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Biochemistry, Nutritional Composition, And Health Benefits of Mango (*Mangifera indica*): A Comprehensive Review

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ABSTRACT

Mango or Mangifera indica L., is a popular tropical fruit that is known for its flavour, vital nutrients, and potentially healing bioactive components. This review explores its biochemical composition, including carbohydrates, proteins, flavonoids, and other phytochemicals. It highlights mango's enzymatic activities, antioxidant mechanisms, and biosynthetic pathways. Health benefits including anti-inflammatory, anticancer, and neuroprotective effects are discussed. The review covers applications in food, nutraceutical, and pharmaceutical industries. It also examines biochemical changes during ripening and postharvest processing. Technological advancements for improving shelf life and quality are addressed. The study emphasizes the need for further research on phytochemical bioavailability. Mango is positioned as a functional food promoting human health. Its potential role in preventive nutrition is significant for future wellness initiatives.

Keywords: *Mangifera indica*; Biochemical composition; Bioactive compounds; Antioxidant activity; Functional foods; Nutraceuticals; Postharvest processing; Mango phytochemicals; Health benefits; Metabolic regulation

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INTRODUCTION

The increasing global interest in plant-based diets and functional foods has drawn significant attention to fruits not only as sources of essential nutrients but also as reservoirs of bioactive compounds with potential therapeutic benefits. Among tropical fruits, mango (*Mangifera indica L.)* holds a prominent place due to its rich flavour, wide cultivation, and diverse phytochemical profile. Mangos, which originated in South Asia, are now widely farmed across tropical and subtropical regions of the world. Because of their nutritional content and sensual appeal, they are regarded as the "king of fruits" in many cultures. Mangoes are utilized in diverse products such as pulp, jams, jellies, canned slices, dehydrated pulp, frozen chunks, pickles, and chutneys [1]. With the potential benefits of every part of the plant—fruit, pulp seed, peel, flowers, leaves, and bark—mangos are popular due to their high nutraceutical and medicinal value. [2]. Mango's global production exceeds 40 million tons, yet only a small fraction is traded internationally; India is the largest producer, followed by China, Thailand, and Mexico, with Mexico leading in international trade, accounting for 20% of the global market [3]. Mangoes are a climacteric fruit, characterized by a surge in ethylene production and respiration during ripening, making them highly perishable with a short shelf life of about 7-9 days at ambient temperature [4]. The United States is the largest import market for mangoes, absorbing more than 32% of global imports [5].

Beyond its culinary popularity, mango is a scientifically recognized source of vital macro- and micronutrients, including carbohydrates, dietary fibre, vitamins A and C, folate, and a variety of essential minerals. More importantly, mango fruits are abundant in bioactive secondary metabolites, such as polyphenols, carotenoids, and Mangifera—a unique xanthonoid with demonstrated antioxidant, anti-inflammatory, and antidiabetic properties. Mango's biochemical complexity is evident in both its potential as a natural remedy and in its function as a nutrient-dense diet. Mangos are a fascinating topic for more research in food science and nutraceutical development since ongoing studies continue to reveal the various biochemical routes and processes by which their phytochemicals have positive impacts on human health. The numerous phytochemicals found in mango leaves, including mangiferin, phenolic acids, benzophenones, and other antioxidants such flavonoids, ascorbic acid, carotenoids, and tocopherols, have been investigated and are known to offer health advantages [6]. These components together with minerals and enzymes contribute to the health and well-being benefits of mango leaves, thus justifying their use as an ethnomedicinal plant [7], [8]. Recent advances in food biochemistry and phytomedicine have underscored the importance of exploring the molecular composition and physiological effects of bioactive compounds in fruits. Understanding the biochemical pathways and mechanisms through which these compounds act is essential for developing functional foods and nutraceuticals. Mango serves as a compelling model due to the synergistic interaction of its nutrients and phytochemicals, which contribute to a variety of health advantages, from improved gut health and metabolic regulation to potential anticancer and neuroprotective effects. Ongoing research continues to elucidate the diverse ways in which mango's bioactive compounds exert their beneficial effects, making it a subject of great interest for further exploration in the realms of food science and nutraceutical development. Mangoes are generally sweet and can be used in Bakery products [9]. Mangoes are an ideal way to increase immunity since they are an excellent source of vitamin C, and unripe mangoes have more vitamin C than ripe ones [10].

The composition of bioactive compounds, including diverse phenolic derivatives, varies significantly among different mango cultivars, as well as in different parts of the fruit, such as the pulp, peel, seed, and seed husk [11]. These compounds exhibit different antioxidant activities, which can be ranked as follows: seed > peel > pulp. Factors such as genetics, environmental conditions, maturity stage, and postharvest handling further influence the concentration and profile of these bioactive molecules. This variability presents both a challenge and an opportunity for researchers to identify and optimize the use of specific mango varieties or fruit fractions to maximize their health-promoting properties. The antioxidant components found in mangoes, such as carotenes, flavonoids, and vitamin C, together with vitamin B, fibre, and minerals like magnesium, help prevent colon cancer and promote cardiovascular health [12]. The rich combination of nutrients in mango makes it a potent immune booster, protects the body from free radical damage, and promotes healthy skin and hair [13]. This review aims to comprehensively explore the biochemical composition of mango fruits, focusing on primary and secondary metabolites, their biosynthesis, and their roles in human health. It further examines the biochemical mechanisms underlying mango's physiological effects, the impact of post-harvest processing on nutrient retention, and the fruit's emerging applications in the food and health industries. By synthesizing current findings from biochemistry, nutrition, and pharmacology, this paper provides a detailed insight into the multifaceted value of mango as both a food and a functional health-promoting agent.

BIOCHEMICAL COMPOSITION OF MANGO FRUITS

The nutritional and health-promoting qualities of mango fruits are attributed to their abundance of several biochemical components. These substances fall into two general categories: primary metabolites, which include organic acids, amino acids, and carbohydrates, and secondary metabolites, which include volatile organic compounds, polyphenols, and carotenoids [14]. Mangoes are a vital part of the human diet because each of these classes contributes significantly to their flavour, scent, nutritional value, and possible health advantages. Nutrients like carbohydrates, vitamin C, and vitamin A are all found in good amounts in mangos [1]. Table 1 displays the nutritional makeup of mango pulp, peel, and seed. Figure 1 displays the flowchart of primary and secondary metabolites in mango.

Table 1: Mango Peel, Seed, and Pulp Nutritional Composition

Nutrient	Pulp (per 100g)	Peel (per 100g)	Seed Kernel (per 100g)
Moisture (%)	83–85	70–75	10–12
Carbohydrates (g)	14–16	10–12	60–70
Proteins (g)	0.8–1.0	2.0–3.0	6–10
Lipids (g)	0.3–0.5	1.5–3.5	8–13
Dietary Fiber (g)	1.6–1.8	4.0–6.0	2–4
Vitamin C (mg)	27–36	45–60	10–15
Total Phenolics (mg GAE)	20–50	100–200	80–150
Carotenoids (μg)	640–1100	200–500	50–150
Minerals (Ca, Mg, Fe)	Present	Higher than pulp	Moderate

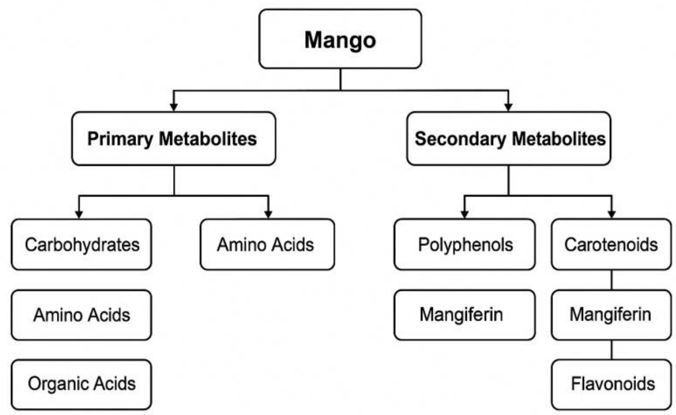

Figure 1 Flowchart of primary and secondary metabolites in mango.

Primary Metabolites

Primary metabolites in mango fruits are essential for the basic metabolic processes and include sugars, organic acids, amino acids, and lipids [15]. These compounds not only serve as energy sources and building blocks for cellular components but also contribute to the overall flavour profile and sensory attributes of the fruit. Sugars are the primary carbohydrates in mangoes, with sucrose, fructose, and glucose being the most abundant [16]. The specific ratios of these sugars vary depending on the mango variety and maturity stage, influencing the sweetness of the fruit. Mangoes are tart and acidic due to organic acids like citric, malic, and succinic acids. The concentration of these acids typically decreases as the fruit ripens, leading to a sweeter and less acidic taste. Amino acids are present in relatively small amounts but are crucial for protein synthesis and contribute to the overall nutritional value. Mangoes also contain a variety of lipids, including triglycerides and fatty acids, which contribute to the fruit's consistency in flavour and texture.

Secondary Metabolites

Despite not being directly involved in the basic metabolic processes, secondary metabolites are a diverse range of chemicals that are important for flavour, colour, and plant defence. In mangoes, the major secondary metabolites include polyphenols, carotenoids, and volatile organic compounds, each contributing unique attributes to the fruit's health-promoting properties. Flavonoids, phenolic acids, and tannins are all members of the broad family of chemicals known as polyphenols. These substances are well-known for their anti-inflammatory and antioxidant qualities, which lower the risk of chronic illnesses and provide other health advantages [17]. Carotenoids are pigments responsible for the vibrant colours of mangoes, ranging from yellow to orange and red. β-carotene is the most abundant carotenoid in mangoes, and it is a precursor to vitamin A, which is necessary for cell growth, immunological response, and eyesight. Volatile organic compounds are responsible for the characteristic aroma of mangoes. They include terpenes, esters, and aldehydes, which collectively contribute to the complex and appealing fragrance of the fruit. The manalagi mango is a popular variety known for its thick, dense flesh, sweet taste, appealing aroma, and vitamin C content [18]. The morphological, physiological, biochemical, mineral, and organoleptic characteristics of twenty mango genotypes cultivated on the Himalayan plains have been described [19].

Vitamin and Mineral Biochemistry

Mango fruits are a notable source of essential vitamins and minerals that contribute to their nutritional value. Mangoes contain several fifteen phenolic compounds, four fatty acids, three tocopherol isomers, and organic acids [20]. Vitamin C, a potent antioxidant, is found in high concentrations in many mango varieties, supporting immune function and collagen synthesis. Vitamin A, derived from β-carotene, is crucial for vision, cell growth, and immune function. Mangoes also provide vitamins B6 and E, which are important for neurological function and antioxidant defence, respectively. In addition to vitamins, mangoes contain essential minerals such as potassium, copper, and magnesium. Potassium helps regulate blood pressure and muscle function, copper is necessary for enzyme activity and iron metabolism, and magnesium is involved in energy production and bone health. The peel and seed contain benzophenones, flavonoids, and anthocyanins [21]. Postharvest light exposure in mangoes enhances the accumulation of flavonoids, which are beneficial secondary metabolites [22].

Mangoes extensively grown in warm and subtropical climates and are highly valued for their flavour, nutritional content, and cultural significance [23]. Characterization of mango germplasm is essential for identifying desired traits for breeding programs [24]. The unique combination of vitamins, minerals, and antioxidants in mangoes makes them a valuable addition to a balanced diet, supporting overall health and well-being. The fruit's organic substance oxidizes and decomposes into water and carbon dioxide, producing a significant quantity of energy [16]. Mangoes are therefore an excellent source of vitamins, minerals, and energy. The acids in unripe mango pulp stimulate bile secretion and act as an intestinal antiseptic [10]. Unripe mango fruit has historically been used in the preparation of various products like pickle, chutney, and dried mango powder [25]. Mango germplasm needs to be preserved since it may have useful resistance to many illnesses [26]. The post-harvest losses of this climacteric fruit are significant due to a lack of proper preservation and processing technologies [27].

Mango peels, often regarded as industrial waste, present a compelling opportunity for valorization due to their rich composition of pectin, cellulose, hemicellulose, lipids, proteins, and enzymes [28]. These peels are also a source of prebiotics and antioxidants, which could be beneficial to human health [29]. Mango peels are produced in substantial quantities by the food processing and agriculture industries and can be further transformed into valuable products, decreasing environmental problems at all levels [30], [31]. Mangoes are an excellent source of bioactive compounds; thus, the use of pre-treatment drying procedures on mango byproducts is a viable option for preserving the active flavouring co [32]. Mango peels contain a high phenolic content, particularly B-type catechin dimers, and exhibit cytotoxicity and anti-inflammatory activity [33]. Recent research indicates that mango peels may have anti-cancer properties, which could be useful in the nutraceutical and pharmaceutical industries. The mango industry has explored various processing techniques to extend shelf life and create new products, including brine-pickled items, syrups, semi-dried and dried products [34]. Mango peel powder can be added to instant drinks to enhance their nutritional profile, thus exploring the use of mango peel in the formulation of instant drinks serves as an experiment to harness its nutrients [35].

Mangoes are abundant in necessary macro and micronutrients. The major macroelements found in mangoes include potassium, calcium, and magnesium. Potassium is essential for controlling blood pressure and muscular contraction, while calcium is vital for bone health and muscle contraction. Magnesium, on the other hand, takes part in the generation of energy and enzymatic reactions. In addition to these macroelements, mangoes also contain important micronutrients such as iron, zinc, and copper. Red blood cell production and oxygen transport depend on iron, wound healing and immunological response depend on zinc, and copper is required for various enzymatic processes and iron metabolism. These essential macro and microelements contribute to the overall nutritional value and health benefits associated with consuming mangoes. Mangoes stand out as a valuable source of nutrients and enzymes that promote human health [36].

Biochemical Pathways and Functional Mechanisms

Mangoes are known for their diverse biochemical pathways and functional mechanisms, which contribute to their unique flavour, aroma, and health benefits. During ripening, mangoes undergo significant biochemical changes, including starch breakdown, sugar accumulation, and the synthesis of volatile compounds. These processes are regulated by various enzymes and metabolic pathways. The cell wall is broken down by enzymes during the fruit softening process, leading to changes in texture and mouthfeel. Mangoes produce a variety of volatile compounds, such as terpenes, esters, and aldehydes, which contribute to their characteristic aroma.

The functional mechanisms of mangoes extend beyond their nutritional composition. Mango bioactive substances such polyphenols and carotenoids have anti-inflammatory, anti-cancer, and antioxidant qualities [37]. These substances can alter gene expression and cellular signalling pathways, which can affect several physiological functions. Research has focused on understanding the molecular mechanisms underlying these health benefits. To maintain the quality of mangoes during storage and transportation, different techniques have been developed to delay ripening, reduce decay, and extend shelf life. These techniques include modified atmosphere packaging, cold storage, and the application of ethylene inhibitors. Postharvest treatments can influence the activity of enzymes involved in ripening and senescence [16], [38].

Biosynthesis of Mangiferin and Phenolics

Mangiferin, a bioactive compound found in mangoes, is synthesized through a complex biosynthetic pathway involving various enzymes and precursors. The shikimate pathway, which yields the aromatic amino acids phenylalanine and tyrosine, is the first step in the biosynthesis of mangiferin. These aromatic amino acids are then converted into phenylpropanoids, which serve as building blocks for the synthesis of flavonoids and other phenolic compounds. The biosynthesis of mangiferin involves the condensation of a phenylpropanoid unit with a sugar moiety, followed by a series of enzymatic modifications. The enzymes involved in mangiferin biosynthesis include chalcone synthase, chalconeisomerase, and flavonoid glucosyltransferase. The biosynthesis of other phenolic compounds in mangoes follows similar pathways, with variations in the specific enzymes and precursors involved. [2], [39].

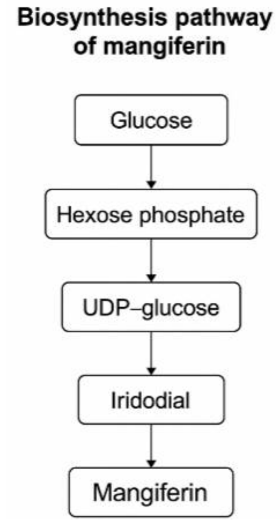

Figure 2 Biosynthesis pathway of mangiferin.

Antioxidant Mechanisms: scavenging of ROS

Mangoes contain a variety of antioxidant compounds that play a vital function in preventing oxidative damage to cells and scavenging reactive oxygen radicals [40]. These antioxidants include polyphenols, carotenoids, and vitamins, which act through different mechanisms to neutralize free radicals and prevent oxidative stress. Polyphenols, such as mangiferin and quercetin, possess hydroxyl groups that can donate electrons to stabilize free radicals. The antioxidant mechanisms of mangoes extend beyond direct scavenging of ROS.

Enzymatic activity (e.g., polyphenol oxidase) in ripening

During ripening, mangoes undergo significant enzymatic changes that contribute to the development of their characteristic flavour, aroma, and texture. These enzymatic activities include starch hydrolysis, cell wall degradation, and volatile compound synthesis. Amylase activity increases during ripening, leading to the breakdown of starch into sugars, which contributes to the sweetness of ripe mangoes [41]. Fruit tissue becomes softer because of the activation of cell wall-degrading enzymes during ripening, such as pectinase and cellulase. Mangiferin's ability to modulate metabolic irregularities and its anti-inflammatory and antioxidant properties have attracted a lot of research; studies have shown that it may help treat metabolic diseases in both humans and animal models [42]. Additionally, mangoes contain secondary metabolites called xanthones, which have a variety of biological actions such as antibacterial, antifungal, anti-inflammatory, and antioxidant qualities [43].

Post-harvest biochemical changes

Post-harvest handling significantly impacts the biochemical processes in mangoes, determining their quality and shelf life. During mango storage and transit, ethylene production can be inhibited by physical and chemical techniques, reducing ripening and senescence. [16].

Harvest maturity, ripening, and treatments using elicitors such as methyl jasmonate and salicylic acid, as well as the availability of enzyme cofactors, influence the concentration of health-promoting compounds [44]. Mango peel accumulation of flavonoids such as flavanols, proanthocyanidins, and anthocyanins is impacted by postharvest light treatment; this treatment also influences fruit quality indicators such as colour, firmness, total soluble solids, total organic acid content, and the solidity-acid ratio [22]. Low doses of gamma radiation have demonstrated the ability to reduce pathogen severity, assist in the ripening process, and preserve chemical properties without damaging the pulp [45]. Treating mangoes with 1-methylcyclopropene (1-MCP) and packaging them in Xtend® bags can improve their quality and extend their shelf life [46]. The mango supply chain emphasizes the critical role of harvesting, pretreatment, packaging, storage, and distribution in preserving fruit quality [47].

The integration of active packaging films, enriched with carboxymethyl cellulose from bleached bagasse, has shown promise in extending the shelf life of mangoes while preserving their physicochemical properties [48].

Harvesting practices significantly determine mango quality, with adherence to proper techniques being essential to prevent mechanical damage [47]. The effects of postharvest treatments, such as irradiation, on the physicochemical and sensory qualities of mangoes must be carefully considered to ensure both safety and consumer acceptance [49]. Mango quality can be evaluated using non-destructive techniques such nuclear magnetic resonance, X-ray, computed tomography, electronic nose, machine vision, ultrasound, and near-infrared spectroscopy [50]. Using better postharvest management techniques and preharvest fruit bagging can help reduce losses and control fruit quality all the way through the mango value chain [51]. Pre-harvest treatments can impact the shelf life and morphological characteristics of mangoes, offering potential strategies for extending their marketability [52]. Irradiating mangoes under nitrogen atmosphere minimizes changes in organoleptic quality, ascorbic acid, and carotenoids, while also reducing fruit spoilage [53].

Health Benefits and Biochemical Mechanisms

There is several health benefits associated with mangoes because of its rich nutritional and phytochemical composition. Antioxidants including beta-carotene, vitamin C, and mangiferin, which are abundant in mangoes, boost immunity and reduce oxidative stress. When combined with digestive enzymes, their dietary fibre improves digestion and promotes gut health. Furthermore, the high vitamin A and C content benefits the health of the skin, eyes, and hair. Additionally, its bioactive components include anti-inflammatory qualities that may help heart health and may also help manage risk factors for diabetes or reduce the risk of several types of cancer. The health benefits associated with mango fruit is shown in Table 2.

Table 2: Health Benefits Associated with Major Mango Phytochemicals

Phytochemical	**Source (Pulp/Peel/Seed)**	**Biological Activity / Health Benefit**
Mangiferin	Peel, Seed	Antioxidant, anti-inflammatory, anti-diabetic
Quercetin	Peel, Pulp	Antiviral, anti-cancer, cardiovascular protection
Gallic acid	Seed, Peel	Antioxidant, antimicrobial, hepatoprotective
Catechins	Seed	Cardioprotective, anti-obesity, neuroprotective
Carotenoids (e.g. β-carotene)	Pulp	Eye health, immune support, antioxidant
Ascorbic Acid (Vitamin C)	Pulp, Peel	Immune function, collagen synthesis, free radical scavenging
Tannins	Seed, Peel	Antimicrobial, anti-parasitic, antioxidant
Phenolic acids	All parts	Anti-inflammatory, anti-mutagenic, neuroprotective

Antioxidant and Anti-inflammatory Effects

The bioactive substances found in mangoes, such as polyphenols, carotenoids, and vitamins, are abundant and varied and together offer strong anti-inflammatory and antioxidant effects. These substances are essential for controlling inflammation and oxidative stress, two major underlying causes of the onset and advancement of chronic illnesses. The health benefits associated with mango consumption are intricately linked to the complex interplay and synergistic effects of the various bioactive constituents within the fruit, which interact with multiple cellular pathways and signalling mechanisms to elicit their protective effects. Known for their strong antioxidant properties, mangoes contain a variety of phenolics, such as flavonoids, tannins, and phenolic acids. Mangiferin, a peculiar C-glucosylxanthone that is mostly present in mangoes, is a particularly strong anti-inflammatory and antioxidant substance that has attracted a lot of interest due to its possible medical uses. [54]

Modulation of the nuclear factor-kappa B and nuclear factor erythroid 2-related factor 2 pathways are two important molecular pathways that mediate the antioxidant and anti-inflammatory properties of mangoes and their bioactive constituents. The transcription factor NF-κB is essential for controlling the expression of genes that promote inflammation, such as adhesion molecules, cytokines, and chemokines. By inhibiting NF-κB activation, mango bioactive can effectively dampen the inflammatory response and reduce producing pro-inflammatory mediators. The Nrf2 pathway, on the other hand, is an essential modulator of the antioxidant defences of cells. activation of Nrf2 leads to the upregulation of Antioxidant enzymes that aid in scavenging free radicals and shielding cells from oxidative damage include glutathione peroxidase, catalase, and superoxide dismutase. Mango polyphenolics have demonstrated to reduce inflammatory reactions by modulating the PI3K/AKT/mTOR pathway, potentially through the upregulation of microRNA-126 expression [55]. There is a biological basis for the anti-inflammatory benefits of mango extracts, which have demonstrated potential in blocking the synthesis of pro-inflammatory mediators such as prostaglandin E2 by targeting COX enzymes [56]. Mango consumption has been linked to beneficial immunomodulatory effects in humans, including a rise in the proportion of natural killer cells and improvements in the proliferation response of stimulated T lymphocytes [57]. The immunomodulatory and anti-inflammatory properties of polyphenols, including those found in mangoes, stem from their capacity to inhibit enzymes like xanthine oxidase and NADPH oxidase, which are involved in the generation of reactive oxygen species, along with their ability to upregulate endogenous antioxidant enzymes [58].

Mangiferin, a significant constituent of mangoes, possesses a redox-active aromatic system and antioxidant properties, which makes it a potential agent for treating metabolic disorders [59]. Mangiferin, found in various plant species including mangoes, exhibits strong antiradical and antioxidant properties due to its four aromatic hydroxyl groups, and it dissolves well in water, facilitating its extraction into infusions [54]. Mangiferin also modulates key inflammatory pathways, which may help prevent cancer progression [60]. The anti-inflammatory properties of compounds such as alpha-mangostin, found in other tropical fruits, highlight the potential of mangoes in managing inflammation-related conditions [61]. Mango seed extracts exhibit antiplatelet activity, likely due to their rich composition comprising benzophenones, ellagic acid, mangiferin, tetra- and penta-galloylglucose, and monogalloyl substances, suggesting that mango seeds could be a natural source of antiplatelet compounds for functional foods [62]. Mangiferin from mangoes can hinder lipid peroxidation, protecting against physiological stresses, enhancing the monocyte-macrophage system, and combating both Gram-positive and Gram-negative bacteria [63]. Traditional medicine practices in regions like India and East Asia have long utilized *Mangifera indica* for its anti-diabetic, anti-viral, anti-inflammatory, and anti-cancer properties, underscoring the historical recognition of mangoes' therapeutic potential

Cardiovascular and Metabolic Health

Mangoes contribute significantly to cardiovascular and metabolic well-being, primarily because of their inherent ability to modulate critical physiological pathways implicated in the pathogenesis of cardiovascular and metabolic disorders. Bioactive molecules found in mangoes such as mangiferin, polyphenols, and dietary fibres, have been demonstrated to have numerous positive impacts on lipid metabolism, glucose homeostasis, and vascular function.

Clinical trials and animal studies have consistently demonstrated the capacity of mangoes to favourably influence lipid profiles, leading to reductions in while concurrently raising HDL cholesterol levels, total cholesterol, LDL cholesterol, and triglycerides. Since raised LDL cholesterol and triglycerides are a major contributing factor to atherosclerosis and coronary heart disease, these changes in lipid metabolism are especially pertinent in these conditions. Mangoes contain bioactive compounds that improve insulin sensitivity and glucose metabolism, which may help in the management of diabetes [64]. Preclinical investigations have revealed that mangiferin and other mango-derived polyphenols can enhance insulin signalling, augment glucose uptake in peripheral tissues, and suppress hepatic glucose production.

Furthermore, mangoes have natural vasoprotective qualities that show themselves in a variety of ways, including as improved endothelial function, decreased oxidative stress, and decreased vascular inflammation. Mangoes contain dietary fibres and antioxidants that reduce blood pressure, lower the risk of heart disease, and protect against hypertension and stroke. The consumption of mangoes may thus lower the risk of cardiovascular and metabolic diseases by modulating gut microbiota and producing beneficial metabolites. Regular intake of mangoes can improve gut health, because it is a strong source of vitamins and minerals, it can strengthen the immune system and lower the risk of chronic diseases. [65], [66]

Anticancer and Immunomodulatory Potential

Mangoes have demonstrated promising anticancer and immunomodulatory potential. Their bioactive constituents, including polyphenols, carotenoids, and vitamin C, synergistically contribute to these health-promoting effects. Strong antioxidant and anti-inflammatory qualities are exhibited by mango polyphenols, such as mangiferin, quercetin, and gallic acid, which can shield cells from DNA damage, stop the growth of cancer cells, and trigger apoptosis. Mango extracts and isolated chemicals have been demonstrated in both in vitro and in vivo experiments to inhibit the growth and metastasis of a variety of cancer cell lines, including those from the breast, colon, lung, and prostate.

The consumption of mangoes could be a useful addition to a balanced diet, given that current scientific knowledge of the fruit's health advantages suggests that it and its byproducts contain bioactive components [65]. The anticancer properties of mangoes are associated with their ability to modulate critical Signalling pathways that contribute to the survival of cells, proliferation, and apoptosis. For instance, mangiferin has been demonstrated to block the PI3K/Akt/mTOR pathway, which is commonly dysregulated in cancer cells and causes apoptosis and cell cycle arrest [67]. Mangoes have demonstrated promising anticancer and immunomodulatory potential. Vitamin C, which is abundant in mangoes, boosts the immune system by promoting the production and activity of white blood cells. Carotenoids, like beta-carotene, which the body converts to vitamin A, also support immune function by preserving the integrity of mucosal barriers and boosting immune cell activity.

Mango consumption over a 12-week period can improve vascular health, boost antioxidant enzyme activity, and positively modulate immune and inflammatory markers [68]. The high dietary fibre content in mangoes also plays a crucial role in supporting immune health by promoting the growth of beneficial gut bacteria, which in turn modulates the immune response and reduces inflammation.

Digestive and Gut Health

Mangoes have positive effects on digestive and gut health. Mango polyphenols have been shown to promote the development of good gut bacteria like Lactobacilli and Bifidobacteria while preventing the growth of harmful bacteria like Salmonella and E. coli. These beneficial changes in gut microbiota composition can enhance intestinal barrier function, improve nutrient absorption, and reduce inflammation in the gut. Mangoes' dietary fibre content helps avoid constipation and encourages intestinal regularity. The dietary fibre in mangoes encourages regular bowel movements and helps avoid constipation [66]. Mangoes can improve gut health and lower the chance of developing chronic illnesses, especially because they are a great source of vitamins and minerals [69], [70]. Regular intake of mangoes can improve gut health, boost the immune system, and lower the chance of developing chronic illnesses because it contains a lot of vitamins and minerals [69].

Mango peel, often regarded as a byproduct of processing, is now recognized for its high dietary fibre and pectin content, with its pectin derivatives, specifically pectic oligosaccharides, garnering attention as novel prebiotics [71]. Mango peel's prebiotic properties have been shown to promote the development of good bacteria in the gut, including as Lactobacillus and Bifidobacterium species [72].

Neuroprotective and Dermatological Benefits

Mangoes exhibit neuroprotective effects that can protect brain cells prevent harm, enhance mental performance, and lower the chance of neurodegenerative illnesses. Mangoes exert dermatological benefits by protecting the skin from UV radiation, reducing inflammation, and promoting wound healing. Mango consumption has been linked to improvements in skin hydration, elasticity, and overall appearance. Mangoes are rich in vitamin A and other retinoids, which are essential for maintaining skin health, promoting cell turnover, and preventing acne and other skin conditions [73].

Recent research suggests that mangiferin, a bioactive compound found in mangoes, may protect skin cells from UVB radiation damage by enhancing antioxidant defences and reducing inflammation [20]. Mangoes are rich in vitamin A and other retinoids, which are essential for maintaining skin health, promoting cell turnover, and preventing acne and other skin conditions.

Since oxidative stress is a primary cause of neurodegenerative disorders, antioxidants and cognitive protection go hand in hand. Given that current scientific understanding of the fruit's health benefits indicates that it and its byproducts include bioactive components, eating mangoes could be a helpful complement to a balanced diet.[65]

Skin barrier effects of vitamins A and C, which are abundant in mangoes, support healthy, radiant skin by encouraging collagen synthesis and reducing oxidative stress brought on by environmental aggressors. Mango fruit is frequently employed in traditional Chinese medicine to address a variety of ailments, such as asthma, constipation, vomiting, and seasickness [74].

Mangoes' neuroprotective properties are attributed to their ability to mitigate oxidative stress in the brain [75], [76]. Studies have shown that mango extracts and isolated compounds can reduce the production of reactive oxygen species and increase the activity of antioxidant enzymes in brain cells [76]. These protective effects can help prevent neuronal damage and cognitive decline associated with aging and neurodegenerative diseases like Alzheimer's and Parkinson's. Mangiferin, a xanthoneglucoside found in mangoes and other plants, has demonstrated neuroprotective effects by activating the Nrf2 signalling pathway, which is critical in maintaining cellular redox homeostasis [77], [78].

The utilization of tropical fruit by-products, such as seeds and skins, presents promising avenues for the cosmeceutical industry, offering sustainable and innovative approaches to address oxidative stress, hyperpigmentation, acne, aging, and UV radiation [79].

Biochemical Changes During Ripening and Processing

During ripening and processing, mangoes undergo significant biochemical changes that affect their nutritional value, sensory attributes, and overall quality. Mangoes have several biochemical changes during ripening, including starch breakdown, acid conversion, and ethylene production. The softening of mangoes is a complex process influenced by the activity of enzymes that break down cell walls, including pectin methylesterase, polygalacturonase, and cellulase. These enzymes break down the complex carbohydrates and pectin in the cell walls, leading to a decrease in fruit firmness and changes in texture [80]. Starch breakdown is a major biochemical change that occurs during mango ripening. The conversion of starch to sugars, such as glucose, fructose, and sucrose, results in the characteristic sweetness of ripe mangoes. Acid conversion also occurs during ripening, involving the conversion of organic acids into sugars, such as citric and malic acid.

Ethylene production is a critical factor in mango ripening. This plant hormone triggers a series of metabolic processes that result in changes in fruit colour, aroma, and texture [81]. Various postharvest treatments, such as 1-methylcyclopropene (1-MCP) application, have been shown to delay ripening They prolong mangoes' shelf life by inhibiting the synthesis of ethylene and lowering the activity of enzymes that break down cell walls [82][46].

Ethylene production increases during ripening, causing colour, scent, and texture changes in the fruit [83]. 1-Methylcyclopropene (1-MCP) treatment, for example, can slow down ripening and extend shelf life by inhibiting ethylene production and cell wall-degrading enzymes [80]. During processing, mangoes are subjected to various treatments, such as heat, drying, and freezing, which can affect their nutritional content and sensory properties. Enzymatic browning, caused by polyphenol oxidase activity, can be inhibited by using pretreatments like ascorbic acid or blanching.

Mango purée pretreatment at 90°C for 150 seconds inactivates browning enzymes [84].The degradation of heat-sensitive vitamins, such as vitamin C and vitamin A, can be minimized by optimizing the processing conditions and using appropriate packaging materials. Irradiation treatments have been shown to influence the maturity index of mangoes, with irradiated fruits exhibiting lower values for texture compared to control samples [85]. During processing, controlled conditions such as specific temperatures and packaging materials can help maintain vitamins like C and A [1].

The application of ionizing radiation to mangoes can affect their postharvest quality characteristics, influencing sensory and physicochemical attributes [86]. Irradiation can affect fruit texture; irradiated samples soften early in storage, and pH changes are less noticeable than in non-irradiated controls [87]. In general, irradiation can improve the shelf life and quality of mangoes by controlling microbial growth and delaying ripening [88]. Specifically, irradiation inhibits the loss of green skin colour associated with fruit ripening [89]. Additionally, irradiation at certain doses can reduce the production of aroma volatiles in mangoes, which may affect their sensory appeal [89].

Quarantine treatments, such as irradiation, can affect the carbohydrate and organic acid content of mangoes [90]. A dose of 150 Gy is considered a safe quarantine treatment for mangoes that are being exported to prevent pests. Irradiating mangoes has only been shown to have a minor impact on their ascorbic acid content [91].

Irradiation is a promising alternative to fumigation, but the non-uniform dose distribution in pallet loads necessitates accurate dose calculation [92]. The feasibility of hydrothermal treatments is limited by fruit quality, particularly when the treatment is done before the fruit reaches adequate physiological maturity [49]. Additionally, the use of synthetic 2-ethyl-5-methylpyrazine and bacterial volatiles to suppress anthracnose while improving fruit quality shows potential for postharvest mango management during storage and transit [93]. The integration of appropriate postharvest treatments and storage conditions is essential to maintain mango quality and extend shelf life.

The current technology can preserve mangoes for about four weeks [94]. Trade is facilitated and unjust trade restrictions are reduced by sanitary and phytosanitary agreements and Technical Barriers to Trade under GATT [94]. Vitamin degradation, textural changes, and flavour loss can all be reduced by proper packaging, storage, and processing techniques. Retention of bioactive during drying/freezing of fruit and vegetable pieces is highly dependent on the glass transition temperature, which dictates the degree of structural collapse at different moisture levels and temperatures.

Applications in Food, Nutraceuticals, and Biochemical Research

Mangoes possess a broad variety of uses in food, nutraceuticals, and biochemical research due to their rich nutritional composition and bioactive compounds. Mangoes are widely consumed fresh or processed into various food products, including juices, jams, pickles, and desserts [8]. Mango pulp is utilized in the beverage, confectionery, and dairy industries. Mangoes are a reliable source of provitamin A carotenoids, vitamin C, and dietary fibre.

Green mangoes are rich in vitamin C, thus boosting immunity [10]. Mango peels contain triterpenoids with anti-diabetic, anti-inflammatory, and anti-cancer properties.

In addition to vitamins E and C, fibre, cellulose, hemicellulose, lipids, protein, enzymes, pectin, and fats, mangoes are a fantastic source of bioactive substances such as polyphenols, carotenoids, and enzymes [3]. Mangoes are widely consumed fresh or processed, and they are appreciated for their health-promoting properties.

In addition to food applications, mangoes have gained attention in nutraceuticals and functional foods due to their potential health benefits. Mangoes are used to make nectar, drinks, jam, jelly, and leather. Mango processing waste has a lot of nutrients and antioxidants, which makes it useful for functional foods [1]. Mango seed kernel, peel, and pulp are abundant in bioactive substances. Mango peel is a source of phytochemicals with potential health benefits [7]. The leaves of the mango plant also possess various health benefits due to the presence of phytochemicals like mangiferin, phenolic acids, and flavonoids [6].

Mango kernel extracts have shown potential in managing hyperlipidaemia. Many Tropical fruits, including papaya, pineapple, bananas, and mangos, contain beneficial phenolic compounds and polysaccharides [95]. Moreover, mangoes are used in cosmetics due to their antioxidant properties, it can shield the skin from the harm that free radicals can do [4], [9], [38].

Functional food formulations can contain mangoes because of their high nutritional and antioxidant contents. Certain mango varieties remain green even when ripe [18]. The fruit is widely consumed because of its pleasant flavour, scent, and high concentration of nutrients and phytochemicals [14].

Limitations and Future Biochemical Research Directions

While mangoes offer numerous health-promoting benefits, some limitations and important future research directions need to be considered.

Further rigorous research is required to fully investigate the bioavailability and physiological efficacy of the diverse bioactive compounds present in mangoes when consumed by humans [38]. Determining the precise mechanisms by which mango-derived phytochemicals, vitamins, and other nutrients are absorbed, distributed, and exert their beneficial effects in the body is crucial to substantiating the purported health claims associated with mango consumption.

Additionally, research is needed to identify the optimal processing and extraction methods that can maximize retention and stability of mangoes valuable bioactive components in food, nutraceutical, and other mango-based products. Preservation of the fruit's nutritional and functional properties during various manufacturing and preservation techniques, such as drying, freezing, and canning, warrants further in-depth investigation.[1]

Additionally, clinical trials are required to validate the health benefits of mango consumption and to determine optimal dosages for therapeutic applications [96]. Exploring novel extraction techniques, such as the recovery of bioactive components from mango by-products can be improved using supercritical fluid extraction and enzyme-assisted extraction techniques [11]. Investigating the synergistic effects of combining mango extracts with other natural compounds can lead to the development of more effective nutraceutical formulations [25].

Future research should focus on developing new mango varieties with enhanced nutritional profiles and improved postharvest characteristics. This could involve genetic and genomic approaches to identify key genes and enzymes responsible for the biosynthesis of valuable bioactive compounds in mangoes.[65]. Comprehensive studies are needed to better understand the biochemical variability among different mango cultivars, at various maturity stages, and under diverse environmental conditions. This knowledge could aid in the strategic selection and management of mango varieties to maximize the retention of beneficial phytochemicals and nutritional quality.[7]

Molecular-level investigations are crucial to elucidate the specific genetic and enzymatic mechanisms underpinning the production of mango's diverse bioactive compounds, such as antioxidants, vitamins, and health-promoting secondary metabolites. Leveraging this mechanistic understanding can enable targeted genetic improvement strategies to enhance the nutritional and functional properties of mangoes.[8] Integrating advanced biochemical, genomic, and metabolomic analyses will be essential to fully characterize the phytochemical diversity within the mango germplasm. This comprehensive evaluation of mango's biochemical composition can inform the selection and development of superior varieties with enhanced nutritional profiles and postharvest performance.[2]

Mangoes have emerged as a promising subject of pharmacological research, with scientists actively exploring their potential for developing novel medications and therapeutic interventions. The rich nutritional profile and diverse bioactive compounds found in mangoes are driving growing interest in harnessing their medicinal properties [12], [97].

The health-promoting benefits of mangoes are gaining widespread recognition, which is fuelling increased demand and applications of this versatile tropical fruit across the food, medicinal, and cosmetic industries [12], [97]. The abundance of antioxidants, vitamins, minerals, and other beneficial phytochemicals in mangoes make them a valuable resource for developing functional foods, nutraceuticals, and skincare products that can offer tangible health advantages to consumers.

Standardized, well-designed clinical trials with comprehensive biochemical endpoints are still needed to rigorously validate the purported health benefits of mangoes, despite the encouraging preliminary data from various preclinical and observational studies. [44] The existing preclinical evidence, while promising, is not sufficient to make definitive claims about the efficacy of mango consumption for specific health outcomes. Conducting robust, placebo-controlled clinical trials that assess the impacts of mango intake on relevant biomarkers and clinical measures will be crucial to substantiating the health-promoting potential of this nutritionally rich tropical fruit. Such studies should explore the dose-dependent effects of mango consumption, identify optimal intake levels, and elucidate the underlying mechanisms by which mango-derived phytochemicals and nutrients exert their beneficial effects in humans. Only through this rigorous clinical validation can the full public health benefits of mangoes be realized and confidently communicated to consumers.[98]

The native Mangifera germplasm must be carefully assessed and preserved, both for its inherent value and because it may include useful resistance to many illnesses. The crop's perennial and monoembryonic characteristics make it ineffective to characterize mango germplasm purely based on visual attributes. By using genomic-based techniques, considerable genetic improvement in mangos can be greatly accelerated [26].

CONCLUSION

Mango (*Mangifera indica* L.) is a nutrient-rich tropical fruit with significant health and therapeutic potential. It contains key metabolites such as carbohydrates, amino acids, polyphenols, and carotenoids that contribute to antioxidant, anti-inflammatory, and anticancer activities. Mango supports cardiovascular, digestive, neuroprotective, and dermatological health. Beyond the pulp, the peel, seed, and leaves also offer value in food, pharmaceutical, and cosmetic applications. Scientific research confirms many of its health benefits, though further studies are needed to explore phytochemical bioavailability and optimal processing methods. Mango is increasingly recognized as a functional food for health promotion and disease prevention. Its nutritional profile and medicinal properties support its role in preventive healthcare. With growing demand for natural wellness solutions, mango holds great promise for future nutraceutical development. As research continues, mango can contribute to sustainable health innovations that benefit public well-being.

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