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Beyond leaves and silk: Expanding the role of fruit mulberry (*Morus* spp.) in functional foods

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Abstract

Mulberry (*Morus* spp.), historically cultivated for sericulture, is increasingly recognized as a multipurpose crop with significant potential in functional foods and sustainable agriculture. This review synthesizes current knowledge on the botanical diversity, nutritional composition, phytochemical profile and functional properties of mulberry fruits, with emphasis on anthocyanins, flavonoids, phenolic acids, vitamins and essential minerals. Evidence from *in vitro*, animal and limited human studies demonstrated strong antioxidant, anti-inflammatory, antidiabetic, cardioprotective, neuroprotective and antimicrobial activities, though clinical validation remains insufficient for definitive health claims. Advances in non-thermal processing, fermentation and encapsulation technologies support the development of juices, wines, vinegars, and nutraceuticals. Beyond nutrition, fruit mulberry contributes to sustainable agriculture through drought tolerance, carbon sequestration, soil conservation and agroforestry suitability. Fruit mulberry emerges as a scientifically promising yet underutilized crop capable of advancing human nutrition, income diversification and climate-resilient farming. Targeted breeding, standardized processing and robust clinical studies are essential to fully realize its potential.

1. Introduction

Mulberry has been cultivated to support sericulture feeding silkworms (*Bombyx mori*) for silk production. Originating in China and spreading *via* the Silk Road, mulberry's economic importance was almost entirely tied to leaf yield. The fruit and other plant parts, though consumed in traditional medicine and regional diets, received little scientific attention until recent decades (Maqsood *et al*., 2022; Sun *et al*., 2023).

A global paradigm shift is now underway. Declining silk trade, competition from synthetic fibres and rapidly growing demand for functional foods have prompted researchers and farmers alike to re-evaluate mulberry as a multipurpose crop (Mo *et al*., 2024). Phytochemical advances reveal that, mulberry fruits rival superfruits such as blueberries and acai in bioactive compound richness (Acharya *et al*., 2022). Simultaneously, the global functional food market exceeding USD 250 billion and expanding at 7-9 per cent annually presents substantial commercial opportunity (Hu *et al*., 2025). Climate pressures further reinforce mulberry's value: its drought tolerance, low-input requirements and suitability for marginal soils position it as an ideal climate-smart crop for smallholder farmers seeking income diversification (Mutebi, 2022; Rohela *et al*., 2020).

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2. Botanical and taxonomic overview

The genus *Morus* (family: *Moraceae*) comprises 10-16 species, with taxonomic complexity arising from natural hybridization and morphological diversity (Matiæ *et al*., 2023). The three primary species are *Morus alba* L. (white mulberry), *Morus nigra* L. (black mulberry) and *Morus rubra* L. (red mulberry). The species, *M. alba* is native to China and most widely cultivated which shows tremendous genetic diversity adapted to leaf production, fruit quality and ornamental use. *M. nigra*, native to southwestern Asia, bears large, anthocyanin-rich fruits preferred for fresh and processed consumption. *M. rubra* is native to eastern North America with distinct phytochemical profiles and temperate climate adaptation (Hussain *et al*., 2021).

Mulberry has an exceptionally wide geographic range spanning temperate to tropical zones across Asia, Europe, Africa and the America. The Himalayan foothills represent the center of origin and diversity (Vijayan *et al*., 2021). *M. alba* tolerates temperatures from -25°C to above 40°C and can grow with annual precipitation as low as 600 mm, enabling cultivation in semi-arid and high-altitude regions increasingly relevant under climate change projections (Oðuz *et al*., 2023).

Morphologically, mulberry trees reach 10-20 m in height with deep, extensive root systems that confer drought resistance and soil stabilization. Fruits are syncarps resembling blackberries, ranging 1-5 cm in length, with color (white, pink, red, purple, black) correlating with anthocyanin content. A critical agronomic constraint is high perishability: fruits have a shelf life of only 1-3 days at ambient temperature, necessitating prompt processing or refrigerated storage (Kamiloglu *et al*., 2013).

3. Nutritional composition and bioactive compounds

3.1 Macronutrients, vitamins and minerals

Fresh mulberry fruits contain 80-85 per cent moisture. Carbohydrates dominate dry weight (60-70%), primarily glucose and fructose, with soluble solids reaching 12-20 per cent depending on cultivar imparting natural sweetness suitable for processing with minimal added sugar. Protein content (1.5-3.0% fresh weight) is comparatively high among fruits and includes essential amino acids. Lipid content is low (0.3-0.6% fresh weight), primarily unsaturated fatty acids. Proximate composition is summarized in Table 1.

Vitamin C content ranges 10-50 mg/100 g. B-complex vitamins (thiamine, riboflavin, niacin, folate) are present in modest amounts. Potassium (150-300 mg/100 g) is the predominant mineral with low sodium content favorable for blood pressure regulation. Iron, Calcium, magnesium, zinc and manganese are also present whereas Iron content can reach 2-5 mg/100 g in selected genotypes. Mineral composition varies with soil environment and cultivar genetics, suggesting biofortification potential.

3.2 Phytochemicals: Anthocyanins, flavonoids, and phenolics

Mulberry fruits possess exceptionally high total phenolic content (100-600 mg GAE/100 g fresh weight), with black mulberry (*M. nigra*) producing the highest concentrations (Matiæ *et al*., 2023). Anthocyanins primarily cyanidin-3-glucoside and cyanidin-3-rutinoside confer the characteristic purple-black color and contribute substantially to antioxidant capacity, with total anthocyanin content ranging 50-400 mg/100 g fresh weight (Skrovankova *et al*., 2022). Key flavonoids include rutin (quercetin-3-rutinoside; 10-50 mg/100 g), quercetin and kaempferol, which support cardiovascular protection through endothelial function improvement and anti-inflammatory mechanisms. Phenolic acids mainly chlorogenic acid, caffeic acid, gallic acid add antioxidant, hypoglycemic and antimicrobial properties. Major phytochemicals are summarized in Table 2.

Table 1: Proximate nutritional composition of fresh mulberry fruits (per 100 g edible portion)

Component	Mean value	Notes on variation
Energy	43 kcal	Depends on cultivar and ripeness
Carbohydrates	9.8 g	Mostly glucose + fructose
Protein	1.4 g	Higher than most berries
Fat	0.4 g	Primarily unsaturated
Dietary fiber	1.7 g	Increases in darker varieties
Vitamin C	36.4 mg	Sensitive to storage
Calcium	39 mg	Soil-dependent
Iron	1.85 mg	Relatively high among fruits

Note: Values represent typical ranges across *Morus* spp. cultivars. Adapted from £ochyñska (2015), Sun *et al.* (2023), and Jan *et al.* (2021).

Table 2: Major phytochemicals identified in mulberry fruits

Compound class	Representative compounds	Typical concentration range
Anthocyanins	Cyanidin-3-glucoside, cyanidin-3-rutinoside	150-300 mg/100 g (black cultivars)
Phenolic acids	Chlorogenic acid, gallic acid	20-80 mg/100 g
Flavonoids	Quercetin, rutin, kaempferol	50-150 mg/100 g
Stilbenes	Resveratrol	0.5-3 mg/100 g
Alkaloids	1-Deoxynojirimycin (trace in fruit)	<1 mg/100 g

Note: Concentration ranges represent values across multiple studies and cultivars. Adapted from Dou *et al.* (2022), Kamiloglu *et al.* (2013) and Aramani *et al.* (2025).

3.3 Antioxidant capacity

Mulberry consistently ranks among fruits with the highest antioxidant capacity across standard assays. DPPH radical scavenging reaches 70-95 per cent at 1-5 mg/ml, comparable to blueberries and blackberries. FRAP values of 10-40 mmol Fe^{2+} equivalents/100 g are highest in black mulberry varieties. Mechanisms include direct free radical scavenging, metal chelation and upregulation of endogenous enzymes (SOD, CAT, GPx). *In vitro* digestion models confirm that a significant proportion of polyphenols survive gastric and intestinal digestion, with unabsorbed fractions metabolized by gut microbiota into systemic health-promoting metabolites (Dou *et al*., 2022).

3.4 Additional bioactive phytochemicals and their pharmacological significance

Beyond anthocyanins, flavonoids and phenolic acids, mulberry fruits contain several unique secondary metabolites that contribute to their pharmacological and nutraceutical potential. These compounds include iminosugars such as 1-deoxynojirimycin (DNJ), stilbenes such as resveratrol, benzofuran derivatives including moracin compounds and glycosylated phenolics such as mulberroside A^+. Although, these phytochemicals are often present in lower concentrations compared with major phenolics, they play significant role in the biological activities attributed to *Morus* species.

One of the most extensively studied compounds is 1-deoxynojirimycin (DNJ), an iminosugar that acts as a potent inhibitor of α-glucosidase enzymes in the intestinal brush border. By competitively inhibiting these enzymes, DNJ delays carbohydrate digestion and reduces postprandial glucose absorption. This mechanism has led to considerable interest in DNJ as a natural antidiabetic compound. Experimental studies demonstrate that DNJ-rich mulberry extracts significantly reduce postprandial blood glucose levels and improve insulin sensitivity in diabetic animal models. Although, DNJ is primarily concentrated in mulberry leaves, trace amounts have also been detected in mulberry fruits, contributing to the overall glycemic regulatory potential of mulberry-derived food products (Guo *et al*., 2018; Chen *et al*., 2021).

Mulberry fruits also contain stilbenoid compounds, particularly resveratrol, which is widely recognized for its antioxidant, cardioprotective and anti-aging properties. Resveratrol exerts biological effects through modulation of multiple molecular pathways, including activation of sirtuin-1 (SIRT1), inhibition of oxidative stress, and regulation of inflammatory signaling cascades such as NF-κB. These mechanisms contribute to improved endothelial function, reduced lipid peroxidation and protection against metabolic disorders. Although, resveratrol concentrations in mulberry fruits are lower than in grapes, its presence enhances the functional food value of mulberry products and contributes synergistically to their antioxidant capacity.

Another distinctive group of phytochemicals in *Morus* species includes moracin derivatives, which are benzofuran compounds reported in mulberry fruits, leaves and root bark. Moracin A, B, and C exhibit diverse pharmacological activities, including antibacterial, anti-inflammatory and anticancer effects. These compounds have been shown to inhibit bacterial growth through disruption of microbial cell membranes and interference with metabolic enzymes. In addition, moracin derivatives demonstrate cytotoxic activity against various cancer cell lines by inducing apoptosis and suppressing cell proliferation pathways.

Mulberroside A^{+}, a glycosylated stilbene derivative, is another important phytochemical reported in mulberry species. It has attracted attention for its potential dermatological and cosmetic applications due to its ability to inhibit tyrosinase activity, thereby reducing melanin synthesis. Consequently, mulberroside A^{+} is increasingly explored as a natural skin-whitening and photoprotective agent in cosmetic formulations. In addition to cosmetic applications, this compound also exhibits antioxidant and anti-inflammatory activities that contribute to the overall pharmacological profile of mulberry (Prasawang *et al*., 2025; Feng *et al*., 2022).

Collectively, these minor phytochemicals complement the major phenolic compounds present in mulberry fruits and enhance their therapeutic potential. The synergistic interactions among anthocyanins, flavonoids, DNJ, resveratrol and other bioactive constituents are believed to contribute to the wide range of biological activities observed in mulberry-based functional foods. However, despite promising experimental findings, further research involving well-designed clinical trials is necessary to confirm the pharmacological efficacy, bioavailability and optimal dosage of these compounds in human health applications. Mulberry fruits contain diverse classes of bioactive phytochemicals including anthocyanins, flavonoids, iminosugars, benzofuran derivatives and stilbene compounds. These phytochemical groups and their representative molecules are illustrated in Figure 1.

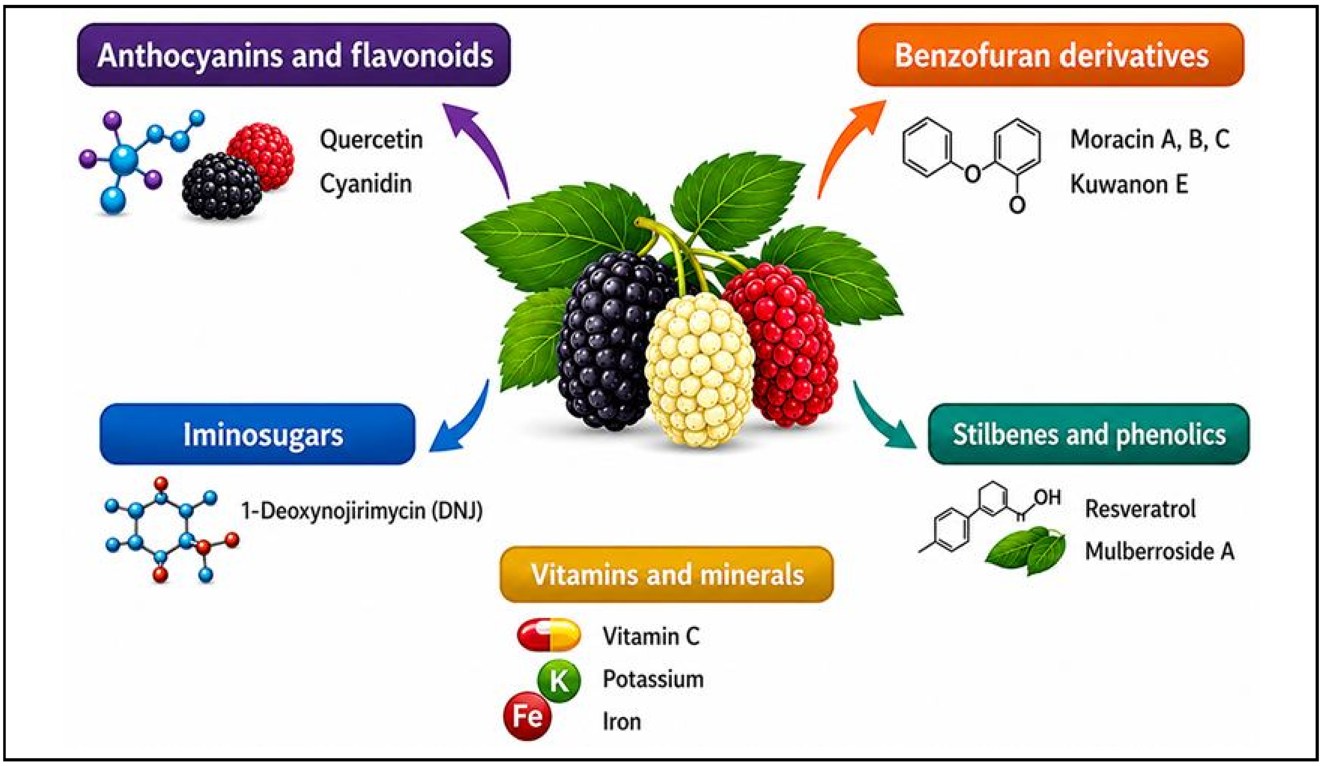

Figure 1: Phytochemical classes present in mulberry fruit and their representative bioactive compounds.

4. Health benefits and functional food applications

4.1 Antioxidant and anti-inflammatory properties

Mulberry polyphenols particularly anthocyanins and flavonoids scavenge reactive oxygen species (superoxide, hydroxyl radicals, hydrogen peroxide) and modulate key inflammatory pathways including NF-κB and MAPKs. *In vitro* and *in vivo* studies demonstrate inhibition of pro-inflammatory cytokines TNF-α, IL-6, IL-1β, and COX-2 (Abbas *et al*., 2024; Aramani *et al*., 2025). Mulberry vinegar has recently been shown to prevent LPS-induced cognitive impairment in mice *via* NF-κB regulation, underscoring the cross-benefit of processed mulberry products (Bang *et al*., 2025). While animal evidence is robust, human clinical data remain limited and further controlled trials are required.

4.2 Antidiabetic effects

Mulberry fruits and extracts exert antidiabetic action through multiple mechanisms: inhibition of α-glucosidase and α-amylase (reducing postprandial glucose spikes), enhancement of insulin sensitivity and protection of pancreatic beta cells from oxidative stress-induced apoptosis. Chlorogenic acid and anthocyanins are the primary active constituents. Animal studies consistently show reduced fasting blood glucose, improved glucose tolerance and GLUT4 upregulation. Preliminary human trials indicate reduced postprandial glucose and insulin levels and improved glycemic indices in prediabetes, though large randomized controlled trials are needed (Hu *et al*., 2025; Guo *et al*., 2018).

4.3 Cardiovascular and neuroprotective effects

Mulberry's high potassium-to-sodium ratio, combined with polyphenol-driven endothelial nitric oxide (NO) synthesis and ACE inhibition, supports blood pressure regulation. Animal studies confirm reduced systolic and diastolic blood pressure in hypertensive models, while flavonoids and dietary fibre improve lipid profiles by inhibiting cholesterol synthesis and promoting bile acid excretion (Aramani *et al*., 2025). Neuroprotective properties are mediated by anthocyanins which cross the blood-brain barrier reducing neuroinflammation, oxidative stress and amyloidogenesis in animal models. Human clinical evidence for both cardiovascular and neuroprotective effects remain preclinical-level.

4.4 Antimicrobial and other therapeutic activities

Mulberry fruit extracts show broad-spectrum antibacterial activity against *Staphylococcus aureus, Escherichia coli, Salmonella* spp. and *Listeria monocytogenes*, as well as antifungal activity against *Candida albicans* and *Aspergillus* spp., primarily through phenolic membrane disruption and enzyme inhibition. Antiviral effects against influenza, herpes simplex virus and HIV have been reported *in vitro*. Reported biological activities are summarized in Table 3.

Table 3: Reported biological activities of mulberry fruit extracts

Activity	Mechanistic basis	Experimental evidence level
Antioxidant	ROS scavenging, lipid peroxidation inhibition	Strong *in vitro*; moderate animal
Antidiabetic	α-Glucosidase inhibition; insulin sensitivity	Animal + limited human
Cardioprotective	LDL oxidation reduction, ACE inhibition	Mostly preclinical
Neuroprotective	Anti-inflammatory + anti-apoptotic	Cell + animal
Antimicrobial	Phenolic membrane disruption	*In vitro*

Note: Adapted from Guo *et al.* (2018), Memete *et al.* (2022), and Bang *et al.* (2025).

4.5 Potential role in functional foods and nutraceutical development

The diverse pharmacological activities of mulberry phytochemicals highlight their significant potential in the development of functional foods and nutraceutical products. Mulberry fruit extracts, powders, and concentrates are increasingly incorporated into dietary supplements, beverages, and fortified food products aimed at promoting metabolic health and antioxidant protection. The presence of multiple bioactive compounds acting through complementary mechanisms provides a strong scientific basis for the use of mulberry fruits as a natural source of health-promoting ingredients. However, despite promising experimental findings, further clinical investigations are necessary to establish standardized dosages, bioavailability profiles, and long-term safety of mulberry-derived nutraceutical formulations. Additional documented activities include anticancer (apoptosis induction in breast, colon, liver cell lines), hepatoprotective, immunomodulatory, and skin-lightening effects via tyrosinase inhibition the latter driving cosmetic applications. Overall benefits of mulberry fruits are given as flowchart in Figure 2.

4.6 Molecular mechanisms of mulberry bioactive compounds

Mulberry (*Morus* spp.) fruits contain diverse bioactive compounds such as anthocyanins, flavonoids, phenolic acids, iminosugars and stilbenes that exert pharmacological effects through several molecular mechanisms. One of the major mechanisms involves the activation of antioxidant defense systems. Anthocyanins and phenolic compounds stimulate the nuclear factor erythroid 2-related factor 2(Nrf2) signaling pathway, which enhances the expression of antioxidant enzymes such as superoxide dismutase, catalase and glutathione peroxidase, thereby reducing oxidative stress and cellular damage (Chen *et al*., 2021; Memete *et al*., 2022).

Mulberry phytochemicals also regulate glucose metabolism and insulin sensitivity. In addition, mulberry anthocyanins activate AMP-activated protein kinase (AMPK), which improves glucose uptake and enhances metabolic regulation (Yuan and Zhao, 2017).

Another important mechanism is the suppression of inflammatory signaling pathways. Flavonoids and phenolic compounds present in mulberry inhibit the activation of nuclear factor-κB (NF-κB) and mitogen-activated protein kinase (MAPK) pathways, leading to reduced production of pro-inflammatory cytokines such as TNF-α and IL-6 (Dhiman *et al*., 2020). Furthermore, stilbene compounds such as resveratrol activate the SIRT1 pathway, improving endothelial function and contributing to cardiovascular protection (Chen *et al*., 2021).

Collectively, these molecular interactions demonstrate that mulberry phytochemicals exert multifunctional biological activities by modulating oxidative stress, inflammation and metabolic pathways, supporting their potential application in functional foods and nutraceutical formulations.

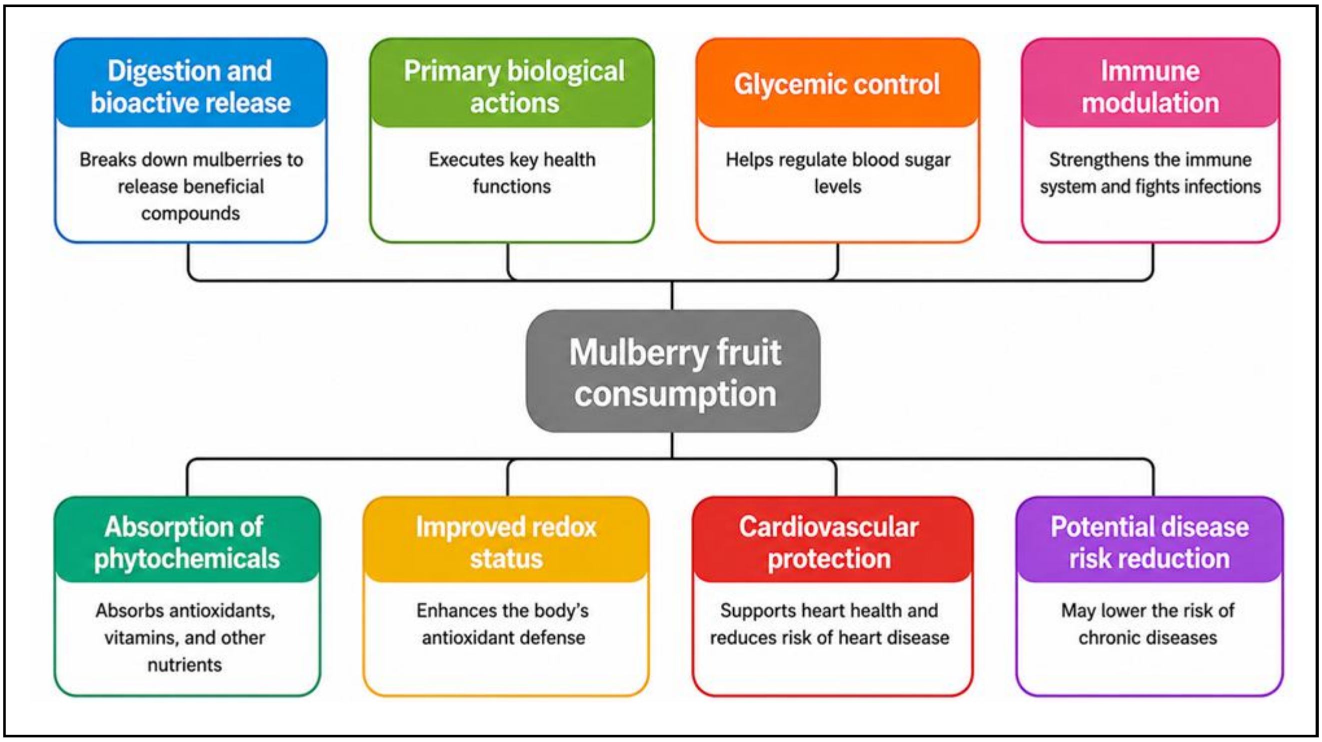

Figure 2: Overall benefits of fruit mulberry consumption.

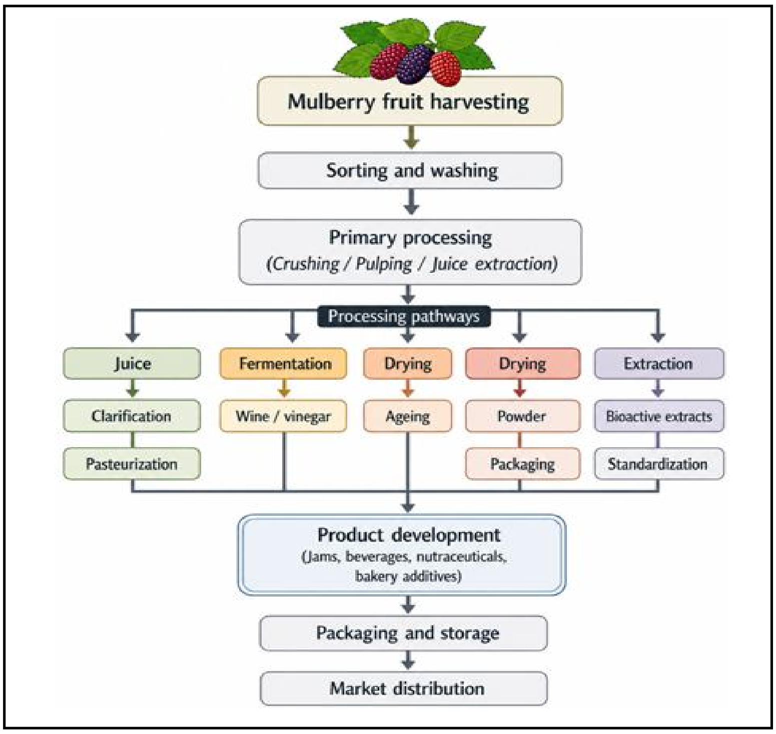

Figure 3: Mulberry product development.

5. Functional food product development

5.1 Processed products: Juices, wines, vinegars and fermented beverages

Processing overcomes mulberry's principal commercial limitation extreme perishability while creating value-added products. Mulberry juice retains high levels of water-soluble bioactives and serves as a base for probiotic fermented beverages. Recent GC-IMS and metabolomics studies show that lactic acid bacteria fermentation induces metabolic remodeling, flavor enrichment and generation of novel bioactive organic acids and volatile compounds (Liu *et al.*, 2025). Mulberry wine (8-12% alcohol by volume) retains substantial polyphenolic and antioxidant properties. Mulberry vinegar, produced *via* sequential alcoholic and acetic acid fermentation, has demonstrated neuroprotective effects in mouse models (Bang *et al.*, 2025).

Non-thermal pre-processing technologies mainly ultrasound, pulsed electric fields (PEF), and high-pressure processing (HPP) improve vinegar quality and bioactive retention, with ultrasound identified as most promising for sustainable production (Boasiako *et al.*, 2024).

5.2 Nutraceuticals, novel foods, and post-harvest technologies

Mulberry extracts standardized to anthocyanins or total phenolics are incorporated into capsules, tablets and powders addressing specific health outcomes (blood sugar control, cardiovascular health, cognition). Spray drying and freeze drying are principal powder production methods; freeze drying offers superior bioactive retention but at higher energy cost (Ma *et al.*, 2018). Micro encapsulation and nano encapsulation enhance stability, mask off-flavors and may improve gastrointestinal absorption. Novel applications span ice cream and frozen desserts, bakery goods, snack bars, breakfast cereals and natural food colorants leveraging the intense anthocyanin pigmentation. Probiotic functional beverages combining mulberry bioactives with beneficial microbial strains represent a particularly promising emerging category (Menaka *et al.*, 2025; Wang *et al.*, 2025). Process of various mulberry product is given in Figure 3.

6. Sustainable agriculture and agroforestry

6.1 Cultivation, climate resilience and environmental benefits

Mulberry thrives across sandy loam to clay loam soils (pH 5.5-7.5), tolerates temperatures from -25°C to above 40°C and survives extended drought once established through deep roots accessing subsoil moisture. This thermo plasticity and drought tolerance make it a climate-smart crop for regions facing increasing water stress (Oðuz *et al.*, 2023). Mulberry plantations sequester 5-15 tons CO, equivalent per hectare per year (£ochyñska and Oleszak, 2011) and perennial growth eliminates annual tillage, preserving soil structure. Extensive root systems reduce soil losses by 70-90% compared to annual cropping systems on erosion-prone land. Bioremediation potential for heavy-metal-contaminated soils has also been reported, though fruit safety monitoring is essential when considering human consumption from such sites.

6.2 Agroforestry integration and economic diversification

Mulberry integrates well into alley cropping (with cereals, legumes, or vegetables), silvopastoral, and home garden systems. Mulberry-based agroforestry sequesters 20-40 per cent more carbon than monoculture systems while enhancing species richness of plants, insects, birds and soil organisms (Mir *et al.*, 2019). For smallholder farmers, mulberry provides concurrent income from fruits, leaves (for silkworm rearing or tea), wood and fodder, smoothing seasonal income variability and reducing climate and market shock exposure (Mutebi, 2022). Irrigation requirements are 30-50 per cent lower than for citrus, mango or apple under comparable conditions, further reducing production costs. Agronomic and sustainability traits are summarized in Table 4.

Table 4: Agronomic and sustainability traits of fruit mulberry

Trait	Functional significance	Agricultural implication
Drought tolerance	Deep root system	Suitable for semi-arid regions
Perennial growth	Multi-year yield	Low replanting cost
Carbon sequestration	Woody biomass + soil organic matter	Climate-smart crop designation
Soil adaptability	Grows in marginal soils	Land-use diversification
Low water demand	30-50% less than citrus/mango	Viable in water-scarce areas

Note: Adapted from Rohela *et al.* (2020), Mutebi (2022), £ochyñska and Oleszak (2011), and Mir *et al.* (2019).

7. Economic potential and value chain development

The global functional food market (>USD 250 billion, growing 7-9% annually) aligns well with mulberry's phytochemical profile and clean-label appeal (Hu *et al.*, 2025). Fresh fruit commands premium prices via direct marketing channels (farmers' markets, pick-your-own operations), while processed products juices, wines, vinegars, dried fruits, nutraceuticals and cosmetic extracts offer scalable, year-round revenue streams accessible through specialty food stores and online platforms. The nutraceutical and cosmetic sectors offer especially high value-to-weight ratios, though market entry requires regulatory compliance, standardized quality protocols and clinical evidence for health claims.

Effective value chain development requires coordinated action across production (improved cultivars, integrated pest management, farmer cooperatives), post-harvest infrastructure (cold chain, storage, transport), and processing (scalable equipment for on-farm value addition to industrial-scale extracts). Protected Designation of Origin (PDO) and Geographic Indication (GI) designations can differentiate regionally distinctive products such as Turkish black mulberry with unique anthocyanin signatures and support premium pricing in export markets including Europe, North America and the Middle East (Skrovankova *et al.*, 2022; Mallick and Sengupta, 2022).

8. Conclusion

This review synthesizes evidence demonstrating that mulberry fruits are nutritionally and phytochemically rich, with validated bioactivities spanning antioxidant, antidiabetic, cardioprotective, neuroprotective and antimicrobial functions. A diverse portfolio of functional food products from fermented beverages and vinegars to nutraceutical encapsulates and natural colorants has been successfully developed, with non-thermal processing technologies improving bioactive compound retention. Agronomically, mulberry offers exceptional climate resilience, environmental benefits, and multipurpose income potential that make it indispensable to sustainable, climate-adaptive agriculture.

Nevertheless, three critical gaps constrain the crop's full realization: (i) insufficient human randomized controlled trials to substantiate health claims and establish effective doses; (ii) lack of cultivars purpose-bred for fruit quality, harvest ease and mechanical picking compatibility; and (iii) underdeveloped post-harvest and value chain infrastructure in key production regions. Addressing these gaps requires interdisciplinary collaboration spanning genomics, clinical nutrition science, food technology, agricultural engineering and policy. With sustained investment in research, infrastructure and market development, mulberry has the potential to transition from a legacy silk industry input to a pillar of global functional food innovation and sustainable agriculture.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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