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Banana (*Musa* spp.) as a functional source of bioactive compounds: Pharmaceutical relevance and perspectives

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Abstract

Banana fruits (*Musa* spp.) are among the most important tropical fruits worldwide, serving as a staple food and a major economic commodity across Asia, Africa, and Latin America. Beyond their nutritional value, banana fruits are rich in diverse bioactive compounds, including phenolic acids, flavonoids, carotenoids, catecholamines, and resistant starch, which contribute to their significant phytomedicinal potential. This review specifically focuses on the bioactive constituents present in banana fruits and examines their pharmacological properties and associated health benefits, such as antioxidant, anti-inflammatory, antidiabetic, cardioprotective, antimicrobial, and neuroprotective effects. Key challenges, including genotypic variability, inconsistency in phytochemical composition, post harvest degradation, and the limited availability of large scale human clinical studies, are critically discussed. The review further highlights recent advancements in extraction technologies and the development of functional foods and nutraceutical formulations aimed at enhancing the bioavailability and therapeutic efficacy of banana fruit bioactives. Emerging evidence suggests their promising role in managing metabolic syndromes, gastrointestinal disorders, and neurodegenerative diseases. Future research directions emphasize the development of improved banana genotypes, sustainable utilization of fruit derived by-products, and the application of advanced delivery systems. With continued scientific validation and clinical research, banana fruits hold substantial potential for expanded applications in therapeutic, nutraceutical and sustainable industrial sectors.

1. Introduction

Plant parts with soft succulent tissues are commonly eaten as fruits and are usually eaten fresh, being an essential component of human balanced diets all around the world. A large body of epidemiological evidence suggests that regular intake of fruits is negatively linked to the incidence of chronic degenerative diseases (Woodside *et al.,* 2023). This protective effect has been largely explained by their high content of vitamins, easily digestible carbohydrates, dietary fiber and a wide spectrum of bioactive phytochemicals, especially phenolic compounds (Cosme *et al.,* 2022). Comprehensive evaluations of worldwide dietary recommendations just further demonstrate this relationship, with each extra 100 g intake of fruit per day linked to a 5-8% decrease in cardiovascular mortality, representing the disease-preventive potential of fruits (Afshin *et al.,* 2019).

Among the fruit crops, bananas (*Musa* spp.) are occupying a special place, due to their availability, price and deep cultural relevance across the globe. Although, they are more similar to woody trees, bananas are actually large perennial herbs that are members of the family Musaceae of the order Zingiberales. This botanical classification reflects the fast growth cycle, herbaceous pseudostem, and unique reproductive biology of these plants (Singh *et al.,* 2020). Banana thrives well in the tropical regions with warm climate. The genus *Musa* has a very important role as a primary source of food and an economic commodity for millions of people in tropical and subtropical areas. However, there is a significant gap between the high level of consumption of the banana fruit and the relatively few

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applications explored in the exploitation of the rich and diverse phytochemical constituents of banana fruit in nutritional and medicinal applications (Afzal *et al.,* 2020). Phylogenomic and metabolomic studies have shown incredible genetic and biochemical diversity in the *Musa* genus that includes more than 70 species and many cultivars that are edible and have been obtained mainly from *M. acuminata* (A genome) and *M. balbisiana* (B genome), which occur in several ploidy forms such as AA, AAA, AAB and ABB (Suvittawat *et al.,* 2025).

A defining feature that makes bananas different from many other fruits is that they undergo a process of climacteric ripening, which involves extensive metabolic reorganization. During the process of ripening profound biochemical changes take place, among which are breaking down of starch to soluble sugars, breaking of organic acids, cell wall reorganization and dynamic fluctuations of phenolics, carotenoids, and biogenic amines. These transformations lead to ripeness-dependent changes in nutritional composition and bioactivity (Li *et al.,* 2025).

This biochemical adaptability makes banana a powerful example for tailored dietary interventions, with unique cultivars and ripeness conditions being paired with different health objectives, for example regulation of blood sugar levels, promotion of digestive health, reduction of cardiovascular risk or increase of cognitive function (Afshin *et al.,* 2019; Suvittawat *et al.,* 2025). Most notably, the most important commercial varieties (such as the Cavendish cultivar) are indigenous and underutilized bananas in the world, including plantains and cooking banana AAB and ABB genome varieties, are more abundant in resistant starch, phenolics, carotenoids, and stress-associated metabolites and are understudied in the nutritional and pharmacological fields (Burkhart *et al.,* 2022).

Advances in analytical methods and metabolomic profiling have also enriched the known information of banana's phytochemistry by identifying specialized metabolites including phenylphenalenones, unique flavonoid glycosides and other low molecular-weight compounds with known pharmacological activities (Krishnamurthy *et al.,* 2023). Experimental and clinical evidence consistently show that compounds from the banana fruit have a broad spectrum of biological effects such as antioxidant, anti-inflammatory, antidiabetic, gastroprotective and cardioprotective effects (Afzal *et al.,* 2022). Emerging research also pointed out neuroprotective, anticancer and immunomodulatory properties, broadening the potential uses of bananas in a trajectory that moves them outside of traditional nutritional functions (Mathew and Negi 2017; Oyeyinka and Afolayan, 2022).

However, despite these advances, a comprehensive and integrated synthesis of the bioactive compounds specifically present in banana fruits and their associated health benefits remains limited. Variability in phytochemical composition across cultivars and differences arising from ripening stages have been widely reported (Suvittawat *et al.,* 2025; Li *et al.,* 2025), while the underutilization of indigenous banana varieties has also been highlighted in recent studies (Burkhart *et al.,* 2022). These factors collectively emphasize the need for a systematic evaluation. Therefore, this review aims to critically compile and analyze the current knowledge on banana fruit bioactive compounds, their pharmacological properties, and potential health benefits, while also addressing existing challenges and future research directions for their effective utilization in functional foods and nutraceutical applications.

2. Nutritional value of banana

Compounds with nutritional importance found in bananas demonstrate their rich and diverse nutritional content, including vitamins, organic acids, and minerals (Figure 1). These contribute to essential bodily functions such as energy metabolism, immune support, nerve function, and the maintenance of healthy blood pressure.

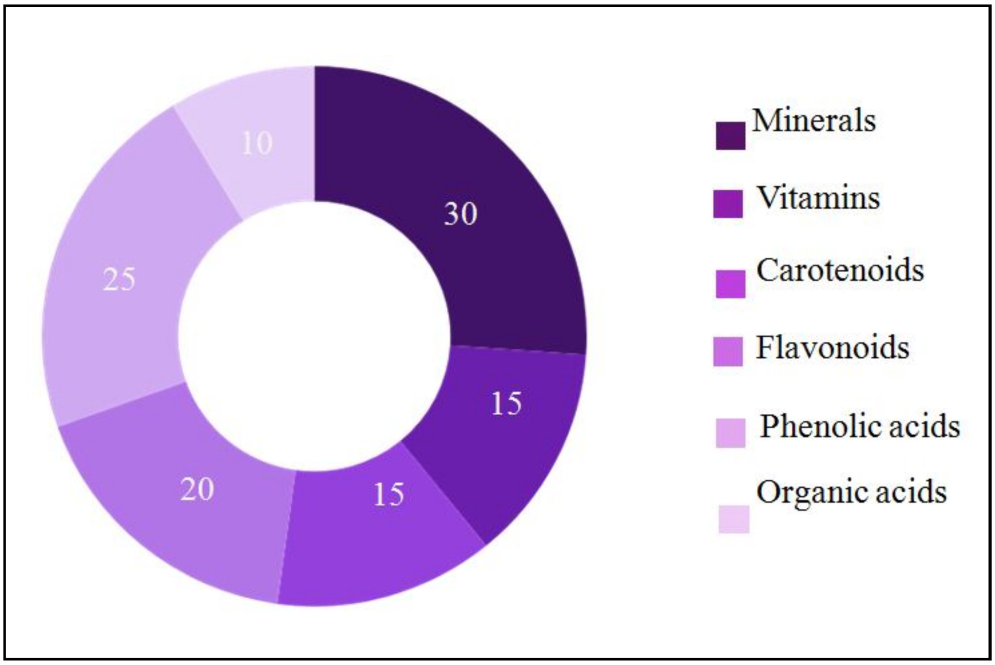


Figure 1: Distribution of major nutritionally important compounds in banana fruit.

2.1 Vitamins

Vitamins present in bananas are important for good health, with vitamin B6 (pyridoxine) found in high amounts. The concentration of this vitamin ranges from 0.38 to 0.42 mg per 100 g of the edible portion of bananas, and it plays a key role in physiological processes such as amino acid synthesis, neurotransmitter production, and cognitive development (Mounika *et al.,* 2025).

The vitamin B6 content varies little across the variously grown dessert banana varieties, such as Cavendish and Lady finger, which implies a low genetic diversity of within variety for this nutrient (Akech *et al.,* 2024). Bananas are a good source of vitamin C, typically delivering moderate concentrations of this nutrient ranging from 8 to 15 mg/100 g depending on the variety. Bananas are also a rich source of folates (Vitamin B9) that contain about 20 mcg per 100 g and smaller amounts of provitamin A carotenoids especially beta carotene (when ripe) along with some of the B complex vitamins such as riboflavin and niacin (Tan *et al.,* 2024).

2.2 Minerals

Bananas are well recognized for their high mineral content especially potassium which is normally between 350-400 mg per 100 g of fresh pulp and plays a vital role in maintaining electrolyte balance facilitating the neuromuscular activities and promoting cardiovascular health (Palma *et al.,* 2022). Plantain cultivars, for example, *M. paradisiaca*, can have higher potassium contents of 15% than that found in dessert bananas, thereby showing huge cultivar dependent variations of mineral contents (Oyeyinka and Afolayan 2020), There are also substantial amounts of magnesium in bananas about 25 to 30 mg per 100 g, which is an essential ingredient in many enzymatic reactions. Discarded banana peels contain high quantities of minerals like iron (around 0.8 mg per 100 g) and zinc (around 0.2 mg per 100 g) as implied in the potential use of these peels in food as well as supplement-related products (Khan *et al.,* 2025). The minor minerals present include phosphorus, calcium, iron and zinc with their combined mineral composition being affected by soil characteristics, type of cultivar and the stage of fruit maturity as summarised in Table 1.

Table 1: Mineral composition of various cultivars of banana

Nutrient	Cultivars	Plant part	Concentration (mg/100 g FW)	Ripeness Stage	References
	Gros Michel (AAA)	Peel	450	Ripe	Rosa *et al.,* 2020
Potassium (K)	French Horn (AAB)	Pseudostem sap	240	Unripe	Islam *et al.,* 2023
	Poovan (AAB)	Male flower	420	Unripe	Das *et al.,* 2021
	Silk fig (AAB)	Bract	120	Ripe	Arunachalam *et al.,* 2020
	Lady finger (AA)	Inflorescence	330	Unripe (cooked)	Rosa *et al.,* 2020
Magnesium (Mg)	Plantain (AAB)	Male flower	35	Unripe	
	Plantain (AAB)	Peel	25	Unripe	Uzairu and Kano, 2021
	Saba (ABB)	Rachis	12	Unripe	Sahadi and Basri, 2025
	Red Banana (AAA)	Inflorescence	45	Ripe	Rosa *et al.,* 2020
Calcium (Ca)	Cavendish (AAA)	Peel	5	Ripe	Keivani Rad *et al.,* 2020
	Plantain (AAB)	Male flower	7	Unripe	Gómez et al., 2021
	Lady finger (AA)	Bract	6	Ripe	Rosa *et al.,* 2020

2.3 Organic acids

Ripening of fruit of banana (*Musa* spp.) is accompanied by significant changes in its organic acid content, which have a significant influence on its sensory characteristics and impact overall metabolic quality. Malic acid is dominant at the unripe stage, and it is the cause of the characteristic sour taste of green bananas. As the ripening continues, the concentration of malic acid decreases while citric acid increases to become the major organic acid when the fruit is fully mature, almost tripling from the mature green to the fully yellow phase, such that its concentration reaches about 0.5 g per 100 g of fresh weight (Zhang *et al.,* 2023). Addition to these major acids, there are smaller proportions of oxalic, succinic and tartaric acids, depending on the different cultivars as well as their ripening stage as given in Table 2, Although bananas contain appreciable levels of organic acids that contribute to overall fruit quality (Polat *et al.,* 2025), total titratable acidity goes down generally during the process of ripening due to the concomitant breakdown process of the starch and accumulation of the soluble sugars. Organic acids like malic and citric acids have been proven to enhance the preservative properties and flavor profile of banana based processed products and thereby increasing the product stability and consumer acceptability (Watharkar *et al.,* 2020).

Table 2: Organic acid composition of dessert and plantain bananas at various maturity stages

Organic acid	Concentration range	Physiological effect	References
Malic acid	Highest, major contributor	Tart flavor, substrate for respiration, enhances chilling tolerance during storage	Huang *et al.,* 2016
Citric acid	Moderate	Sour taste, pH regulation, antioxidant activity	Maduwanthi and Marapana, 2019
Oxalic acid	Low	Calcium binding, forms insoluble oxalate crystals	
Succinic acid	Trace	Krebs cycle metabolite	

3. Phytochemical profile of banana

Bananas contain a wide range of phytochemicals that contribute to their health-promoting properties. The major bioactive compounds present in banana tissues include various classes of phenolics. The phenolic composition identified in different biological parts of banana cultivars is summarized in Table 3. These compounds mainly comprise phenolic acids such as gallic acid, ferulic acid, and caffeic acid, flavonoids including catechins, myricetin and quercetin derivatives. These phytochemicals responsible for antioxidant, anti-inflammatory and antibacterial activity has also been attributed to these phytochemicals (Bashmil *et al.,* 2024).

Table 3: Phenolic components were identified in specific biological parts of banana cultivars

Variety	Biological part analyzed	Analytical method	Key phenolic compounds identified	References
Cavendish (AAA)	Whole green banana	*In vitro* digestion and colonic fermentation	Phenolic compounds with high bioaccessibility, kaempferol detectable after fermentation	Bashmil *et al.,* 2024
Lady finger (AA)	Whole green banana		Highest resistant starch (49%), significant total phenolic content (2.32 mg GAE/g)	de Sousa *et al.,* 2025
Ducasse (ABB)	Whole green banana		Highest dietary fiber concentration (38.73%)	
Dwarf Prata (AAB)	Inflorescences	Steam distillation, Soxhlet extraction (water, ethanol, 2-MeTHF), Supercritical fluid extraction (SFE)	Highest total phenolic content (water extract), highest total flavonoid contentreported (32.1 mg CE/g)	

GAE : Gallic acid equivalents, DW: Dry weight, FW: Fresh weight, C3GE: Cyanidin-3-glucoside equivalents

3.1 Polyphenol

Naturally occurring bioactive compounds include polyphenols, which are among the most extremely distributed secondary metabolites in the plant kingdom. Polyphenols are closely related to physical and structural properties of foods. Fruits, vegetables, whole grains and beverages, such as tea, chocolate and wine, are known to be rich dietary sources of polyphenols. These compounds function as antioxidants by enhancing the activity of antioxidant vitamins and enzymes, thereby helping to counteract the damage caused by excessive reactive oxygen species (Bhavani *et al.,* 2023). Polyphenols are characterised based on their origin, biological function and their chemical structure, with different polyphenol subgroups possessing different physiological functions, level of bioavailability and stability. Banans represent an important source of the polyphenols, among which several phenolic acids and flavonoids. The concentration of bioactive compounds in the banana peel is higher, such as ferulic and flavonol glycosides, compared to those in the pulp, partly contributes to its fruit's antioxidant and antidiabetic effects (Tongkaew *et al.,* 2022).

3.2 Phenolic acids

Phenolic acids are a large group of bioactive compounds found in banana fruit and are broadly classified into two types: hydroxybenzoic acids (*i.e.*, gallic, protocatechuic, vanillic, and syringic acids) and hydroxycinnamic acids (*i.e.*, ferulic, chlorogenic, caffeic and *p*-coumaric acids) (Kritsi *et al.,* 2023). Among these, ferulic acid has been reported as a major phenolic acid in several *Musa acuminata* cultivars (Borges *et al.,* 2020). Phenolic acid profiles vary depending on cultivar, tissue type and ripeness; banana peel contains higher phenolic content than pulp and phenolic composition changes significantly during ripening (Borges *et al.,* 2020). Environmental factors such as soil, altitude, and postharvest handling further influence phenolic composition and extractability (Bashmil *et al.,* 2024). Banana phenolic acids exhibit strong antioxidant, anti-inflammatory, antidiabetic, and antimicrobial activities, including enzyme inhibition and modulation of inflammatory pathways such as NF-κB (Sarma *et al.,* 2021). The development of more advanced analytical methods and extraction techniques, especially environmentally sustainable methods such as ultrasound-assisted deep eutectic solvents, has led to improving the accurate quantification of banana phenolics and improving the bioaccessibility of phenolics (Cegledi *et al*., 2024). Table 4 depicts the bioactive components lurking in different parts of various banana varieties.

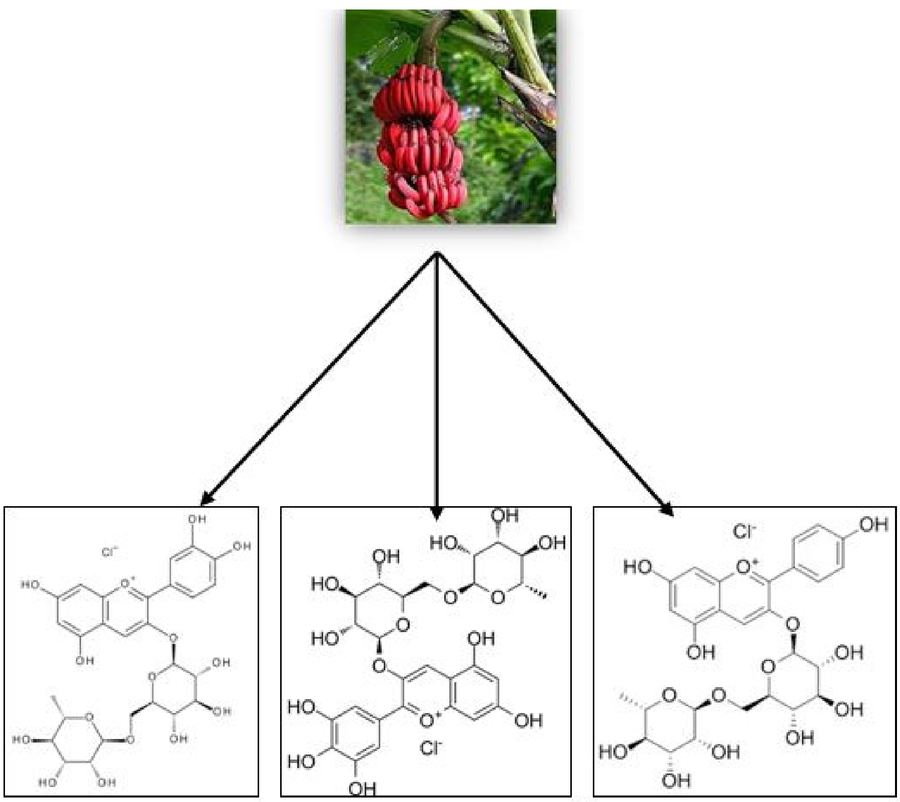
3.3 Flavonoids

Banana flavonoids are characterized structurally by a C_6-$C_{3-}C_6$ polyphenolic frame and play a central role in the biofunctional characteristics of the fruit (Borges *et al.,* 2020). They have strong antioxidant, anti-inflammatory, antimicrobial, antidiabetic and cardioprotective activity. Major flavonoids found in banana include catechin, epicatechin, rutin, isoquercitrin, myricetin and kaempferol derivatives (Afzal *et al.,* 2022). Flavonoids concentrations are much higher in the peel (usually 5-10-fold higher than those of the pulp), as well as in different cultivars, tissue and maturation stages (Borges *et al*., 2020). Rutin and isoquercitrin have been specifically shown to be linked with β-glucosidase inhibition and glycemic regulation (Sarma *et al.,* 2021). Flavonoid biosynthesis is controlled by the phenylpropanoid biosynthesis, mainly phenylalanine ammonia-lyase (PAL) and chalcone synthase (CHS), depending on genotype and acting in environmental conditions (Davies *et al.,* 2020). Functionally, banana flavonoids act as effective reactive oxygen species scavengers, inhibit carbohydrate hydrolyzing enzymes such as α-amylase and α-glucosidase, modulate inflammatory signaling pathways including NF-κB, MAPK, and Nrf2, and exhibit antimicrobial effects such as membrane disruption and biofilm inhibition (Maduwanthi and Marapana, 2019; Vu *et al.,* 2018).

Table 4: Comparative bioactive compound profiles of major banana varieties

Variety / cultivar	Genome group	Bioactive class	Highest reported concentration	Plant part analyzed	References
Cavendish (Grand Nain, Robusta)	AAA	Phenols	400-600 mg GAE/100 g DW	Peel	Bashmil *et al.,* 2024
Cavendish (Grand Nain, Robusta)	AAA	Flavonoids	120-180 mg QE/100 g DW	Peel	
Saba	ABB	Phenols	850-1200 mg GAE/100 g DW	Peel	Reginio *et al.,* 2020
Saba	ABB	Flavonoids	250-350 mg QE/100 g DW	Peel	
Pisang Awak	ABB	Phenols	1000-1500 mg GAE/100 g DW	Peel	Ha *et al*., 2023
Red Banana	AAA	Anthocyanins	2-5 mg C3GE/100 g FW	Peel/pulp	
Red Banana	AAA	Phenols	900 mg GAE/100 g DW	Peel	Oyeyinka and Afolayan, 2020
Pisang Raja	AAB	Carotenoids	350-500 µg/100 g FW	Pulp	Suvittawat *et al.,* 2025
Karpuravalli	ABB	Phenols	1000-1400 mg GAE/100 g DW	Peel	Ha *et al.,* 2023
Malbhog	AAB	Phenols	42.38 mg GAE/100 g (bread enrichment)	Peel powder	
Malbhog	AAB	Flavonoids	9.46 mg QE/g (bread enrichment)	Peel powder	Akhter *et al.,* 2024
Kluai Nam Wa Pakchong 50	ABB	Phenols	High levels (ripe pulp)	Pulp	Suvittawat *et al.,* 2025
Kluai Pakchong KU 46	AAA	â-carotene	High levels (ripe pulp)	Pulp	

GAE: Gallic acid equivalents, QE: Quercetin equivalents, C3GE : Cyanidin-3-glucoside equivalents, DW: Dry weight, FW: Fresh weight



Cyanidin-3-rutinoside Delphinidin-3- rutinoside Pelargonidin-3-rutinoside

Banana variety	Plant part analyzed	Major anthocyanin
Red Dacca	Peel and pulp	Cyanidin-3-rutinoside
Musa paradisiaca	Peel and bracts	Delphinidin-3-rutinoside
Musa sapientum	Peel and flower bracts	Pelargonidin-3-rutinoside

Figure 2: Occurrence and molecular structure of the major anthocyanin present in bananas.

3.4 Anthocyanins

Anthocyanins are water-soluble flavonoids which give red, purple and blue color and can be found primarily in red banana cultivars such as *Musa paradisiaca* and *Musa sapientum* especially in peels, bracts and flowers and not in pulp (Senevirathna, 2025). Cyanidin-3-rutinoside is the main anthocyanin, contributing to the almost 80% of the total anthocyanins in 'Red Dacca' pulp together with delphinidin-, pelargonidin-, peonidin- and malvidin-3-rutinosides (Thakur *et al.,* 2026) (Figure 2). It is especially known for bracts and peels, as well as pigments which are more concentrated than the pulp, and that efficient extraction *via* the use of acidified solvents and ultrasonic processes (Sarma *et al.,* 2021). Anthocyanin biosynthesis is controlled by R2R3-MYB transcription factors forming MBW complexes that activate structural genes that opens up potential for genetic biofortification (Busche *et al.,* 2023). These compounds have high antioxidant, antimicrobial and anticancer activity and have the potential for use as natural food colorants and nutraceutical ingredients. However, their stability is affected by pH, light and temperature which requires stabilization mechanisms such as microencapsulation for better functional uses (Tarone *et al.,* 2020).

3.5 Carotenoids

Carotenoids contents in banana are made up of mainly provitamin A compounds including beta carotene, alpha carotene, beta cryptoxanthin, lutein, zeaxanthin and are distributed mostly in the pulp and peel of some cultivars including Fe_3, asupina and plantain (Netshiheni *et al.,* 2020). β-carotene and α-carotene compounds constitute almost 50-70% of total carotenoids compounds and increase significantly during ripening as a result of the upregulation of key biosynthesis genes including phytoenone synthase (PSY). Marked genotype-dependent variation exists with yellow to orange-fleshed Fe^{2+} bananas having extraordinarily high provitamin A content up to 1412 µg per 100 g FW (Netlak *et al.,* 2023) (Figure 3).

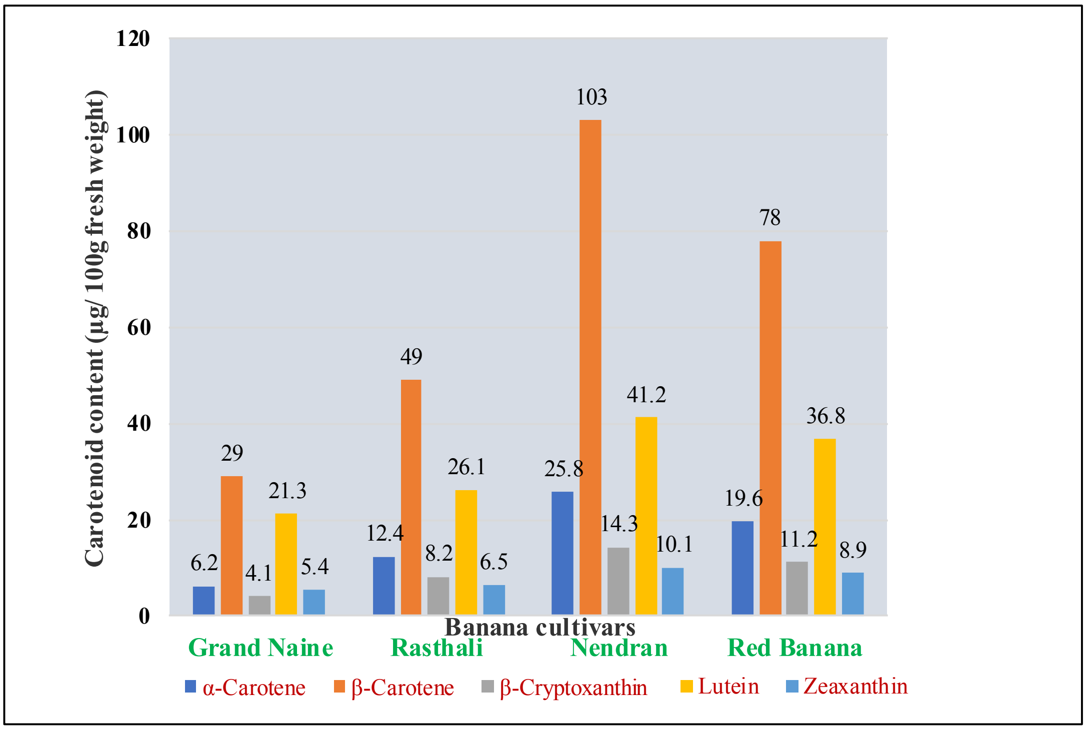


Figure 3: Variation in major carotenoids among banana cultivars.

4. Extraction methods and bioavailability of phytochemicals in banana

Phytochemicals, including dopamine, phenolic acids, flavonoids (such as catechins) and carotenoids, are abundant in bananas (*Musa* spp.), especially in the peel and can be extracted using various methods (Vu *et al.,* 2018). The yield, purity and the final bioavailability of these bioactive chemicals depends highly on the extraction method used which is explained in Figure 4, whereas the feasible extraction techniques are explained in Table 5 with comparison of the extraction efficiency of the developed approach. Enzyme-assisted extraction is for example particularly efficient at yielding bound phenolic compounds, which represents a major tribute in bananas (Islam *et al.,* 2023). While ultrasound-assisted extraction gives reinforcement of phenolics antioxidants due to intensive cell wall disruption (Chen *et al.,* 2024). Supercritical fluid extraction with carbon dioxide is reported to be ideal for the extraction of high purity, solvent-free extracts of heat sensitive carotenoids from banana peel (Bello *et al.,* 2023). These varying factors must emphasize the selection of proper extraction technologies. These conventional extraction technologies, advanced extraction technologies, or hybrid extraction technologies depending upon the selectivity in the phenological class and end type of application since this will influence compound stability, compound recovery efficiency and functional performance (Soni *et al.,* 2025).

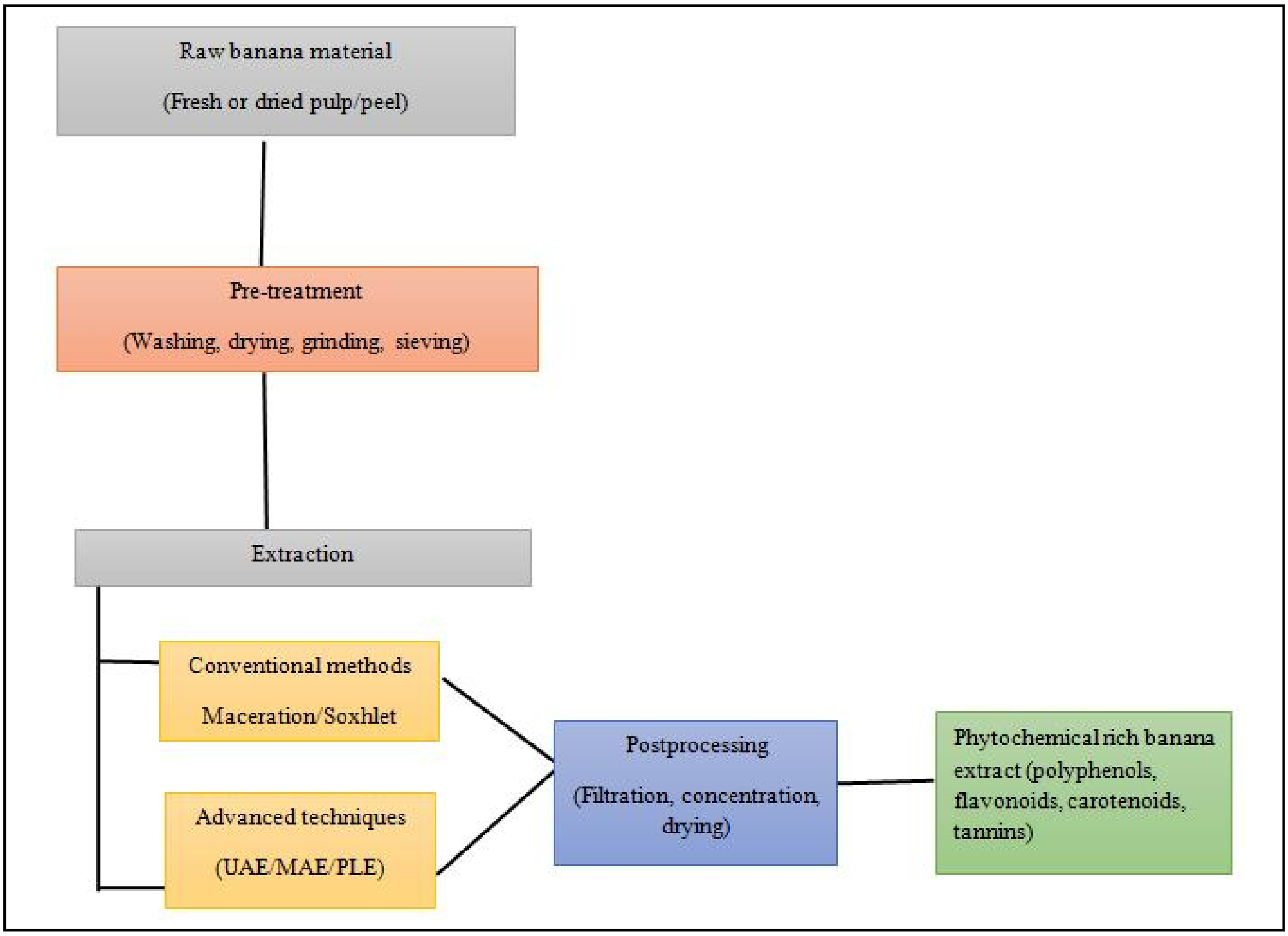


Figure 4: Extraction of phytochemicals from banana.

Table 5: Extraction techniques for phytochemicals in banana

Extraction technique	Principle and process	Target phytochemicals	References
Ultrasound-assisted extraction (UAE)	Ultrasonic cavitation disrupts cell walls, enhancing solvent penetration and compound release	Phenolic acids, flavonoids, anthocyanins (peel)	Granella *et al*., 2023
Microwave-assisted extraction (MAE)	Microwave heating causes rapid cell rupture and release of intracellular compounds	Polyphenols, pectin	Roselli *et al.,* 2024
Supercritical fluid extraction (SFE)	Supercritical CO_2 under controlled pressure and temperature extracts bioactives	Carotenoids, tocopherols, lipophilic antioxidants	Bello *et al.,* 2023
Enzyme-assisted extraction (EAE)	Enzymatic hydrolysis degrades cell wall polysaccharides to release bound compounds	Bound phenolics, pectin	Islam *et al.,* 2023
Pressurized liquid extraction (PLE)	Elevated temperature and pressure enhance solvent efficiency	Polyphenols, flavonoids	Roselli *et al.,* 2024

5. Pharmacological properties

Numerous phytomedicinal advantages, including antioxidant, anti-inflammatory, antidiabetic, cardioprotective, gastroprotective, immunomodulatory, neuroprotective and antibacterial properties, are imparted by the numerous bioactive chemicals found in bananas (*Musa* spp.). These health promoting qualities are primarily attributed to phenolic acids, flavonoids, dopamine, catechins, carotenoids, phytosterols, resistant starch, dietary fiber, vitamins, vital minerals such as potassium and magnesium and organic acids present in both pulp and peel (Bashmil *et al.,* 2024). According to recent studies, dietary fiber and banana polyphenols play an important role in scavenging free radicals, regulating lipid and carbohydrate metabolism, improving gut microbiota composition and reducing the risk of metabolic and cardiovascular diseases (Ferrari, 2023). Furthermore, the concentration and bioactivity of these phytochemicals are greatly affected by environmental factors especially during their cultivation because of their biological biosynthesis and accumulation by the environmental factors. Major environmental factors affecting phytochemical composition in banana are summarized in Table 6.

Table 6: Environmental factors influencing phytochemical composition in banana

Environmental factor	Effect on bioactive compounds	Mechanism of influence	Optimal conditions	Industrial implications	References
Temperature	Increases phenolics under mild stress, heat degrades vitamin C and carotenoids	Cold stimulates antioxidant synthesis, heat accelerates degradation	25-30°C (day), 13-15°C storage	Requires efficient cold chain management to preserve quality	Xiao *et al.*, 2023
Sunlight exposure	Increases phenolics and flavonoids	Activates phenylpropanoid pathway (PAL)	Moderate-high sunlight	Peel is useful for nutraceutical extraction	Chen *et al.*, 2022
Soil composition and nutrition	Balanced nutrition increases carotenoids, excess N lowers phenolics	Micronutrients act as cofactors, stress induces phenolics	pH 5.5- 6.5, balanced fertilization	Supports biofortification	Orr *et al.*, 2023
Irrigation practices	Mild stress increases phenolics, severe drought reduces content	ABA and ROS activate antioxidant pathways	Controlled deficit irrigation	Premium "stress-enhanced" produce	Bello *et al.,* 2023
Postharvest storage	Controlled atmosphere preserves phenolics and vitamin C	Low O_2 reduces respiration	13-15°C, 90-95% RH	MAP and CA storage innovation	Ren *et al.,* 2024

5.1 Antioxidant activity

Bananas have a potent antioxidant activity, which is achieved through a number of processes such as metal chelation, the inhibition of enzymes, and the scavenging of free radicals. Reactive oxygen species (ROS), including DPPH, superoxide, and hydroxyl radicals, are efficiently neutralized by phenolic constituents, such as gallic acid and catechin, and catecholamines, such as dopamine (Chiang *et al.,* 2020). Additionally, the fruit's constituents exhibit the ability to chelate pro-oxidant metal ions, especially ferrous (Fe^{2+}) and cuprous ($Cu+$) ions, which aids in preventing the initiation of oxidative damage caused by the Fenton reaction (Mohamed *et al.*, 2020). This metal chelating capacity is strongly correlated with the total phenolic content of the extract. Furthermore, banana extracts have demonstrated inhibitory effects on important prooxidant enzymes that support the body's general antioxidant defense system. For instance, peel extracts rich in flavonoids have been shown to inhibit xanthine oxidase, a key enzyme in uric acid and superoxide radical production, and lipoxygenase, an enzyme involved in inflammatory lipid peroxidation (Widoyanti *et al.,* 2023).

5.2 Anti-inflammatory activity

Bananas have strong anti-inflammatory effects with the primary modes of action being the modulation of cytokine production and the inhibition of key pro-inflammatory enzymes. The activity of the inducible cyclooxygenase-2 (COX-2) and 5-lipoxygenase (5-LOX), the enzymes involved in the biosynthesis of the inflammatory prostaglandins and leukotrienes, respectively, have been inhibited by extracts of various cultivars of bananas, particularly from peels and pulp (Hong *et al.,* 2023). This dual inhibition of the arachidonic acid pathway is signature of potent anti-inflammatory agents of natural origin. Additionally, bioactive substances contained in bananas such as flavonoids and phenolic acids reduce the formation and signaling cascade of inflammation by inhibiting the formation and release of key pro-inflammatory cytokines, such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-alpha) (Sandjo *et al.,* 2019). This cytokine suppression is mediated, in part, through the inhibition of the nuclear factor-kappa B (NF-κB) signaling pathway, a primary regulator of inflammatory gene expression (Rangra *et al.,* 2025). The medicinal potential of the fruit in the fight against diseases associated with inflammation is justified by its dual mechanism of action at both the enzymatic pathway and cytokines mediators.

5.3 Antidiabetic activity

Bananas have significant antidiabetic effects through various complementary mechanisms. Their rich content of bioactive compounds especially flavonoids (*e.g.* quercetin) and phenolic acids effectively inhibits intestinal enzymes alpha glucosidase and alpha amylases, leading to a slowing down of carbohydrate digestion, and less-importantly, to a reduction in postprandial hyperglycemia (Maduwanthi and Marapana, 2019). In addition, some phytochemicals and resistant starch naturally found in bananas are responsible for improving peripheral insulin sensitivity by influencing the activity of important proteins involved in the signaling mechanism AMP-activated protein kinase (AMPK) and phosphatidylinositol 3-kinase (PI3K) to improve glucose uptake by cells (Yang *et al.,* 2020). The fermentation of resistant starch by gut microbiota also gives rise to the production of short-chain fatty acids, in particular butyrate and propionate, which promote metabolic function in the general population, enhance the insulin system, and have an anti-inflammatory effect in adipose tissue (Dibakoane *et al.,* 2022). Together with its prebiotic action, which promotes a better state of the intestinal microbiome, resistant starch is a multifaceted strategy for better glycemic control.

5.4 Antiobesity activity

Bananas have a lot of potential in reducing obesity through mechanisms that are focused on its high resistant starch and fiber content. Bioactive compounds but especially polyphenols contained in the banana peel extracts can inhibit the activity of pancreatic lipase, an enzyme essential for the digestion of fats, which subsequently reduces its absorption from the diet (Bagabaldo *et al.,* 2023). The resistant starch component is instrumental in the studies responsible for improving the sensation of satiety, increasing gastric volume, reducing caloric intake and having a positive effect on lipid metabolism. Acting as prebiotic, this starch will be fermented in the colon producing short-chain fatty acids (SCFAs), such as butyrate and propionate. These metabolites exert an anabolic effect by strengthening the intestinal barrier and stimulating the secretion of anorexigenic hormones like glucagon-like peptide-1 (GLP-1) and peptide YY (PYY) which have an inhibitory effect on the thirst mechanism (Chen *et al.,* 2024). Additionally, SCFAs aid in activating metabolic pathways such as the AMP kinase signalling in the peripheral tissues resulting in fat burning and curtailing the storage of fats in fat cells, all advocating for weight management and positive metabolic functions (Chen *et al.,* 2024).

5.5 Anticancer mechanisms

Bioactive substances such as polyphenols (such as ferulic acid and gallic acid) and lectins can fully activate the endogenous apoptosis pathway in malignant cells by the up-regulation of pro-apoptotic proteins (such as Bax) and down regulation of anti-apoptotic Bcl-2 (such as the down-regulation of anti-apoptotic proteins). Furthermore, these substances, particularly polyphenolic extracts from banana pulp, can inhibit cancer cell proliferation by inducing cell cycle arrest at the G2/M or S phases, thereby suppressing tumour cell growth (Srinivas *et al.,* 2021). Additionally, including by interfering with the signalling pathway of the hormone (VEGF), which is crucial for the development of new tumour-feeding blood vessels, several of the ingredients of bananas have shown substantial anti-angiogenic activity, thus reducing tumour growth and metastasis potential (Raj *et al.,* 2017; Srinivas *et al.,* 2021).

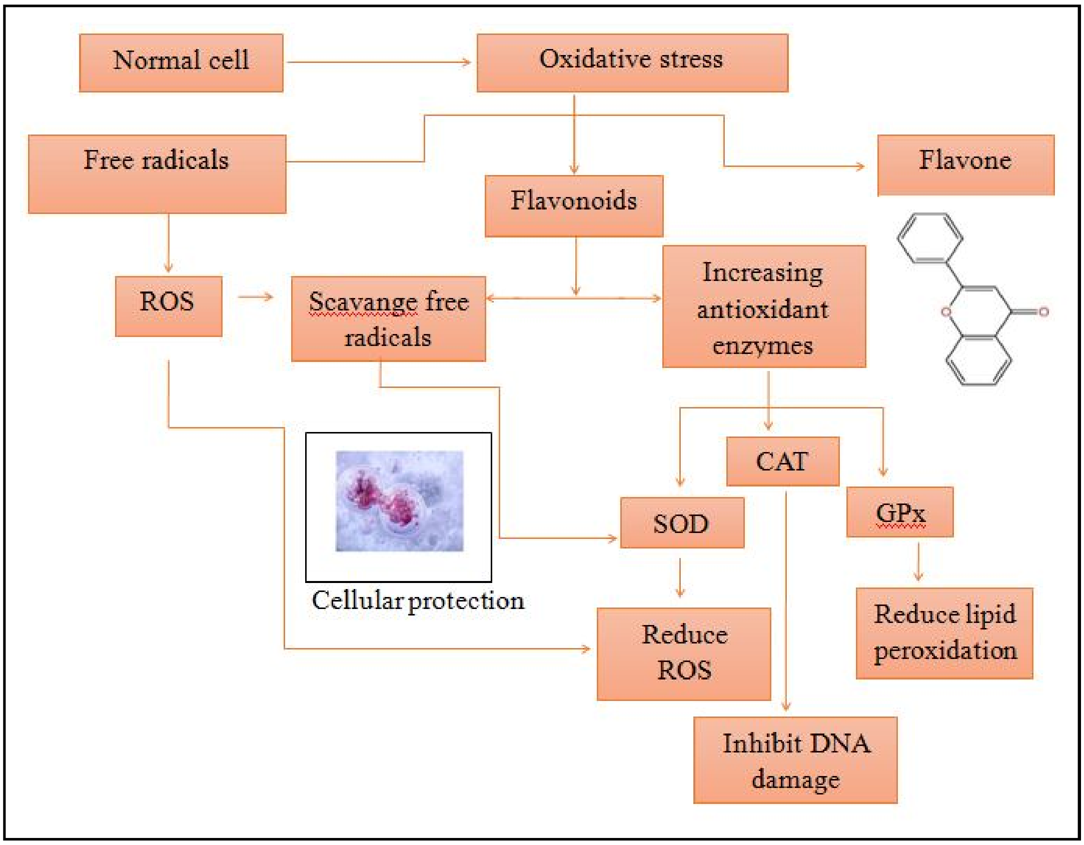


Figure 5: Mechanism of flavonoids as antimicrobial activity

5.6 Neuroprotective activity

The neuroprotective property of bananas has been associated with their unique biochemistry. A major contributor has been the notable concentration of dopamine and related catecholamines, which are considered important neurotransmitters and powerful endogenous antioxidants inside the brain that directly jumpstart the oxidative stress inside the neuronal or brain cells (Muhammad Ansari *et al.,* 2023). This activity is supported by the rich profile of antioxidant compound phenolics in the fruit in the form of gallic and ferulic acid, both of which offer a powerful free radical scavenging capacity (Bashmil *et al.,* 2021). Experimental studies in neurodegenerative disorders models such as Parkinson's disease and Alzheimer's disease have shown that the extracts from bananas exert the neuroprotective effects through antioxidant effects, inhibition of lipid peroxidation and attenuation of neuroinflammation and help preserve cognitive and motor function **(**Sun *et al.* 2021).

6. Clinical evidence and human trials on banana

Bananas (*Musa* spp.) have attracted considerable clinical interest owing to their diverse bioactive compounds, including resistant starch, phenolics, fructooligosaccharides, dopamine, and potassium, with clinical and human trials evaluating their therapeutic potential summarized in Table 7.

6.1 Resistant starch and glycemic control

Human intervention studies have identified a role of green banana biomass with resistant starch in enhancing postprandial glycemic overload and insulin sensitivity. Clinical trials show that green banana flour supplementation can significantly decrease blood glucose and HbA1c levels in people with type 2 diabetes and prediabetes with its properties as a functional prebiotic that regulates the release of hormones by the gut. The fermentation of this resistant starch by the gut microbiota produces shortchain fatty acids (SCFAs) such as butyrate that is directly associated with an improvement in metabolic markers (Munir *et al.,* 2024; Rammohan *et al.,* 2025).

6.2 Phenolic compounds and cardiovascular health

Randomized controlled trials have examined the acute and chronic impact of nutrients of banana flavonoids and phenolic acids on cardiovascular risk factors. A crossover study found that the consumption of a fruit daily phenolic-rich banana smoothie (e.g., Morado) over a 4-week period in hypertensive adults resulted in a significant decrease in systolic blood pressure and an improvement in endothelial function, more so than a matched control beverage. These effects were attributed to enhanced nitric oxide bioavailability and a decrease in systemic oxidative stress (Ottaviani *et al.*, 2023).

6.3 Gastroprotective and gut health effects

Human intervention studies have shown that green banana biomass containing high contents provide resistant starches improves glycemic control after meals and insulin sensitivity. Green banana flour has also shown prebiotic activity by mediating the changes of the gut microbiota and increasing the production of short-chain fatty acids also known as SCFAs, which are correlates to positive metabolic health effects (Baptista *et al*., 2024; Viana *et al*., 2025).

6.4 Antioxidant and anti-inflammatory markers

Human studies and experimental evidence using biomarker assessments confirm the bioactivity of antioxidant and anti-inflammatory properties of bioactive compounds from bananas. Banana polyphenols have been shown to lower the level of oxidative stress and inflammatory markers such as malondialdehyde (MDA) and interleukin-6 (IL-6) due to the modulation of antioxidant defense systems and the inflammatory system (Liao *et al.,* 2024; Bashmil *et al.,* 2024; Hong *et al.,* 2023; Al Mamun *et al.,* 2024).

Table 7: Clinical implications of banana bioactives in human health

Clinical condition	Mode of administration	Dosage & duration	Mechanism of action	References
Type 2 diabetes mellitus /prediabetes	Oral-green banana flour capsules/supplement	20-40 g/day for 8-12 weeks	Production of short-chain fatty acids enhances insulin sensitivity and increases glucagon-like peptide-1 secretion	Munir *et al.,* 2024
Metabolic syndrome/ postprandial glycaemia	Oral-green banana biomass	25 g/day for 6 weeks	Modulation of gut microbiota reduces hepatic glucose output and delays gastric emptying	Rammohan *et al.,* 2025
Hypertension/Endothelial dysfunction	Oral-Phenolic-rich smoothie	300 ml/day for 4 weeks	Increased nitric oxide bioavailability improves endothelial function and promotes vasodilation	Ottaviani *et al.,* 2023
Gut dysbiosis/Inflammatory bowel conditions	Oral-green banana flour	15-30 g/day for 8 weeks	Enhancement of beneficial gut microbiota and butyrate production attenuates intestinal inflammation	Baptista *et al.,* 2024
Oxidative stress/ Chronic inflammation	Oral-banana polyphenol extract	500 mg/day for 12 weeks	Activation of antioxidant enzymes and suppression of inflammatory pathways reduce oxidative stress	Liao *et al.,* 2024

7. Potential applications of banana in medicine and industry

Bananas (*Musa* spp.) contain a large amount of bioactive compounds, including resistant starch, phenolic acids (*e.g.,* gallic and ferulic acid), flavonoids (*e.g.,* catechins and quercetin), carotenoids (*e.g.,* beta-carotene), dopamine and phytosterols that have various applications in both the medical and industrial fields (Vu *et al.,* 2018).

7.1 Medical applications

Banana biomass has emerged as a valuable resource in the medical field due to the wide range of bioactive compounds it contains, many of which exhibit therapeutic and nutraceutical benefits. For instance, resistant starch obtained from unripe bananas is widely used as a dietary supplement for managing blood glucose levels and metabolic syndrome. It functions as a prebiotic, supporting the growth of beneficial gut microorganisms and thereby improving overall digestive health (Bomfim *et al.,* 2024). In addition to this, banana-derived polysaccharides have shown promising immunomodulatory properties, contributing to enhanced gut immunity and overall health (Liu *et al.,* 2026). Compounds such as β-sitosterol, found in banana peels, play an important role in lowering cholesterol levels. At the same time, dopamine and various phenolic compounds extracted from the peel are increasingly being incorporated into advanced delivery systems, such as nanoencapsulation, to enhance their neuroprotective effects against oxidative stress and related disorders (Vu *et al.,* 2020; Athanasopoulou *et al.,* 2025). These phenolics also exhibit strong antioxidant and anti-inflammatory activities, making them beneficial in reducing the risk of chronic diseases, including cardiovascular conditions and certain types of cancer (Kumari *et al.,* 2025). Banana peel and flower extracts are also gaining attention in wound care and dermatology. Their antimicrobial and collagen-promoting properties make them suitable for use in gels and topical formulations designed to treat burns, ulcers, and other skin conditions (Kundarto *et al.,* 2020). More recent developments include the synthesis of metal nanoparticles, such as silver and zinc oxide, using banana peel extracts, which have demonstrated enhanced antimicrobial activity, particularly against drug resistant microorganisms (Yasin *et al.,* 2025).

7.2 Industrial Applications

In the industrial domain, banana by-products are increasingly recognized as sustainable raw materials that contribute to the development of a circular bioeconomy. Banana peel flour, for example, is commonly used to enrich bakery and snack products with dietary fiber, improving both their nutritional value and functional characteristics. Similarly, pectin extracted from banana peels serves as a natural gelling and stabilizing agent widely used in the food industry (Liu *et al.,* 2026; Athanasopoulou *et al.,* 2025). Additionally, the antioxidant rich extracts from banana peels are being incorporated into functional foods and beverages to enhance their health benefits (Kumari *et al.,* 2025). Fibers obtained from the banana pseudostem, which are rich in lignocellulose, are being utilized in the production of biodegradable packaging materials, textiles, paper, and reinforced biocomposites. These materials offer an environmentally friendly alternative to conventional plastics due to their biodegradability, low density, and good mechanical strength (Yasin *et al.,* 2025; Kumari *et al.,* 2025). Such properties also make them suitable for applications in sectors like construction and automotive manufacturing.Banana biomass is also gaining importance in the energy sector. Agricultural waste from bananas can be converted into renewable energy sources such as biogas, bioethanol, and biohydrogen through processes like anaerobic digestion and fermentation (Abd-Alla *et al.,* 2026). In parallel, banana peel-derived products such as biochar and activated carbon are being used in environmental applications, particularly for the removal of heavy metals and pollutants from wastewater, demonstrating high adsorption efficiency (Hazarika *et al.,* 2026). Moreover, banana-based materials are being developed into biodegradable films and edible coatings that help extend the shelf life of food products while reducing post-harvest losses (Athanasopoulou *et al.,* 2025). Advances in nanotechnology have further enabled the extraction of nanocellulose from banana fibers, which is now being explored for use in high performance composites, biomedical materials, and smart packaging systems (Liu *et al.,* 2026).

8. Challenges and future prospects

In limiting problems for the study of phytochemical and pharmaceutical properties of diverse bananas genotypes. Key barriers are the high genotypic variability of bioactive compounds levels which hinders the standardisation for commercial application (Netshiheni *et al.,* 2020), and the high lack of human clinical trials and almost all evidence is still available from preclinical studies. Further complications arise as result of unforeseen extraction methods and degradation of sensitive phytochemicals, such as polyphenols, in post-harvest handling, preventing a largescale production. Despite these obstacles, there are opportunities in the future with novel tools for improved biotechnology, such as marker-assisted selection and metabolomics, which will facilitate the establishment of banana varieties with optimized bioactive content (Mondal *et al.,* 2021). Also processing agricultural waste products, including peels, stems *etc*., to generate high value nutraceuticals and pharmaceutical ingredients contributes to sustainable circular economy models (Zou *et al.* (2022). Expanding clinical research of genotype specific health effects also has the potential to aid in the design of customized functional foods and plant based medicines (especially for metabolic and digestive disorders, and inflammatory diseases) (Zheng *et al.,* 2023), which would place banana genotypes as valuable sources of new natural health products.

9. Conclusion

Bananas (*Musa* spp.) comprise great riches of bioactive compounds and great potential applications in the field of phytomedicine and functional food. While research determining the existence and properties of banana bioactives is extensive, there is a need for dedicated research to provide information on specific cultivars and genotypes to provide substantiation for their unique claims and applications in relation to health. Present limitations like excessive genotypic variability, non-constant phytochemical composition and the lack of large-conducted human testing remain challenges. However, emerging solutions, such as advanced extraction technologies, precision agriculture for biofortification and valorisation of agro-waste in circular economy models offer great opportunities. In the same vein, to fully exploit the therapeutic and commercial potential of bananas, further cultivar specific phytochemical profiling, sound clinical validation as well as genotype specific products development are of paramount importance. With concerted scientific attention and cross-sector innovation bananas could breakthrough from a dietary staple to become a cornerstone of next-generation natural health products and sustainable biomaterials.

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Conflict of interest

The authors declare no conflict of interest relevant to this article

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