

Nutritional Value, Phytochemical Profiling, and Pharmacological Properties of Custard Apple (*Annona squamosa* L.)

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Custard apple (*Annona squamosa* L.) is a tropical fruit of growing interest in food and nutrition research due to its unique sensory attributes, high nutritional value, and diverse bioactive profile. In addition to being a rich source of carbohydrates, dietary fiber, vitamins (notably vitamin C and B-complex vitamins), and essential minerals, custard apple contains a wide range of phytochemicals such as flavonoids, phenolic acids, alkaloids, and annonaceous acetogenins. These compounds have been associated with antioxidant, anti-inflammatory, antidiabetic, cardioprotective, antimicrobial, neuroprotective, and anticancer activities. The present review critically evaluates current scientific evidence on the nutritional composition, phytochemical diversity, and health-promoting effects of *A. squamosa*, with particular emphasis on mechanisms relevant to food and nutrition sciences. Traditional uses are discussed alongside recent in vitro, in vivo, and emerging clinical findings. Research gaps, safety considerations, and future opportunities for the development of custard apple-based functional foods, nutraceuticals, and dietary interventions are highlighted. This review aims to provide a comprehensive and up-to-date resource for researchers and professionals in food, nutrition, and health-related disciplines.

Keywords: *Annona squamosa*; custard apple; functional foods; bioactive compounds; antioxidants; food and nutrition; nutraceuticals.

Introduction

The role of diet in the prevention and management of chronic diseases has become a central focus of food and nutrition research (Kumar et al., 2020). Increasing consumer demand for natural, plant-based foods with added health benefits has stimulated interest in fruits that serve both nutritional and functional roles (Almeida et al., 2020). Custard apple (*Annona squamosa* L.), belonging to the Annonaceae family, represents one such fruit with considerable yet underexplored potential in the context of human nutrition.

Traditionally cultivated in tropical and subtropical regions, custard apple is widely consumed as a fresh fruit due to its sweet taste and creamy texture. Beyond its culinary appeal, various parts of the plant have been used in traditional medicine systems to manage digestive disorders, metabolic diseases, infections, and inflammatory conditions (Dey & De, 2022). Recent advances in analytical and biomedical research have begun to validate many of these ethnomedicinal claims, linking them to the fruit's rich nutritional composition and diverse phytochemical profile (Chaudhary et al., 2021).

From a food and nutrition perspective, custard apple is particularly interesting due to its high energy value, significant dietary fiber content, and abundance of antioxidant compounds (Mishra et al., 2023). These attributes suggest a potential role in functional food formulations aimed at improving gut health, metabolic regulation, immune function, and overall nutritional status (Patel & Goyal, 2022). This review synthesizes current scientific literature on *A. squamosa*, focusing on its nutritional relevance, bioactive constituents, and

evidence-based health effects, while identifying research gaps and future directions for its application in food and nutrition systems.

Botanical Description and Geographical Distribution

Annona squamosa is a small to medium-sized, semi-deciduous tree typically growing 3–6 m in height. The leaves are simple, oblong to lanceolate, and emit a characteristic aroma when crushed. Flowers are greenish-yellow, fragrant, and borne singly or in small clusters. The fruit is a syncarp composed of loosely fused carpels, giving it a characteristic segmented appearance. The pulp is creamy white, sweet, and aromatic, enclosing numerous glossy black seeds. The species is believed to have originated in the tropical regions of Central America and the Caribbean (Dey & De, 2022). Over centuries, it has spread widely across tropical and subtropical regions, including India, Southeast Asia, Africa, South America, and Australia (Chaudhary et al., 2021). Its adaptability to dry climates, tolerance to poor soils, and relatively low cultivation requirements have contributed to its widespread distribution. In many developing countries, custard apple plays an important role in food security and rural livelihoods.

Nutritional Composition

The nutritional profile of custard apple underscores its value as a functional food (López-Vargas et al., 2021). The fruit pulp is rich in carbohydrates, primarily in the form of natural sugars, providing a quick source of energy (Chaudhary et al., 2021). It contains moderate amounts of protein and minimal fat, making it suitable for a balanced diet. Custard apple is a notable source of vitamin C, which plays a critical role in immune defense, collagen synthesis, and antioxidant protection (Silva et al., 2020). The fruit also contains B-complex vitamins such as thiamine, riboflavin, niacin, and pyridoxine, which are essential for energy metabolism and nervous system function. Mineral content includes potassium, magnesium, calcium, phosphorus, and iron, all of which contribute to cardiovascular health, bone integrity, and neuromuscular function (Chaudhary et al., 2021). Dietary fiber present in custard apple supports gastrointestinal health by promoting regular bowel movements, improving gut microbiota composition, and aiding in the regulation of blood glucose and lipid levels (Patel & Goyal, 2022). The synergistic interaction between these nutrients enhances the overall health-promoting properties of the fruit (Almeida et al., 2020).

Phytochemical Profile

The therapeutic potential of *Annona squamosa* is largely attributed to its rich and diverse phytochemical composition (Dey & De, 2022). Phytochemical investigations have identified several classes of bioactive compounds, including:

- **Flavonoids (e.g., quercetin, kaempferol, rutin):** Known for antioxidant, anti-inflammatory, antidiabetic, and anticancer activities (Mishra et al., 2023).
- **Phenolic acids (e.g., gallic acid, caffeic acid):** Contribute to free radical scavenging and cytoprotective effects (Mishra et al., 2023).
- **Alkaloids:** Exhibit analgesic, antimicrobial, and neuroactive properties (Dey & De, 2022).
- **Annonaceous acetogenins:** Unique to the Annonaceae family, these compounds demonstrate potent cytotoxic activity against cancer cells through inhibition of mitochondrial energy production (Górnaś & Rudzińska, 2021).

These phytochemicals are distributed across different plant parts, with leaves and seeds often showing higher concentrations than the fruit pulp (Borges et al., 2019). The complexity and diversity of these compounds make custard apple a promising candidate for drug discovery and functional food development (Kumar et al., 2020).

Antioxidant Properties and Mechanisms

Oxidative stress, resulting from an imbalance between reactive oxygen species and antioxidant defenses, is implicated in the pathogenesis of numerous chronic diseases. Custard apple exhibits strong antioxidant activity due to its high content of vitamin C, polyphenols, and

flavonoids (Silva et al., 2020). The antioxidant mechanisms include direct scavenging of free radicals, chelation of metal ions, inhibition of lipid peroxidation, and upregulation of endogenous antioxidant enzymes such as superoxide dismutase, catalase, and glutathione peroxidase (Mishra et al., 2023). Through these mechanisms, *A. squamosa* helps protect cellular components from oxidative damage, thereby reducing the risk of degenerative diseases (Almeida et al., 2020).

Anti-Inflammatory Activity

Chronic inflammation is a central feature of many metabolic, cardiovascular, and neurodegenerative disorders. Bioactive compounds in custard apple, particularly flavonoids and acetogenins, have been shown to modulate inflammatory pathways (Dey & De, 2022). These compounds inhibit the production of pro-inflammatory cytokines and suppress the activity of key enzymes involved in inflammation (López-Vargas et al., 2021). By regulating signaling pathways such as NF- κ B and MAPK, custard apple constituents reduce inflammatory responses at the molecular level (Mishra et al., 2023). This anti-inflammatory potential supports its traditional use in managing pain, swelling, and inflammatory conditions (Dey & De, 2022).

Cardiovascular Health Benefits

Custard apple contributes to cardiovascular health through multiple mechanisms. Potassium and magnesium help regulate blood pressure and maintain vascular tone (Chaudhary et al., 2021). Dietary fiber assists in lowering serum cholesterol levels by reducing intestinal absorption of lipids (Patel & Goyal, 2022). Antioxidants present in the fruit protect endothelial cells from oxidative injury, thereby preventing the development of atherosclerosis (Silva et al., 2020). Collectively, these effects suggest that regular consumption of custard apple may reduce the risk of hypertension, coronary artery disease, and stroke (Almeida et al., 2020).

Digestive Health and Gut Microbiome Modulation

The high fiber content of custard apple plays a pivotal role in maintaining digestive health. Fiber promotes intestinal motility, prevents constipation, and supports the growth of beneficial gut microbiota (Patel & Goyal, 2022). Additionally, polyphenols act as prebiotic substrates, further enhancing microbial diversity and metabolic activity (Mishra et al., 2023). A balanced gut microbiome is closely linked to immune function, metabolic regulation, and mental health. By supporting gut homeostasis, custard apple may contribute to systemic health beyond the gastrointestinal tract (Patel & Goyal, 2022).

Role in Diabetes Management

Emerging evidence suggests that custard apple may be beneficial in diabetes management. Fiber slows glucose absorption, preventing postprandial spikes in blood sugar levels (Patel & Goyal, 2022). Phytochemicals such as flavonoids and alkaloids enhance insulin sensitivity and protect pancreatic β -cells from oxidative stress (Mishra et al., 2023). Experimental studies have demonstrated hypoglycemic effects of leaf and seed extracts, indicating their potential as complementary agents in diabetes care (Dey & De, 2022). However, controlled clinical trials are necessary to establish safety and dosage guidelines.

Immune-Modulatory Effects

Custard apple strengthens immune function through its vitamin and phytochemical content. Vitamin C enhances the activity of immune cells, while polyphenols modulate inflammatory and immune signaling pathways (Silva et al., 2020). Certain compounds have been shown to stimulate natural killer cell activity and improve host defense mechanisms (Dey & De, 2022). These properties highlight the fruit's potential role in enhancing resistance to infections and supporting immune balance (Almeida et al., 2020).

Anticancer Potential

The anticancer activity of *Annona squamosa* has been extensively investigated, particularly focusing on annonaceous acetogenins (Dey & De, 2022). These compounds selectively target

cancer cells by disrupting mitochondrial energy metabolism, leading to apoptosis (Górnaś & Rudzińska, 2021). Flavonoids and phenolic compounds further contribute to cancer prevention by reducing oxidative DNA damage and inhibiting tumor-promoting inflammation (Mishra et al., 2023). While preclinical studies are promising, translational research and clinical validation are essential before therapeutic application.

Neuroprotective Properties

Oxidative stress and inflammation are major contributors to neurodegenerative diseases. Bioactive compounds in custard apple exhibit neuroprotective effects by reducing oxidative damage, modulating neurotransmitter activity, and inhibiting neuroinflammatory pathways (Dey & De, 2022). These findings suggest potential applications in the prevention and management of disorders such as Alzheimer's and Parkinson's diseases (Mishra et al., 2023).

Skin and Hair Health Benefits

Custard apple supports skin and hair health through its antioxidant and vitamin content. Vitamin C promotes collagen synthesis, improving skin elasticity and wound healing (Silva et al., 2020). Antioxidants protect skin cells from environmental stressors, while minerals support hair growth and scalp health (Chaudhary et al., 2021). Traditional topical applications of leaves and pulp further highlight its dermatological relevance (Dey & De, 2022).

Traditional Medicinal Uses Across Cultures

Across Ayurveda, Traditional Chinese Medicine, African folk medicine, and Latin American healing systems, custard apple has been used to treat fever, infections, digestive disorders, parasitic infestations, and inflammatory conditions (Dey & De, 2022). These ethnomedicinal practices provide valuable leads for modern pharmacological research.

Future Prospects in Nutraceutical and Pharmaceutical Applications

The diverse bioactivities of custard apple position it as a promising candidate for nutraceutical and pharmaceutical development (Kumar et al., 2020). Advances in extraction technologies, formulation science, and clinical research could facilitate the development of standardized products with enhanced bioavailability and efficacy (López-Vargas et al., 2021). Sustainable cultivation and value addition will be critical to meeting future demand while preserving biodiversity (Borges et al., 2019).

Conclusion

Custard apple (*Annona squamosa* L.) represents a nutritionally valuable and biologically active tropical fruit with strong relevance to food and nutrition sciences. Its richness in dietary fiber, essential micronutrients, and diverse phytochemicals underpins a wide range of health-promoting effects, including antioxidant, anti-inflammatory, antidiabetic, cardioprotective, immunomodulatory, and anticancer activities. While traditional consumption and preclinical evidence strongly support its functional potential, translation into evidence-based dietary strategies requires further human intervention studies, bioavailability assessments, and safety evaluations. From a food and nutrition perspective, *A. squamosa* holds considerable promise as an ingredient in functional foods, nutraceutical formulations, and health-oriented diets. Strategic research integrating food processing, clinical nutrition, and molecular mechanisms will be essential to fully harness its benefits and ensure its sustainable utilization.

Research Gaps and Future Perspectives

Despite growing interest, several gaps remain in the food and nutrition research on custard apple. Most available data are derived from in vitro or animal studies, with limited well-designed human clinical trials. The bioavailability and metabolism of key phytochemicals, particularly annonaceous acetogenins and flavonoids, remain insufficiently characterized. Additionally, the impact of food processing, storage, and formulation on the stability and functionality of bioactive compounds requires systematic investigation. Future research should prioritize human intervention studies, standardized extraction methods, safety evaluations, and

the development of custard apple-based functional foods tailored to metabolic health, gut health, and immune support.

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