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REVIEW ARTICLE

An extensive review of bioactive compounds in bananas (*Musa* spp.) as well as banana stems and their health benefits

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Abstract

Frequently observed in both fully matured ripe bananas and raw unripe green bananas, along with banana stems, these three parts have garnered substantial interest from nutritionists, biochemists, botanists, industrialists and researchers alike, owing to their rich array of bioactive compounds. Through this extensive review, diligent attempts were made to affirm the establishment that bananas are a good source of natural antioxidants and a substantial reservoir of diverse bioactive molecules. The paper also emphasises the potential pharmaceutical applications of these phytoactive compounds isolated from the members of the Musaceae family, ranging from the treatment of common ailments to the treatment of serious diseases, including cancer. The utility of this plant and its various parts extends far beyond medical and pharmaceutical applications, reaching into diverse non-medical fields such as culinary arts, cosmetics, textiles and biofuel production. From enhancing flavours in the kitchen to providing sustainable materials for fashion and art, this plants' versatility makes it a valuable resource across multiple industries. Pharmaceutical and non-pharmaceutical commercial products can effectively employ bananas, including even their peels, as food ingredients. Research on bananas, their stems and their by-products may open up new possibilities as this plant has proven to be a cornerstone in both traditional and innovative practices, demonstrating its profound impact on everyday life.

Keywords: antioxidants; banana; bioactive compounds; health benefits; *Musa* spp.; non-pharmaceuticals; pharmaceuticals

Introduction

Bananas, widely regarded as a superfood, are increasingly consumed worldwide as part of a nutritious diet. Belonging to the order Zingiberales, family Musaceae and genus *Musa,* bananas are considered one of the oldest fruits, growing all over the world. Asia is the worlds' largest banana producer, accounting for about 54.4 % of global production (1). Banana ranks fifth among the most cultivated crops in global trade (2). From a global perspective, Brazil, Ecuador, China, India and the Philippines are the main producers of bananas (3). At various stages of maturation, bananas' nutritional content varies. Green bananas contain considerable quantities of starch and just a little amount of sugar. Throughout the full-ripening phase, the sugar content rises while the starch amount drops (4). Protein composition also increases on ripening (5). It is also a good source of micronutrients, viz, sodium, potassium, iron, copper, phosphorus, manganese and zinc (6). The mineral composition has been demonstrated to be significantly affected by abiotic factors and agricultural practices in addition to genetic factors (7). The macro and microminerals like calcium, sodium, magnesium, zinc, phosphorus, iron, boron, manganese, potassium and copper are found in different varieties of bananas. In mature bananas, vitamins A, C and B complex are quite abundant, whereas vitamin B_6 is fairly prevalent (8). Nearly 119.83 million tons (mt) of bananas and plantains were grown globally, according to the Food and Agriculture Organisation. Bananas have been grown in tropical and subtropical locations across the world, with annual output anticipated to exceed 102 mt of fresh fruit (9). Bananas can be classified either as dessert bananas (yellow and ripe) or as plantains (green cooking bananas) (10). Regardless of ripening stage, both raw and ripe bananas contain numerous bioactive compounds such as antioxidants, carotenoids, phytosterols, phenolics and flavonoids, offering significant health benefits (11).

All parts of the banana, starting from its inflorescence, sap, seeds, roots, peel and pulp, are filled with nutritious components and health-supporting compounds. For example, banana blossom is used to relieve bronchitis, dysentery and ulcers and helps reduce blood sugar level (12). Banana sap is used for the treatment of leprosy, insect bites and haemorrhage (13). Seeds and roots are used to treat several digestive disorders (14). Pulp is considered a rich source of phytonutrients along with phenolics, vitamins (B3, B6, C and E), simple and complex carbohydrates (15). Bananas are valued for their high digestibility, making them a quick source of energy. In spite of having a low proportion of protein and fat, it can be a staple food product that is used in a supplemented diet. The

reason bananas are so popular is that they are a natural source of bioactive compounds like carotenoids, flavonoids and amines, which have numerous health benefits for humans (16, 17). Bananas can also provide nutrients like carbohydrates, vitamins, minerals and other nutrients (18). Numerous studies have been conducted on the proximate composition and nutritional qualities of bananas; it has been noted that there is a significant variety of nutrients found in different cultivars and even within the same cultivar grown in various geographical areas (19, 20). Banana leaves are used as dining platters and wrapping material for various cultural as well as household purposes. The Cavendish banana, the most popular variety, is usually soft, sweet and commonly consumed as a dessert in Western countries. On the other hand, plantains are much starchier, firmer and better suited for cooking as vegetables. Cavendish banana peels are primarily used to make a variety of commercial goods, including peel flour, bread, pasta and biscuits. They can also be used as a flavouring ingredient (21). Banana peels also satisfy the requirements for physical water filtration methods without altering the flavour or aroma of the water (22). Flour produced from raw, unripe bananas has a high fibre content and also contains a considerable amount of resistant starch (23). Banana fibres can be extracted from the pseudostem region, where the inner portion of this is taken as a popular vegetable and has good medicinal values (24). Banana stems are used in industries such as paper production, handicrafts making and textiles production. Desert banana and plantains, both ripe and unripe forms, have ethnic and medicinal values. Banana peels have also been extensively utilised as organic fertiliser and as animal feed. This review aims to evaluate the nutritional composition, health benefits and industrial applications of various parts of the banana plant by analysing the available bioactive compounds.

Bioactives found in banana

Phenolics

Phenolic compounds are key bioactive constituents in bananas. Phenolics can donate a hydrogen atom, enabling them to act as free radical scavengers; this property is referred to as free radical scavenging activity (25). Antioxidants inhibit the damaging effects of free radicals and help maintain cellular health. In a work on the Cavendish variety of banana, it identified different phenolic compounds were identified at different stages of banana ripening. The study includes both analytical and *in-silico* pipelines useful for the estimation of phenolics and their health benefits. Results obtained from spectrophotometric methods indicate a high positive correlation of phenolic compounds with anti-radical and anti-oxidant capacity. Liquid chromatography mass spectroscopy (LC-MS) analysis has found phenolics and vitamins in banana. Phenolic compounds detected from both pulp and peel include catechin, epicatechin, myricetin, kaempferol, cynadin, quercetin, also some phenolic acids, i.e., ferulic acid, vanillic acid, chlorogenic and other phenols found are tannins and lignin compounds (26). Salicylic acid, gallic acid, p-hydroxybenzoic acid, ferulic acid, sinapic, gentisic and vanillic substances are present in considerable amounts in bananas' and the substances have acts as anti-inflammatory, anti-bacterial, anti-viral and vasodilatory activities (27). It has been found that the peels of bananas have more antioxidant properties than their pulp. They also stated that flavonoids contain the major portion of phenolic substances. The presence of tannins in banana peel enhances the healing and anti-microbial effect (28).

Phytosterols

In the book entitled "Handbook of Banana Production, Postharvest Science, Processing Technology and Nutrition", found that both ripe and raw bananas have a unique matrix of bioactive substances called phytosterols, carotenoids, phenolics and biogenic amines. These substances are very beneficial to human health and well-being and are therefore widely desired in diets (29). Due to their structural similarity to cholesterol, phytosterols can compete with dietary and biliary cholesterol for intestinal micelle distribution. They lower blood LDL cholesterol level by eliminating cholesterol and minimising its absorption due to their poor absorption and active excretion (30). In spite of various nutritional constituents and lots of bioactives, banana peel contains phytosterols that can compete with the hypercholesterolemia condition (31). In the unripe stage of the *Musa* Cavendish dwarf banana variety, gas chromatography–mass spectrometry (GC-MS) was used to identify important phytosterols, including lipophilic substances (32). Three important phytosterols in *Musa spp*. like a triterpenoid 31-norcyclolaudenone that exhibits anti-diabetic and anti-HIV properties, beta-sitosterol and a tetracyclic triterpenoid (24R)-4 alpha,14 alpha,4-trimethyl-5 alpha-cholestra-8,25(27)-dien-3 beta-ol. A common sterol, i.e., Beta-sitosterol, isolated from species of banana has activity against hyperplasia, hyperglycemia and prostate cancer (33).

Carotenoids (vitamin A)

The ripening process and genotype of bananas that influence their carotenoid concentration and bioaccessibility. In a study, 27 edible banana species were collected from the banana collection of the Dole Food Company in Rio Frio, Costa Rica and then three main varieties of bananas seen in markets: plantain, cooking and dessert bananas (34). Carotenoid-containing fruits are used as an immune booster and to reduce the risk of diseases (35). Provitamin A and minerals, such as zinc and iron, were found in 171 and 47 genotypes of *Musa* spp., respectively (36). The presence of such provitamins and trace elements acts as a developmental strategy for banana-consuming populations. Carotenoids are isoprenoid units that some of these have the precursor of provitamin A and the others have strong antioxidant ability to protect from reactive oxygen. Some varieties harbour active carotenes such as alpha carotene, beta carotene, zeaxanthin and lycopene, an important carotenoid that is useful for protecting from prostate cancer and lutein, another carotenoid, inhibits age-related macular degeneration (37-38). Both of them have anti-oxidant capacity that delays ageing processes (39).

Biogenic amines and polyamines

Biogenic amines are nitrogen-containing compounds formed either through the decarboxylation of amino acids or by the amination of aldehydes and ketones. Commonly, in the case of plant species, polyamines play a role in various developmental processes such as biotic and abiotic stress responses (40). Banana species containing neurotransmitters like dopamine, serotonin have antioxidant capacity and also have anti-inflammatory effects, just like vitamin C (41). Nine types of biogenic amines were found in fresh bananas and analysed using high-performance liquid chromatography (42). Certain biogenic amines, including serotonin, tryptamine, tyramine and phenylethylamine, are aromatic amino acids that have vasoconstricting properties that lower the amount of oxygen used in the peripheral tissues (43). Storage of bananas in a refrigerator can cause a significant decrease in phenylalanine and a

Table 1. Bioactives found in parts of the banana

Compound type	Compound	References
Phenolics	Catechin, epicatechin, myricetin, kaempferol, cynadin, quercetin and other tannins and lignin compounds.	(26)
Phenolic acids	Salicylic acid, gallic acid, p-hydroxybenzoic acid, ferulic acid, sinapic acid, gentisic acid, chlorogenic acid and vanillic acid.	(1, 26)
Phytosterol	Triterpenoid 31-norcyclolaudenone; Beta-sitosterol ; Tetracyclic triterpenoid (24R)-4 alpha,14 alpha,4-trimethyl-5 alpha-cholestra-8,25(27)-dien-3 beta-ol; β-carotene, α-carotene, 24-methylene cycloartenol.	(33)
Carotenoids	Alpha carotene, beta carotene, zeaxanthin, lycopene, lutein	(37)
Biogenic amines	Serotonin, tryptamine, tyramine and phenylethylamine	(43)

considerable increase in tryptophan concentration. Putrescine is the most widely found bioamine in their study. The concentration of biogenic amines is changed upon refrigeration (44). The summerized version of major bioactives found are mentioned in Table 1.

Health benefits of bananas

Kidney health maintenance

Excessive secretion of calcium in the urine leads to the formation of a kidney stone. Since bananas contain high potassium, they reduce the risk of kidney stones forming and maintain good kidney health. Both raw and cooking forms of *Musa accuminata* have constituents that help maintain kidney health (45). When working separately, work on cooked and raw bananas, raw banana stem juice is found effective as an anti-nephrolithiatic (the capacity of disintegration of kidney stone). The reduction in nutritional potential upon cooking indicates the temperature dependence of the nutritional qualities present in food. The pseudostem of the banana has a high content of fibre and low caloric value, which aids in detoxification and may reduce overall body weight (46).

Cancer prevention

The anti-cancer property of banana blossom was examined in vitro study where both HeLa and CHO cells and found to have a decreasing viability effect of these cells on increasing the exposure time in ethanol extracts of banana flower. Same study, when done on normal lymphocytes of humans, the viabilities are almost the same in all examined concentrations and seem to be safe for humans. So it is considered a potent natural anti-cancer agent with almost no side effects (47). Bananas exhibit different forms of cancer -preventive formulations. Extracts of ethanol found in Musa paradisica contain anti-cancer activities against HeLa cells, human oral squamous cells and also in carcinoma cell lines (48). Besides that, *Musa sapientum* bananas containing the hexane function can prevent colon cancer. In a study, the green peel of the Cavendish banana has antiproliferation capability against hepatic carcinoma cells. Nendran bananas are ideal for cooking purposes and have methanol extracts that serve as an anti-diabetic agent (49).

Hyperglycemia, hypertension and hypercholesterolemia treatment

When consumed in moderation, bananas can help maintain certain health problems. It is regarded as a natural remedy for these. Elevations in low-density lipoprotein, commonly referred to as "bad cholesterol," have been associated with hypertension. Bananas, due to their high potassium content, can help regulate blood pressure and cholesterol. Flavonoids, tannins, terpenes and steroids are components of bananas responsible for lowering blood sugar levels of blood. *Musa acuminata* juice is easily absorbed and can be consumed by all age groups, including the elderly (50). Additionally, they have biological properties as healing of wounds, hypoglycemia, anti-oxidant, anti-microbial, anti-ulcerative, antidiarrheal and anti-cancer action. Vitamin B6, which is abundant in its pulp, may have a positive effect on mental health. It also contains amine compounds, carotenoids, flavonoids and dietary fibre. Both soluble and insoluble dietary fibre, which are indigestible carbohydrate polymers, are found in them (51). The effects of *Musa acuminata* peel on both hepatic and renal areas of normal rats were investigated, resulting in considerable effects on both the liver and kidneys of rats. *Musa acuminata* peel is used for the control of high pressure and cardiovascular disease treatment (52).

Ulcer prevention

Bananas contain nutrients that act as prebiotics, promoting the selective growth of good gut health. The increase in good gut bacteria helps combat diarrhoea and dysentery and promotes the healing of stomach lesions in ulcerative colitis (53). *Musa paradisiaca* bananas contain leucocyanidin, an active antiulcer compound that gives protection against aspirin-induced ulcers. This natural flavonoid protects the stomach mucosa from the damage caused by aspirin (54). Methanol extracts of the peels of *Musa sapientum* have both anti-ulcerative as well as ulcer healing properties identified from the study on laboratory rats (55). *Musa paradisiaca* fruits are a promising option for evaluating potential anti-ulcer medicines (56).

Menstruation reliever and anti-depressant

Due to the presence of nutrients such as vitamin B6, magnesium and potassium, bananas can regulate proper blood sugar levels and aid in the production of new blood cells, thereby enhancing mood a which enhance mood and reducing menstruation-related cramps (57). Bananas also contain tryptophan, an amino acid, which is converted into the secondary metabolite serotonin, the hormone with regulatory action and neurotransmitter function (58). The potentiality and permissibility of banana fibre-based sanitary pads to promote healthy menstruation and then indirectly help to maintain a sustainable environment (59). Banana has efficiency in relieving pain for adolescents, such as menstrual as well as pre-menstrual cramps (60). Having banana blossom with curd or yoghurt is the most effective cure for heavy menstrual bleeding. This combination raises progesterone levels, reducing menorrhagia-related bleeds (61). Along with the gymball therapy, consumption of an Indonesian variety called Ambon bananas helps during menstruation as it is rich in nutrients such as potassium, magnesium, carbohydrate, sugar, phosphorus, vitamins and some water content (62). The high potassium content in bananas is useful in relaxing muscle fibres and facilitating nerve transmission (63). It is also beneficial to females suffering from polycystic ovarian syndrome. The phytoestrogens present in bananas have a favourable effect on estrogen insufficiency in the female body and are beneficial to reproductive wellness (64). The health benefits are

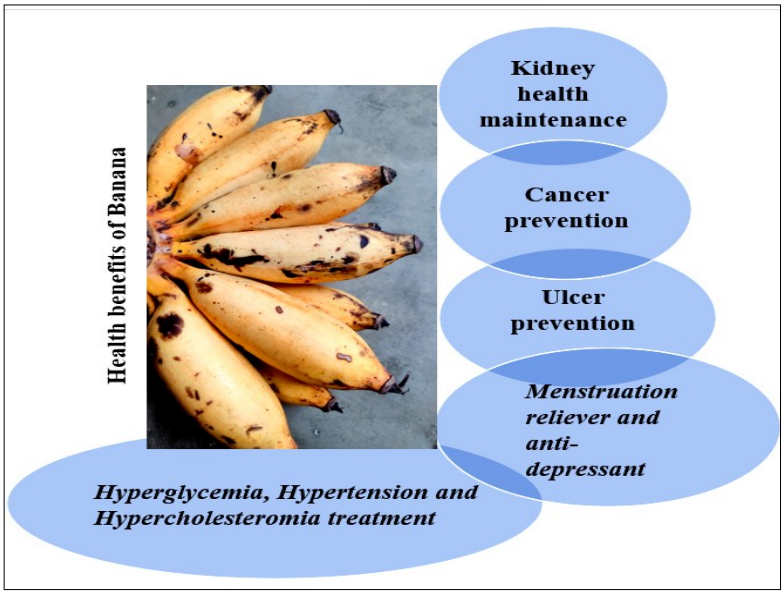

Fig. 1. Health benefits of banana.

Table 2. Some important constituents of the banana with their health benefits

Compound	Health benefits	References
High potassium	Anti-nephrolithiatic; regulation of blood pressure; relaxation of muscle fibre, relief from PCOS	(45, 64)
Flavonoids, carotenoids, tannins, terpenes, steroids, dietary fibre	Wound healing, hypoglycemia, anti-oxidant, anti-microbial, anti-ulcerative, antidiarrheal and anti-cancer action.	(50, 51)
Potassium, magnesium, carbohydrate, phosphorus, vitamins and water content	Management of blood sugar level and pressure level; menstrual cramp reliever, mental health elevator.	(62)
Extracts of methanol, ethanol and leucocyanidin	Anti-ulcerative; anti-cancer; anti-diabetic.	(55, 58, 49)

also mentioned in Fig 1 and Some important constituents present in banana with their health benefits are recapitulated in Table 2.

Research gaps

Although bananas and banana stems are recognised as abundant reservoirs of bioactive compounds, several critical research gaps continue to hinder their full exploitation in nutritional, pharmaceutical and industrial usage.

Bioavailability and metabolic pathways

Despite extensive characterisation of phytochemicals such as phenolics, flavonoids, carotenoids, saponins and alkaloids in bananas, very limited research exists on their bioavailability in humans. The majority of studies rely on *in vitro* antioxidant or antimicrobial assays, which cannot adequately predict *in vivo* efficacy. Furthermore, the digestive stability of banana-derived compounds and their interaction with gut microbiota remain poorly understood. Future work should include studies on absorption, distribution, metabolism and excretion profiles; in vivo validation of bioactive stability during gastrointestinal digestion; and microbiome interaction studies to evaluate whether banana compounds act as prebiotics or are metabolised into secondary bioactive metabolites.

Optimal dosages and standardisation

There is currently no consensus on the quantity of banana or banana-stem-derived compounds required to exert measurable physiological benefits. Variability in cultivar type, growing conditions, degree of ripeness and processing methods can significantly alter phytochemical concentrations. Without standardised extraction protocols or bioassay-guided fractionation, comparisons across studies remain inconsistent. To advance this field, research should focus on establishing standardised extraction and quantification methods for reproducible results, conducting dose-response studies in animal models and human populations to determine safe and effective intake levels and developing bioactive-rich standardised formulations for nutraceutical applications.

Conclusion and Prospects

It should be emphasised that bananas and all of their parts are a rich source of bioactive substances with important industrial, medical and nutritional uses. Their potential to prevent and manage a wide range of diseases is highlighted by their significant antioxidant content and varied phytoactive compounds. Beyond the pharmaceutical industry, bananas are used extensively in the food, cosmetics, textile and biofuel sectors, demonstrating the plants' adaptability and significance in meeting the worlds' needs for sustainable resources. Future studies need to focus on using advanced biotechnological techniques to isolate, characterise and use compounds obtained from bananas on a large scale. Waste conservation and green economy models can be supported by placing more emphasis on investigating underused banana by-products, such as peels and stems. Additionally, incorporating banana-derived products into the majority of industrial and therapeutic sectors could open the door for revolutionary treatments, eco-friendly materials and new functional foods. As a result, bananas have great potential as a multipurpose, sustainable crop that could revolutionise global industry, environmental policies and health.

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Authors' contributions

DB carried out the studies of bioactives and their health benefits and drafted the manuscript. RKN conceived of the study, carried out the abstract and conclusion parts, and also modified some parts in the drafted manuscript. RK initiated the summary tables and edited some parts. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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