidiabetic	Flavonoids, dietary fiber, resistant starch, triterpenoids (lupenone)	Inhibition of α-amylase and α-glucosidase, reduction of oxidative stress	Diabetic-friendly foods, nutraceuticals	Santos *et al*. (2019); Hikal *et al*. 2022 [9, 21]
Anti-inflammatory	Quercetin, phytosterols, phenolic compounds	Suppression of pro-inflammatory cytokines and oxidative stress pathways	Functional foods, therapeutic formulations	Martins *et al*. (2019) [14]
Anticancer	Phenolic compounds, flavonoids, carotenoids	Induction of apoptosis, inhibition of cell proliferation and angiogenesis	Pharmaceutical research	Someya *et al*. (2002); Nirmala & Murthy, (2023) [17, 23]
Anti-ulcer / Gastro protective	Flavonoids, pectic polysaccharides	Strengthening of gastric mucosal barrier and antioxidant protection	Herbal therapeutics	Ansari *et al*. (2023) [1]
Wound-healing	Polyphenols, tannins, dopamine	Enhanced collagen synthesis, antimicrobial protection	Topical formulations, herbal medicine	Vu *et al*. (2019) [28]; Hikal *et al*. (2022) [9]
Prebiotic & gut-health	Dietary fiber, resistant starch, polysaccharides	Promotion of beneficial gut microbiota	Functional foods, feed additives	Kraithong & Issara, (2011) [12]
Cholesterol-lowering	Phytosterols, soluble fiber	Reduced intestinal cholesterol absorption	Functional foods, dietary supplements	Martins *et al*. (2019) [14]
Neuro protective	Dopamine, serotonin, phenolics	Antioxidant defense and neurotransmitter modulation	Neuro-therapeutic formulations	Someya *et al*. (2002) [23]

Antioxidant

Banana peel is widely recognized as a rich source of natural antioxidants, capable of neutralizing free radicals and protecting biological systems from oxidative damage. Numerous studies have demonstrated strong antioxidant activity of banana peel extracts using various *in vitro* assays such as DPPH, ABTS, FRAP, and ORAC, highlighting their potential application as natural preservatives in food systems (Someya *et al*., 2002; Zaini *et al*., 2020; Hikal *et al*., 2022) [9, 23, 32]. Due to increasing safety concerns and regulatory restrictions associated with synthetic antioxidants, natural antioxidants derived from fruit by-products such as banana peel have gained considerable attention (Santos *et al*., 2019) [21]. Banana peel contains significantly higher concentrations of phenolic compounds than the edible pulp, including gallic acid, catechin, epicatechin, gallocatechin, tannins, and anthocyanins (Emaga *et al*., 2007; Jamilah *et al*., 2011) [7, 10]. Reports indicate that banana peel possesses nearly five times higher gallocatechin content than pulp, contributing substantially to its antioxidant potency (Someya *et al*., 2002) [23]. Among individual compounds, dopamine, ferulic acid, and caffeic acid exhibit strong radical scavenging activity, with dopamine from banana peel reported to possess antioxidant capacity comparable to ascorbic acid and gallocatechin gallate, and higher than glutathione, BHT, catechin, and quercetin (Kanazawa & Sakakibara, 2000; Gonzalez-Montelongo *et al*., 2010) [8, 11]. Moreover, antioxidant activity of banana peel is strongly influenced by the stage of ripening. Several studies have shown that antioxidant capacity increases during ripening due to enhanced phenolic accumulation, while over-ripening leads to partial degradation of bioactive compounds (Emaga *et al*., 2007; Vu *et al*., 2018) [7, 27]. During ripening, carotenoid and flavonoid contents reportedly increase by approximately 50% and 27%, respectively, whereas chlorophyll degradation may reach nearly 90%, further enhancing antioxidant potential (Zaini *et al*., 2022) [33]. These findings indicate that maturity stage selection is critical when banana peel is intended for antioxidant-rich applications.

Antimicrobial Activity

Plant-derived bioactive compounds have long been utilized for the treatment of infectious diseases, and banana peel extracts have emerged as promising sources of antimicrobial agents. Both green and ripe banana peel extracts have demonstrated inhibitory activity against a wide range of Gram-positive and Gram-negative bacteria, including *Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus,* and *Bacillus subtilis* (Chabuck *et al*., 2013; Hikal *et al*., 2022) [5, 9]. Alcoholic and methanolic extracts of Musa acuminata peel have shown measurable inhibition zones against pathogenic bacteria such as *E. coli* (ATCC 25922), *P. aeruginosa*, *Staphylococcus aureus* (ATCC 25923), *Proteus vulgaris*, and *Salmonella paratyphi*, with inhibition generally increasing at higher extract concentrations (Chabuck *et al*., 2013; Nirmala & Murthy, 2023) [5, 17]. Tannins present in banana peel are considered major contributors to antibacterial activity due to their ability to precipitate microbial proteins and disrupt cell membranes (Barman *et al*., 2015; Hikal *et al*., 2022) [4, 9]. Aqueous banana peel extracts have also demonstrated strong antibacterial effects against Gram-positive bacteria such as *Streptococcus pyogenes* and *Staphylococcus aureus*, while showing variable sensitivity toward Gram-negative strains including *Klebsiella pneumoniae* and *Enterobacter aerogenes* (Chabuck *et al*., 2013) [5]. These results support the potential use of banana peel extracts as natural antimicrobial agents in food preservation and pharmaceutical formulations.

Anticancer Agent

Despite significant advancements in cancer therapy, conventional chemotherapeutic agents often exhibit non-selective cytotoxicity, resulting in severe side effects. Banana peel has recently attracted interest as a source of plant-derived anticancer compounds. Non-polar extracts, particularly hexane fractions of banana peel, have shown selective cytotoxicity against human cancer cell lines such as colon (HCT-116) and breast (MCF-7) cancer cells while exhibiting minimal toxicity toward normal cells (Nirmala & Murthy, 2023) [17]. Comprehensive reviews indicate that banana peel extracts and isolated phytoconstituents exert anticancer effects through mechanisms including induction of apoptosis, inhibition of cell proliferation, suppression of angiogenesis, and modulation of oncogenic signaling pathways (Sharma & Sharma, 2021; Nirmala & Murthy, 2023) [17]. These findings highlight the therapeutic potential of banana peel-derived bioactives as complementary agents in cancer prevention and treatment.

Antidiabetic Activity

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from impaired insulin secretion or action. Several studies have reported antidiabetic properties of banana plant parts, including peels (Zaini *et al*., 2022) [33]. Banana peel contains bioactive compounds such as flavonoids, catecholamines, and triterpenoids that contribute to glycemic control through antioxidant and enzyme inhibitory mechanisms. Lupenone, first identified in banana peel, has been reported to exhibit antidiabetic activity and may serve as a supportive agent in type 2 diabetes management (Hikal *et al*., 2022) [9]. Additionally, dopamine and L-DOPA (L-3,4-Dihydroxyphenylalanine) present in banana peel possess strong antioxidant properties, which help mitigate oxidative stress-associated diabetic complications (Kanazawa & Sakakibara, 2000) [11].

Anti-Fungal Activity

The necessity for natural substitutes is highlighted by the fact that synthetic antimicrobial medicines frequently fall short of offering broad-spectrum efficacy (Hikal *et al*., 2022) [9]. Because banana peels can suppress a variety of germs and fungi, they present a possible option, with bioactive substances such as tannins, alkaloids, saponins and flavonoids responsible for the antibacterial properties of banana peels (Chabuck *et al*., 2013) [5]. *Aspergillus niger, Aspergillus flavus, Penicillium digitatum, Fusarium oxysporum*, *Candida albicans*, *Saccharomyces cerevisiae* and *Penicillium citrinu*m are among the fungi against which banana peel extracts have demonstrated inhibitory effects (Chabuck *et al*., 2013; Hikal *et al*., 2022) [5, 9]. Their potential application as natural food preservatives is further supported by their efficacy against *Rhizopus stolon*ifer and *Aspergillus oryzae* (Chabuck *et al*., 2013) [5].

Wound Healing Activity

Complex cellular and molecular processes are involved in wound healing, which aims to repair injured tissue (Hikal *et al*., 2022) [9]. Numerous substances produced from plants have been demonstrated to support tissue healing and hemostasis, and flavonoids, saponins and tannins found in banana peels, especially those from Musa paradisiaca L. (Kepok banana), greatly aid in the healing of wounds (Hikal *et al*., 2022; Mohapatra *et al*., 2010) [9, 15]. Tannins cause capillary vessels to constrict, flavonoids improve capillary blood vessel function and saponins increase hemostasis by decreasing bleeding. One of the main phenolic compounds found in banana peels, gallocatechin, has potent antioxidant properties, and gallocatechin-rich extracts (106.6 µg/mL) from the peel of Musa spp. considerably shortened the time required for epithelialization, allowing wounds to heal in nine days, and increased the amount of hydroxyproline, a marker of improved collagen production (Hikal *et al*., 2022) [9].

Conclusion

Banana peel, an important agro-industrial by-product, is a rich source of bioactive compounds such as phenolics, flavonoids, dietary fiber, minerals, and antioxidants. Scientific evidence supports its antioxidant, antimicrobial, anti-inflammatory, and anticancer activities, highlighting its potential applications in food, pharmaceutical, and nutraceutical industries. Advances in processing and extraction technologies have improved the recovery and functional properties of banana peel–derived compounds, enabling their use in value-added products.

Utilization of banana peel in functional foods, biodegradable packaging, and phytomedicinal formulations offers a sustainable strategy for waste valorization. However, issues related to compositional variability, standardization, and limited *in-vivo* and clinical validation remain. Future research should emphasize process optimization, safety evaluation, and large-scale industrial applications. Overall, banana peel represents a cost-effective and sustainable resource with significant potential for functional food and nutraceutical development, contributing to circular economy and sustainable food systems.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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