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Bioactive Compounds in *Musa spp*.: Opportunities for Herbal Drug Development

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Abstract
Bananas and plantains (*Musa* spp.) are globally recognized for their nutritional significance, but their role as reservoirs of pharmacologically active phytochemicals is gaining increasing attention. Different plant parts, including peel, pulp, pseudostem, flowers, and leaves, contain a wide spectrum of bioactive compounds such as phenolics, flavonoids, carotenoids, sterols, phytosterols, biogenic amines, and polysaccharides. These metabolites exert antioxidant, anti-inflammatory, antimicrobial, antidiabetic, anticancer, and neuroprotective effects, offering substantial opportunities for herbal drug development. In recent years, scientific evidence has strengthened the traditional medicinal uses of *Musa*, while novel technological strategies such as nanocarrier-based delivery and biofortification have addressed limitations related to bioavailability and compound stability. Despite these advances, major challenges including phytochemical variability, clinical validation, and regulatory compliance must be overcome. This paper synthesizes the biochemical and pharmacological evidence for *Musa*-derived compounds, highlights their mechanistic pathways, and evaluates their prospects for integration into modern herbal therapeutics.

Keywords: *Musa* spp., bioactive compounds, phytochemicals, phenolics, flavonoids, carotenoids

Introduction
The genus *Musa* occupies a pivotal role in both global food systems and traditional medicinal practices. Bananas are cultivated in more than 130 countries, with an annual production exceeding 125 million tonnes, making them the most traded fruit worldwide [1]. While their contribution to caloric intake and nutritional balance is widely acknowledged, the medicinal relevance of *Musa* has often been overshadowed by its dietary importance. Ethnomedical practices across Africa, Asia, and Latin America have consistently documented the therapeutic use of banana fruit, peel, flower, pseudostem, and roots for conditions such as diarrhea, ulcers, diabetes, inflammation, and infections [2].

Phytochemical investigations over the past three decades have identified a wide spectrum of metabolites, particularly phenolic acids, flavonoids, carotenoids, sterols, and amines, which underpin the pharmacological activities associated with *Musa*. The molecular actions of these compounds involve modulation of oxidative stress, regulation of inflammatory mediators, inhibition of microbial enzymes, modulation of glucose metabolism, and induction of apoptosis in tumor cells [3]. Such diverse biological activities position *Musa* as an underexploited yet highly valuable candidate for herbal drug development.

The global herbal drug industry, valued at more than USD 200 billion and projected to double by 2030, reflects the demand for natural and plant-based medicines [4]. In this context, banana-based phytoconstituents offer unique prospects not only for drug development but also for sustainable waste valorization, since byproducts such as peel and pseudostem are often discarded despite their rich phytochemical profiles [5]. This review provides a comprehensive account of bioactive compounds in *Musa*, their pharmacological properties, opportunities for drug development, and challenges in translation to clinical practice.

Phytochemical Diversity of *Musa* spp.
The biochemical diversity of *Musa* is vast, spanning phenolic acids, flavonoids, carotenoids, sterols, phytosterols, and bioactive amines. Banana peel, often regarded as waste, is particularly enriched in phenolics and sterols, whereas pulp contains higher levels of amines such as dopamine and serotonin. Flowers are reservoirs of flavonoids, while orange-fleshed cultivars contain high carotenoid concentrations.

Table 1: Major classes of bioactive compounds in *Musa* spp. and their distribution

Class of Compound	Examples	Main Source in *Musa*	Key Pharmacological Role
Phenolic acids	Gallic acid, Ferulic acid, Chlorogenic acid	Peel, pulp	Antioxidant, antidiabetic
Flavonoids	Quercetin, Rutin, Catechin, Kaempferol	Flowers, peel	Anti-inflammatory, antimicrobial
Carotenoids	β-carotene, Lutein, α-carotene	Orange-fleshed cultivars	Antioxidant, provitamin A
Biogenic amines	Dopamine, Serotonin, Norepinephrine	Pulp, peel	Neuroprotection, mood regulation
Sterols/phytosterols	β-sitosterol, Stigmasterol, Campesterol	Peel, pseudostem	Cholesterol-lowering, anticancer
Polysaccharides	Resistant starch, dietary fibers	Pseudostem, unripe pulp	Gut health, immunomodulation

The phytochemical richness of *Musa* reflects an evolutionary adaptation to diverse environments, and it offers an extensive pharmacological toolkit for developing therapeutic interventions.

Pharmacological Activities of *Musa*-Derived Compounds

The pharmacological properties of *Musa* bioactives are mediated through complex biochemical pathways. Phenolic acids act through free radical scavenging and modulation of endogenous antioxidant enzymes. Flavonoids downregulate pro-inflammatory mediators such as COX-2 and NF-κB. Carotenoids prevent oxidative DNA damage, while dopamine and serotonin protect neuronal cells from reactive oxygen species. Phytosterols regulate cholesterol metabolism and induce apoptosis in cancer cells. Resistant starch modulates gut microbiota, improving glucose metabolism and immune regulation.

Table 2: Pharmacological activities and mechanisms of selected *Musa* bioactives

Bioactive	Activity	Mechanism of Action	Key Reference
Dopamine	Antioxidant, neuroprotective	Radical scavenging, metal chelation, mitochondrial protection	[16, 17]
Quercetin	Anti-inflammatory	Inhibition of NF-κB and MAPK pathways, reduction of cytokines	[11, 12]
Ferulic acid	Anticancer	Suppression of VEGF-mediated angiogenesis	[37]
β-sitosterol	Anticancer, hypocholesterolemic	Induction of apoptosis, inhibition of cholesterol absorption	[21]
Resistant starch	Antidiabetic, prebiotic	Modulation of gut microbiota, improved GLP-1 signaling	[23, 24]

These pharmacological effects highlight the multi-target potential of *Musa*-derived compounds, a feature highly desirable in herbal drug development.

Opportunities for Herbal Drug Development

The valorization of banana bioactives offers opportunities in nutraceuticals, pharmaceuticals, and functional foods. Peel and flower extracts can be standardized into herbal capsules targeting diabetes or infections, while resistant starch from unripe bananas can be formulated into functional foods for glycemic control. Carotenoid-rich cultivars present biofortified solutions for addressing vitamin A deficiency in developing countries.

Nanotechnology further enhances the feasibility of *Musa*-based therapeutics. Encapsulation of phenolics into liposomes or polymeric nanoparticles improves their solubility and gastrointestinal stability. Such delivery systems allow controlled release and targeted delivery, overcoming major limitations of natural product pharmacology.

Table 3: Opportunities for developing *Musa*-based herbal therapeutics

Application Area	Potential Product	Targeted Health Domain
Nutraceuticals	Banana peel extract capsules	Diabetes, antioxidant therapy
Functional foods	Resistant starch-enriched flour	Gut health, glycemic control
Herbal medicine	Banana flower extract syrup	Anti-inflammatory, gynecological health
Nanophytomedicine	Polyphenol-loaded nanoparticles	Neuroprotection, anticancer therapy
Biofortification	Provitamin A-rich cultivars	Micronutrient deficiency (Vitamin A)

These opportunities align with both healthcare needs and sustainable development by reducing agricultural waste and improving health outcomes.

Challenges in Clinical Translation

Despite promising prospects, the transition of *Musa* bioactives into market-ready herbal drugs faces critical challenges. Phytochemical variability across cultivars, environmental conditions, and ripening stages complicates standardization. Low bioavailability and poor pharmacokinetics of polyphenols and carotenoids remain major bottlenecks. Stability issues arise from oxidative degradation during processing and storage. Moreover, rigorous clinical trials are required to substantiate therapeutic claims, and regulatory frameworks often present additional hurdles.

A forward-looking strategy must therefore combine advanced metabolomic profiling, pharmacokinetic modeling, and nanotechnology-based formulations. Simultaneously, robust preclinical and clinical trials are necessary to establish efficacy and safety benchmarks comparable to conventional pharmaceuticals.

Conclusion

Musa spp. exemplify the potential of staple crops as reservoirs of pharmacologically active compounds with wide-ranging therapeutic applications. From antioxidant and antimicrobial to antidiabetic and anticancer properties, banana-derived phytochemicals hold considerable promise in the development of herbal drugs. Valorization of byproducts such as peel, pseudostem, and flowers not only enhances sustainability but also creates low-cost raw materials for phytopharmaceutical industries. While challenges in standardization, stability, and regulatory approval remain, innovations in nanotechnology, biofortification, and integrative medicine provide feasible pathways to overcome these barriers. As science converges with traditional knowledge, *Musa*-based phytotherapeutics may significantly contribute to the future of global herbal medicine.

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