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Review article

A Comprehensive Review of the Phytochemistry and Pharmacological Profiles of *Musa acuminata* (Family: Musaceae)

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ABSTRACT

Musa acuminata, commonly called the banana plant, is a cornerstone of tropical agriculture and also in traditional medicine, recognized for its extensive phytochemical composition encompassing phenolic compounds, flavonoids, alkaloids, and terpenoids. Each segment of the plant includes the fruit pulp, peel, leaves, and pseudostem—harbors bioactive constituents that manifest a wide spectrum of pharmacological activities, such as anti-inflammatory, antimicrobial, antidiabetic, antioxidant, and cardiovascular effects. This review consolidates traditional knowledge and contemporary research to elucidate the therapeutic potential of *M. acuminata* in modern medicine. It underscores the imperative for further investigation into the plant's genetic attributes to fully harness its pharmacological capabilities. By highlighting both the nutritional value and the diverse traditional and prospective therapeutic applications, this review provides a foundational framework for future research endeavors aimed at advancing global health and agriculture through the utilization of *M. acuminata*.

Introduction

Throughout history, botanicals have played a pivotal role in medicine and healthcare. Traditional practices, documented in ethnobotanical literature, have long relied on plant extracts, infusions, and powders as remedies for various ailments. Across different cultures worldwide, different parts of plants have served as primary treatments for diseases and injuries, persisting as traditional therapies in many regions.[1] As scientific research advances, increasing evidence supports the efficacy of traditional remedies, challenging their perception as solely historical practices. The World Health Organization (WHO) highlights the critical role of medicinal plants, especially in developing countries where many people rely on traditional medicine for primary healthcare. This recognition has led to a rising demand for such plants in both developed and developing nations. However, unsustainable harvesting from wild sources threatens many plant species with extinction. Numerous studies have revealed the therapeutic potential of plant-derived medicines, leading to the discovery of valuable drugs such as aspirin, atropine, and taxol.[2] Research has revealed the health-promoting and disease-preventing potential of plant bioactive compounds, leading to significant scientific interest in their functional properties. Wild plants serve as both food and medicine, providing affordable and locally accessible resources that enhance nutrition and health. However, the loss of traditional knowledge among rural and tribal communities threatens this valuable ethnobotanical heritage, highlighting the need for its documentation and conservation. Additionally, many wild plants contain phytochemicals linked to reduced disease risk.[3] Identifying these active principles and understanding their mechanisms of action are crucial, necessitating research on both crude plant extracts and isolated compounds.

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Occurrence of *Musa acuminata*

The Musaceae family, to which *M. acuminata* belongs, originates from Southeast Asia's tropical regions, with Malaysia identified as its primary origin, particularly for AA and AAA cultivars.[4] However, due to its economic significance and adaptability to tropical climates, it has been widely cultivated in various parts of the world with suitable environmental conditions. Its spread in India, Burma introduced it to *M. balbisiana*, leading to natural hybridization and the development of AAA cultivars, making India a crucial center for banana diversity with over 300 of the 600 known Musa varieties.[5] Historical references in Indian texts like the Ramayana and Arthasastra highlight the long history of banana domestication in India. The genus name *Musa* honors Roman botanist Antonius *Musa*, with "acuminata" referring to the fruit's pointed tip. Present in India's Kaziranga and Khasi ranges, Andaman Islands, and Western Ghats,[6] *M. acuminata* is now widely cultivated globally, with leading producers including Brazil, China, and India.

Banana cultivation is heavily impacted by annual rainfall, with limited precipitation reducing productivity, especially in rain-fed areas. Enhancing drought resilience in bananas necessitates exploring the genetic resources of wild relatives. Despite progress in molecular genetics and next-generation sequencing (NGS) revealing drought stress tolerance pathways in cultivated bananas, the genetic potential of wild varieties remains largely untapped.[7] Northeastern India, a critical center for Musaceae diversity, hosts over 30 taxa with 19 unique species, accounting for 81% of wild banana species. Understanding the molecular responses of diverse banana genotypes from this region to water scarcity is crucial. Such insights could aid in developing drought-tolerant commercial varieties, enhancing banana cultivation globally in drought-prone areas. This emphasizes the need to integrate wild genetic resources into cultivated varieties for improved environmental stress adaptation.[8]

Fig. 1: Plant of *Musa acuminata*

Botanical Classification

M. acuminata, commonly referred to as the banana plant, belongs to the Musaceae family within the plant kingdom (Fig. 1). It is a perennial herbaceous plant characterized by its large, elongated leaves and distinctive pseudostem, which gives the appearance of a tree-like structure. The banana plant is known for its banana fruits, which develop in clusters and undergo a color transformation from green to yellow as they ripen.

Kingdom: Plantae
Order: Zingiberales
Family: Musaceae
Genus: *Musa*
Species: *acuminata*

Botanical Characterization of *M. acuminata*

M. acuminata is a perennial, herbaceous monocot characterized by underground rhizomes and corms, and a pseudostem of tightly packed leaf sheaths. It exhibits sparse to abundant stooling, with 1 to 30 stems reaching 3 to 5 meters in height and up to 25 cm in diameter. The oblong leaves, 2.0 to 2.5 m long and 0.4 to 0.6 m wide, vary in base and apex shape, and their color ranges from green to purple with potential purplish-brown upper surface pigmentation. The waxy leaves feature adaptable petioles aiding attachment to the pseudostem. Inflorescences range from subhorizontal to vertically deflexed, with either pubescent or smooth peduncles and rachises. Female flowers in two-row bracts precede variably colored male flowers. The geotropic fruit straightens upon ripening, features a yellow pericarp, and contains black, smooth, or slightly textured seeds. This complex morphology highlights the plant's adaptation to diverse environmental conditions and its significance in the Musaceae family.[9]

Genetic Diversity

The genetic landscape of modern edible bananas, formed by the hybridization of *M. acuminata* and *M. balbisiana*, displays diverse genomic groups, including diploid, triploid, and tetraploid forms. This diversity emphasizes bananas' role as a staple food and highlights the genetic wealth of their wild relatives. Global banana germplasm preservation, with over 75 wild species from India's and the Pacific's tropical forests, is crucial for enhancing crop resilience against environmental stresses like drought. Recent genetic research using SNP markers and RADseq technologies has explored the genetic intricacies of diploid bananas, revealing their distribution, diversity, and evolutionary history. These findings underscore the importance of genetic diversity for banana adaptability and set the foundation for breeding strategies to address challenges like climate change and pests.[10] The ability to identify and harness specific genetic markers related to desirable traits, such as drought tolerance, from the plant's wild counterparts could revolutionize banana breeding, enhancing yield, disease resistance, and environmental adaptability.

This genetic exploration serves as a foundation for addressing one of the significant hurdles in banana production—drought stress—exacerbated by the escalating impacts of climate change. Despite the inherent vulnerability of bananas to drought, genotypes carrying the "ABB" genome exhibit a heightened tolerance, presenting a beacon of hope for developing drought-resilient varieties.[11] The pursuit of climate-smart banana varieties hinges on deciphering the genetic underpinnings of drought tolerance found in wild banana species, with cutting-edge techniques like high-throughput phenotyping, next-generation sequencing, and CRISPR/Cas genome editing playing pivotal roles.[12] These modern biotechnological approaches, complemented by continuous exploration for drought-tolerance traits in wild bananas, particularly those from northeastern India's rich biodiversity, are instrumental in crafting commercial banana cultivars that can thrive amidst climatic adversities. In synthesizing these genetic insights with biotechnological innovations, the future of banana cultivation looks promising. Developing stress-tolerant bananas through integrated biotechnological, conventional, and molecular breeding demonstrates the crucial role of genetic resources in sustaining food security. Furthermore, by focusing research efforts on the nucleotide-level characterization of drought stress tolerance and unraveling the complete genome sequences of various *Musa* species, the potential for leveraging these genetic treasures for the benefit of modern cultivars becomes increasingly tangible.[5] In doing so, the path is laid not only for overcoming the challenges posed by drought but also for fortifying global food security through the development of robust, climate-resilient banana varieties, ensuring the longevity and prosperity of this vital crop for generations to come.

Nutritional Value

Bananas, recognized for their high caloric content, offer remarkable nutritional benefits spanning various forms. Members of the *Musa* genus are rich in starch, fructans, phenolic acids, anthocyanins, terpenoids, and sterols. In unripe plantains, starch makes up over 80% of the dry weight of the pulp, with lipids contributing only about 0.5%, thus having a minimal impact on their caloric content.[13] The protein concentration in plantain pulp exceeds 3.5% upon ripening, slightly diminishing in the fresh fruit. Sugars, initially constituting about 1.3% of the unripe plantains' dry matter, escalate to nearly 17% as the fruit matures. Bananas are rich in vitamins such as carotene (A), thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6), and ascorbic acid (C). Notably, pyridoxine is vital for managing neuritis, and anemia, and lowering homocysteine levels, which are linked to a reduced risk of coronary artery disease and stroke.[14] Bananas are rich in potassium, which supports muscle function and reduces muscle spasm risk and may lower blood pressure and stroke risk in potassium-deficient individuals. Magnesium and manganese in bananas enhance bone strength and heart health, with manganese serving as a co-factor for superoxide dismutase. Copper aids red blood cell production. The fruit's fructose and sucrose content make it a strong energy booster. Bananas also contain flavonoids, polyphenolic antioxidants like lutein and zeaxanthin, and minor amounts of β- and α-carotenes, combating oxidative stress. Unripe banana peels contain lipophilic compounds like phytosterols steryl glucosides (e.g., campesterol, β-sitosterol, cycloartenol, stigmasterol), while the pulp is richer in free fatty acids and sterols. Bananas are also a valuable source of essential minerals for both human and animal health.[14]

The Multifaceted Benefits of *M. acuminata*

The Cavendish banana, known botanically *M. acuminata*, is an essential crop in the warmer regions of the world due to its wide-ranging applications in food, medicine, and environmental management. It is a nutrient-rich food, including vitamins (vitamins C and various B vitamins), and minerals such as potassium, dietary fiber, and carbohydrates, making it an excellent food source and a common first food for infants because of its nutritional value and soft consistency.[15] The banana and its peel have been utilized in folk remedies for their health benefits; the fruit aids in managing gastrointestinal issues like constipation and diarrhea due to its pectin content, while the peel has been used topically to alleviate skin irritations, such as bites and warts, thanks to its soothing effects.[16] The fruit is also noted for its antioxidant compounds, including dopamine and catechins, which play a role in reducing inflammation and combating oxidative stress.[17] Beyond its direct human use, *M. acuminata* contributes to environmental sustainability. The plant's by-products, such as the pseudostem and leaves, are recycled as organic compost, enhancing soil health and supporting eco-friendly farming practices. Additionally, the plant's robust root system is effective in preventing soil erosion, showcasing its ecological benefits.[18] Through these diverse applications, *M. acuminata* demonstrates its significant impact on both human well-being and environmental conservation.

Ethnomedical Applications of *M. acuminata* Across Diverse Cultures

M. acuminata, commonly known as the wild banana, has been utilized in various traditional medical practices around the globe. Its different parts serve a myriad of ethnomedical purposes, tailored to the specific needs and traditional knowledge of indigenous tribes and ethnic groups across different geographical locations. In the Loitoktok district of Kenya, the fruit of *M. acuminata* is commonly consumed to manage blood pressure. The ripe fruit is simply eaten, a practice that has been documented in the region.[19] Similarly, on the Tropical Island of Mauritius, the fruit is employed to combat diabetes. Here, it is either cooked alongside other vegetables or added as a spice in foods. This is particularly notable, where one ripe fruit is eaten daily each morning as a traditional remedial measure.[20] In Nigeria, ripe fruit is used for its potential benefits against anemia.[21] Meanwhile, in rural Honduras Central America, the roots of *M. acuminata* are decocted and consumed during menstruation as a contraceptive measure.[22] The use of the root extends to the United States, where it has been used as a treatment for snake bites. The root extract can consumed orally as well as applied externally over the wound.[23] In South Africa, the roots are part of a complex mixture, including leaves from *Senecio serratuloides* and chopped *Hypoxis hemerocallidea* corm. This concoction is boiled and consumed thrice daily as a treatment for HIV/AIDS-related infections and other sexually transmitted infections.[24-26] In Western Uganda, the roots are traditionally used to induce labor, either by squeezing them by hand or chewing them after roasting.[27] In Mexico, the stem is consider as a potential treatment for tuberculosis and other respiratory diseases, where the extract of the stem is consumed as a drink. In the Philippines, the sap of *M. acuminata* is extracted and consumed to alleviate fever.[28] In Lao PDR, the inflorescence and young pseudostem are used during postpartum recovery. The inflorescence is roasted before consumption, while the pseudostem is prepared as soup, both of which support recovery and act as a galactagogue.[29] In Bangladesh, the root is utilized for treating piles through the consumption of juice prepared from the crushed root.[30] In India, and northeastern states, specifically Mizoram and Manipur, the leaves are used to dress wounds and blistered skin, with oil smeared on the leaves for application.[6] Additionally, in Tripura, India, multiple parts of the plant are used. Flower extracts are particularly utilized for treating bronchitis and managing allergy-related symptoms. The inner core is consumed to treat dysentery, while the stem juice and bark fibers from mature plants are utilized for allergic complaints.[31,32] In States of India notably Assam, West Bengal, and Meghalaya, root is noted for its anthelmintic properties and is used in Ayurvedic preparations and tonics.[6] In Arunachal Pradesh, the flowers are boiled and consumed with salt and oil to alleviate joint pain and improve blood circulation. In Kerala, the leaves are used for asthma and wheezing, where the ash obtained by burning the leaves is inhaled as a remedial measure.[6] This extensive use of *M. acuminata* across different cultures underscores its significant role in traditional medicine, illustrating a rich tapestry of ethnomedical knowledge and practices around this tropical plant.

The dwarf banana has a long history in ethnomedicine, serving as a key element in traditional healing across cultures. Used to treat ulcers, its gastroprotective properties are attributed to its rich pectin content, forming a protective stomach layer. *M. acuminata* has also been traditionally used for both diarrhea and constipation due to its high fiber content, which aids digestion and regulates bowel movements, supported by recent research on gut microbiome balance. Additionally, banana peels have been applied to soothe skin irritations, leveraging their antimicrobial and anti-inflammatory properties. Studies highlight the bioactive compounds in the peel, including antioxidants and phytochemicals, promoting skin health and healing.[33] Moreover, the scientific community has recognized *M. acuminata*'s pharmacological potential, exploring its use in treating cardiovascular diseases due to its potassium-rich fruit and its role in managing diabetes and reducing cancer risk through antioxidant properties. These findings validate traditional uses and suggest new medical applications. The integration of traditional knowledge with scientific research highlights *M. acuminata*'s relevance in modern medicine. This convergence underscores the plant's historical, cultural, and scientific significance, affirming the enduring value of traditional remedies in contemporary therapeutic practices.[34,35]

Phytochemical Richness and Therapeutic Potential of *M. acuminata*

Research on *M. acuminata* has identified a diverse array of phytochemicals, including saponins, terpenoids, steroids, anthocyanins, fatty acids, tannins, phenols, and alkaloids, found in various parts of the plant such as the fruit, peel, flower, leaf, pseudostem, and rhizome. The concentration of these compounds varies depending on the extraction method and the specific plant part analyzed.[36] *M. acuminata* and its variants serve as a vital reservoir of bioactive compounds, underscoring the importance of plants in the discovery and development of novel therapeutic agents. This pursuit of new chemical entities from plant sources necessitates a comprehensive approach, merging the knowledge from ethnobotanical studies, phytochemical investigations, and biological assays. Among the myriad of bioactive substances identified in different Musa varieties, several noteworthy compounds such as apigenin-7-glucoside, myricetin-3-O-galactoside, myricetin-3-O-rutinoside, naringenin-7-O-glucoside, kaempferol-3-O-rutinoside, dopamine, N-acetyl serotonin, and rutin have been pinpointed. These substances are lauded for their potential health benefits, including antioxidant, anti-inflammatory, and neuroprotective properties.[2] The variability in phytochemical content across *M. acuminata* plant emphasizes the complexity and richness of plant-based compounds. This diversity not only provides a vast potential for the finding of novel drugs but also highlights the need for an integrated, multidisciplinary approach to harness the therapeutic effect of these bioactive compounds. By combining traditional knowledge with modern scientific techniques, researchers can unlock the full pharmacological importance of *M. acuminata* and other medicinal plants, paving the way for innovative treatments and therapies.

Phytochemicals recognized in *M. acuminata* reveals a wide array of bioactive compounds extracted from various parts of plant, demonstrating its health and medicinal benefits (Table 1). The ripe fruit pulp is rich in phenolics, vitamin C, and flavonoids such as quercetin, proanthocyanidins, and catechin, in addition to pro-vitamin carotenoids and unique proteins like banana lectin (Ban-Lec), banana thaumatin-like protein (Ban-TLP), and banana endo-β1,3-glucanase (Ban-Glu).[37-39] Different solvents like ethanol, dichloromethane, methanol, and acetone extract a diverse range of substances: ethanol pulls out alkaloids, saponins, and tannins;[40] dichloromethane is effective for fatty acids and sterols such as campesterol and β-sitosterol;[41] methanol yields tannins and various flavonoids;[42] while acetone reveals phenolic compounds and acids.[43] Unripe fruit shows distinct chemistries in the pulp and peel, with the former containing unique compounds such as 2-(4′-hydroxyphenyl)-naphthalic anhydride and the latter rich in catecholamines and anthocyanins.[38,44] Other plant parts like flowers, leaves, bracts, corms, and rhizomes are rich in glycosides, phenols, and unique phytochemicals like anthocyanins, coumarins, sterols, and terpenoids.[4,36] The root and seeds house less common phytochemicals such as Anigorufone and leucoanthocyanidins.[45] Additionally, the fruit cell wall and pseudostem yield important phytochemicals, including hydroxycinnamic and ferulic acids, as well as a mix of alkaloids, flavonoids, and other compounds.[42] The sap and vegetative parts of the plant, like petioles and leaf blades, contain compounds including caffeoylquinic acid and steryl glycosides, underscoring the diverse phytochemical richness of *M. acuminata* and its extensive potential in health and medicine applications.[4]

Phytochemicals Observed in *M. acuminata*

The diverse phytochemical composition of *M. acuminata*, highlighting the plant's significant pluripharmacological properties (Table 2). These phytochemicals, including a variety of compounds like BanLec—a lectin identified in the pulp of ripe *M. acuminata* fruit—are noted for their varied therapeutic potentials, such as anti-HIV activity. Table 2 elaborates on the chemical properties of these compounds, including their molecular structures, formulas, and weights, providing an essential scientific basis for further research and application in pharmacology.

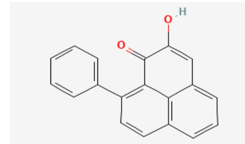
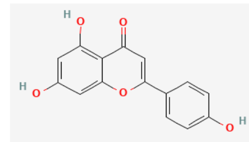
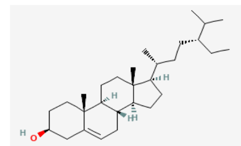
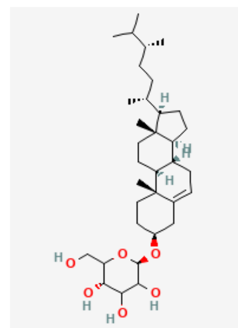
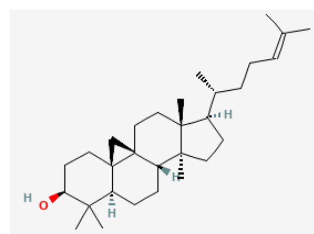
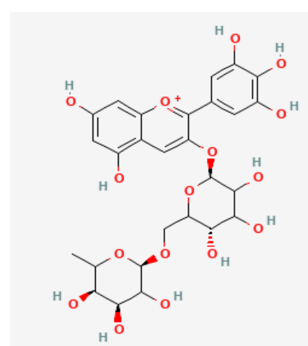
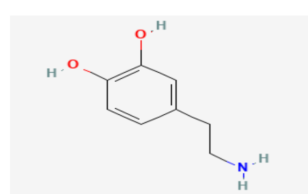
Comprehensive Pharmacological Benefits of *M. acuminata*

The diverse phytochemical profile of *M. acuminata* provides a wide range of pharmacological activities. Compounds like anigorufone and REF20 exhibit significant leishmanicidal activities. Alkaloids act as painkillers, while α-tocopherol combats cardiovascular diseases and cancer. Apigenin and

Table 1: General overview of the phytochemicals found in the Musaceae plant, with specific solvents used for extraction

Plant part	*Solvent*	*Identified phytochemicals and active compounds*	*References*
Ripe fruit pulp	-	Phenolics, vitamin c, flavonoids, pro-vitamin carotenoids, banana-specific proteins	[46,47]
Fruit	Ethanol	Alkaloids, saponins, tannins, terpenes, flavonoids	[21,40]
Fruit	Dichloromethane	Fatty acids, sterols, tocopherol	[41]
Fruit	Methanol	Saponins, triterpenes, catechins, procyanidins, phenolics	[42,48]
Fruit	Acetone	Catechin hydrate, phenolic acids	[30]
Unripe fruit	-	Unique organic compounds	[44]
Peel	Various	Phenolics, dopamine, anthocyanins, various metabolites	[38]
Flower	Methanol	Glycosides, tannins, saponins, phenols, steroids, flavonoids	[36]
Leaf	Various	Phenolics, tannic acid, other metabolites	[49]
Leaf powder	-	Cinnamic acid, ferulic acid	[39]
Bract	Methanol	Anthocyanins, alkaloids, tannins, flavonoids, other phenolics	[4,36]
Corm	Ethanol	Sterols, flavonoids, glycosides, terpenoids, tannins	[50]
Root	Methanol	Anigorufone, other phenalenones	[45]
Seeds	Acetone	Leucoanthocyanidin	[51]
Fruit cell wall	Chloroform:Methanol	Hydroxycinnamic acids, ferulic acid, procyanidins	[52]
Sap	Ethanol	Hydrocinnamic acid, caffeoylquinic acid, flavonoids	[4]

Table 2: Major phytochemicals present in *M. acuminata*

Compound name (PubChem/ChemSpider ID)	*Molecular formula*	*Systemic name*	*Molecular weight*	*Structure*
Anigorufone (PubChem CID 636472)	C19H12O2	2-Hydroxy-9-phenyl-phenalen-1-one	272.30 g/mol	
Apigenin (PubChem CID 5280443)	C15H10O5	5,7-dihydroxy-2-(4-hydroxyphenyl)chromen-4-one	270.24 g/mol	
β-sitosterol (PubChem CID 222284)	C29H50O	Dodecahydro-1H-cyclopenta[a] phenanthren-3-ol derivative	414.71 g/mol	
Campesteryl glucoside (PubChem CID 70699334)	C34H58O6	Cyclopenta[a]phenanthren-3-yl derivative	562.82 g/mol	
Cycloartenol (PubChem CID 92110)	C30H50O	9beta,19-cyclo-24-lanosten-3beta-ol	426.72 g/mol	
Delphinidin-3-rutinoside (PubChem CID 44256887)	C27H31O16+	Chromenylium derivative	611.53 g/mol	
Dopamine (PubChem CID 681)	C8H11NO2	4-(2-aminoethyl)benzene-1,2-diol	153.18 g/mol	

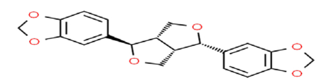
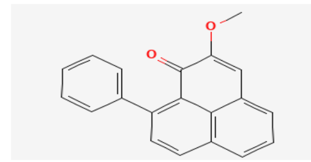
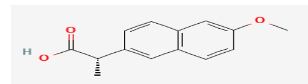
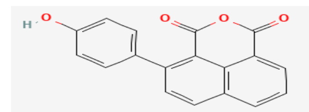
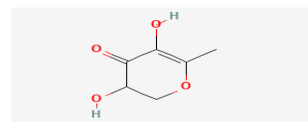
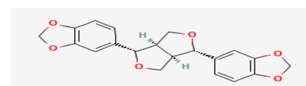
Episesamin (ChemSpider ID 10043748)	C20H18O6	Tetrahydro-1H,3H-furo[3,4-c] furan derivative	354.35 Da	
Methoxyanigorufone (PubChem CID 10085389)	C20H14O2	2-methoxy-9-phenyl-phenalen-1-one	286.32 g/mol	
Naproxen (PubChem CID 156391)	C14H14O3	(2S)-2-(6-methoxynaphthalen-2-yl)propanoic	230.26 g/mol	
Phenyl-phenalenone (PubChem CID 10424295)	C18H10O4	2-(4-hydroxyphenyl) naphthalic anhydride	290.27 g/mol	
Pyranone (PubChem CID 119838)	C6H8O4	3,5-dihydroxy-6-methyl-2,3-dihydropyran-4-one	144.13 g/mol	
Sesamin (PubChem CID 72307)	C20H18O6	Hexahydrofuro[3,4-c]furan derivative	354.35 g/mol	

Table 3: Pharmacological activities of phytochemicals in *M. acuminata*

Phytochemical	*Pharmacological activity*	*Notable effects*	*References*
Anigorufone	Leishmanicidal activity	Antifungal, anti-leishmanial	[53]
Alkaloids	Analgesic	Pain relief	[40]
α-Tocopherol	Supports cardiovascular health, anticancer	Prevents age-related diseases	[41]
Apigenin	Anticancer	Cell cycle arrest, promotes apoptosis	[4]
β-Sitosterol	Anti-mutagenic, anticancer	Reduces cancer risk	[41]
Caffeoylquinic acid	Antioxidant	Reduces oxidative stress	[4]
Dopamine	Vasoconstrictor	Regulates blood pressure	[4]
Epi-sesamin	Antioxidant, anticholesteremic, antihypertensive	Lowers cholesterol and blood pressure	[54]
Flavonoids	Broad spectrum: antioxidant, anti-inflammatory, hepatoprotective	Enhances liver health	[40]
Glycosides	Cardiac benefits	Treats heart failure and arrhythmias	[36]
Kaempferol	Anti-inflammatory	Reduces inflammation	[4]
Lectin (BanLec)	Immunopotency, anticancer	Boosts immune response, fights cancer	[37,55]
Omega fatty acids	Reduces chronic disease risk	Beneficial for cardiovascular and bone health	[41]
Phytosterols	Lowers plasma cholesterol	Reduces risk of heart disease	[41]
Quercetin	Antivenom, strengthens capillaries	Stops bleeding, reduces venom effects	[4]
Saponins	Treats epilepsy, excessive salivation	Neuroprotective	[51]
Sesamin	Antioxidant, anticholesterolemic	Lowers cholesterol	[53]
Naproxen	Anti-inflammatory	Treats inflammation, comparable to synthetic forms	[53]

β-sitosterol have anticancer properties, promoting arrest in cell cycle and apoptosis. Caffeoylquinic acid, dopamine offer strong antioxidant and vasoconstrictive effects. The phytochemical 2,3-dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one provides anti-inflammatory, antioxidant, and anti-proliferative benefits. Epi-sesamin has antioxidant and antihypertensive properties. Various flavonoids and glycosides deliver antioxidant, anti-inflammatory,

Table 4: Therapeutic implication of *M. acuminata*

Derivative of M. acuminata	*Therapeutic application*	*Benefits*	*References*
Fruit pulp (Catechins, Hydroxycinnamic acids)	Antioxidant properties	Provides strong antioxidant activities which reduce the risk of chronic diseases such as cardiovascular diseases, diabetes, and cancer.	[57]
Kepok banana peel (Saponins, Flavonoids)	Cardiovascular health	Lowers cholesterol levels and supports cardiovascular health, potentially reducing risks of heart disease.	[58]
Unripe fruit (Methanolic extracts)	Liver and gastrointestinal protection	Exhibits hepatoprotective and anti-ulcerogenic effects, offering a natural alternative for liver protection and ulcer prevention.	[59]
Ethanol extracts (Phenolics, Flavonoids)	Oncological applications	Demonstrates anticancer properties by inducing apoptosis in cancer cells, inhibiting cell proliferation, and preventing metastasis.	[60]
Banana peel flour	Metabolic and immunological benefits	Shows antidiabetic properties by lowering blood glucose levels and enhances immune responses, particularly in aquatic animals.	[52]
Banana peel and leaf extracts	Dermatological and antimicrobial efficacy	Enhances wound healing, supports tissue repair, and exhibits antibacterial properties against both Gram-positive and Gram-negative bacteria.	[61]
Phytoalexins	Anti-leishmanial activity	Displays potential as effective anti-parasitic agents against Leishmania species, suggesting a new avenue for treating leishmaniasis.	[62]

and heart condition treatments. Lectin (BanLec) shows potential in cancer treatment due to its immune potency and mitogenic activity. Omega fatty acids help reduce the risk of chronic diseases. Saponins traditionally treat epilepsy and migraines. Quercetin and tannins offer antivenom and strong antioxidant activities. Roots and rhizomes produce phytochemicals with potent anti-inflammatory and antifungal activities, demonstrating the plant's adaptive responses.[43] It is listed in (Table 3).

Therapeutic Application

M. acuminata, rich in phytochemicals, offers significant nutritional and therapeutic potential. Its various parts—fruits, peels, flowers, leaves, pseudostems, and rhizomes—contain saponins, phenols, anthocyanins, terpenoids, steroids, fatty acids, tannins, and alkaloids, contributing to diverse health benefits. Compounds like kaempferol-3-O-rutinoside, apigenin-7-glucoside, and myricetin-3-O-galactoside highlight its pharmacological properties. Flavonoids such as myricetin and kaempferol provide antioxidant protection, reducing chronic disease risks. Saponins and terpenoids offer anti-inflammatory effects, beneficial for conditions like arthritis. Dopamine and N-acetyl serotonin show neuroprotective potential for neurodegenerative diseases. Anthocyanins and alkaloids exhibit antimicrobial properties, effective against bacterial and fungal infections. This pharmacological profile positions *M. acuminata* as a valuable source for novel therapeutic strategies.[56] Through a blend of *in-vitro* and *in-vivo* studies the therapeutic implications of these compounds are being explored, shedding light on their action mechanisms and health impacts. This exploration not only affirms the traditional uses of *M. acuminata* but also opens new doors for the development of drugs and therapies, leveraging the plant's vast medicinal potential (Table 4).

Cardiovascular health enhancement

Research into the cardiovascular benefits of *M. acuminata*, particularly the kepok banana peel, shows promising cholesterol-lowering effects due to its rich content of saponins, tannins, and flavonoids. Studies involving obese *Mus musculus* mice demonstrated that kepok banana peel extract significantly reduces total cholesterol levels, an important risk factor for cardiovascular diseases.[63] Saponins interfere with cholesterol absorption, tannins offer antioxidant protection against atherosclerosis, and flavonoids provide antioxidant, anti-inflammatory, and anti-atherogenic effects.[63,64] These compounds improve blood lipid profiles, reduce blood pressure, and enhance endothelial function, collectively preventing heart disease. These findings highlight the potential of incorporating kepok banana peel into the diet for cardiovascular health and call for further research to develop natural therapies for managing cardiovascular diseases.[34,65]

Antioxidant potency

The fruit pulp of *M. acuminata*, rich in catechins and hydroxycinnamic acid derivatives, exhibits strong antioxidant activity, highlighting its health-promoting potential. Compounds released by enzymatic and acid hydrolysis increase the total phenolic content in cell walls, providing natural antioxidants that scavenge free radicals and lower the risk of chronic diseases such as cardiovascular disease, diabetes, and cancer. The findings suggest that consuming *M. acuminata* can provide similar antioxidant benefits within the human digestive system. Catechins and hydroxycinnamic acids, known for their health benefits, support heart health, weight management, brain function and possess anti-inflammatory, anticancer, and antimicrobial properties. This underscores the value of whole fruit consumption, including often-discarded parts like the banana peel, for their nutrients and bioactive compounds. Further research on these antioxidant mechanisms and their metabolism could enhance disease prevention and health promotion strategies.[52]

Liver and gastrointestinal protection

Research on methanolic extracts of unripe *M. acuminata* has revealed significant hepatoprotective and anti-ulcerogenic effects, suggesting its potential as a natural alternative to conventional drugs for liver protection and ulcer prevention. The therapeutic efficacy is attributed to its rich composition of saponins, flavonoids, and triterpenes. Saponins modulate immune responses and reduce inflammation, aiding liver detoxification and protection.[51] Flavonoids has antioxidant properties, neutralizing free radicals and reducing oxidative stress, which leads to protecting the liver and preventing ulcers. Triterpenes possess anti-inflammatory and anticancer properties, enhancing the overall protective effects on the liver and gastrointestinal tract. These findings emphasized on need for further research to fully uncover the mechanisms of these bioactive compounds, optimize extraction processes, identify potent compound combinations, and develop new formulations to maximize health benefits. *M. acuminata* holds promise for developing novel, effective, and natural therapies for liver and gastrointestinal diseases, contributing to the broader field of natural health products.[65,66]

Oncological applications

Research into the ethanol extracts of *M. acuminata* reveals promising anticancer properties, highlighting its rich phenolic and flavonoid content known for antioxidant and anticancer activities. These compounds induce apoptosis, interfere in cell proliferation, and block metastasis in cancer cells. Their antioxidant properties also reduce oxidative stress, a key factor in cancer progression. *In-vitro* studies show that ethanol extracts show significant inhibition in the growth of various cancer cell lines, suggesting their potential to target cancer cells while sparing healthy cells. This highlights *M. acuminata*'s promise in developing less harmful cancer therapeutics compared to conventional chemotherapy. Further research is needed to isolate specific compounds and understand their mechanisms, with clinical trials necessary to establish efficacy and safety in humans. This highlights the significance of natural products in drug discovery, with *M. acuminata* emerging as a promising source of anticancer agents.[60]

Metabolic and immunological benefits

Studies on *M. acuminata* have demonstrated its antidiabetic properties, with results indicating a reduction in blood glucose levels in normoglycemic rats in a dose-dependent manner, suggesting its potential as a natural alternative to synthetic antidiabetic drugs. Additionally, banana peel flour has been found to enhance growth and immune markers in *Labeo rohita*, suggesting its use as a functional food ingredient in aquaculture. This highlights the bioactive compounds in the banana peel that modulate immune responses, promoting health and disease resistance. These findings underscore *M. acuminata*'s as a promising functional food ingredient, with implications for managing diabetes and strengthening the immune system in humans. Further research into these bioactive compounds could lead to innovative, natural health solutions, demonstrating the value of integrating traditional knowledge with modern scientific research.[67]

Dermatological and antimicrobial efficacy

Research on *M. acuminata* banana peel extracts has demonstrated significant wound-healing capabilities in rabbit models, enhancing wound contraction and re-epithelialization by stimulating cellular proliferation and migration. Additionally, *M. acuminata* leaf extracts exhibit antibacterial properties against gram-positive and gram-negative bacteria, highlighting their importance in preventing wound infections and broader infection control. The antibacterial activity is likely due to bioactive compounds that disrupt bacterial cell walls or inhibit essential bacterial enzymes. These findings underscore the potential clinical applications of *M. acuminata* extracts in wound healing and infection prevention.[61] These findings collectively highlight *M. acuminata*, both its peels and leaves, as a valuable natural resource with therapeutic applications in wound care and infection management. The implications of such research are broad, opening avenues for the development of natural, plant-based treatments that could complement or serve as alternatives to conventional wound care products and antibiotics.[68] Further exploration and characterization of the bioactive compounds within *M. acuminata* could lead to innovative solutions in healthcare, particularly in wound management and the prevention of infection.

Anti-leishmanial activity

The exploration of *M. acuminata*'s phytoalexins against *Leishmania* species marks a significant advance in developing natural anti-parasitic agents. Leishmaniasis, a major global health challenge, often faces issues with costly, toxic, and drug-resistant treatments. Phytoalexins from *M. acuminata* have shown efficacy against *Leishmania*, suggesting their potential as sustainable and less toxic leishmanicidal compounds. Beyond anti-parasitic properties, *M. acuminata*'s diverse bioactive compounds offer metabolic, cardiovascular, anticancer, antimicrobial, and immunomodulatory benefits, highlighting its potential as a multi-target pharmacological resource.[62] Further research is crucial to transition from exploratory studies to clinical applications of *M. acuminata*. This involves isolating and identifying active compounds, understanding their modes of action, and corroborating their efficacy and safety in clinical settings. Such studies will enhance our knowledge of the plant's medicinal properties and aid in developing new drugs for various diseases, including leishmaniasis. The development of leishmanicidal treatments illustrates the fusion of traditional knowledge with modern research, emphasizing the potential of natural products as therapeutic agents and the importance of exploring them to tackle global health challenges.[53]

Conclusion

The extensive review of *M. acuminata* highlights its critical role in traditional medicine and agriculture while charting a path for future research. Advanced genetic sequencing and bioinformatics will uncover genes and bioactive compounds for stress resistance and health benefits. Sustainable agricultural practices and biofortification can address nutritional deficiencies and global health challenges. The pharmacological properties identified call for clinical validation to develop new therapeutic agents. Conservation efforts and preservation of ethnobotanical knowledge are essential for maintaining genetic diversity and cultural heritage. Integrating traditional uses with scientific research can lead to novel therapeutic applications, promoting health, environmental sustainability, and economic benefits for farmers. Incorporating *M. acuminata* into public health strategies offers solutions for malnutrition and chronic diseases, marking a new chapter in its research and utilization.

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