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Nutritional, phytochemical, and processing perspectives of custard apple (*Annona squamosa*): A comprehensive review

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Abstract
Custard apple (*Annona squamosa* L.), a fruit-bearing member of the Annonaceae family, holds significant nutritional, medicinal, and commercial value. Widely cultivated in tropical and subtropical regions, particularly in India, it is prized for its creamy, sweet pulp rich in sugars, vitamin C, potassium, and dietary fiber. This review synthesizes current knowledge on the botanical characteristics, nutritional composition, phytochemical profile, medicinal properties, and processing technologies of custard apple. The plant contains a variety of bioactive compounds, including acetogenins, flavonoids, phenolics, and alkaloids, which have demonstrated antioxidant, antimicrobial, antidiabetic, and anticancer activities in several preclinical studies. Despite its nutritional richness and therapeutic potential, custard apple faces significant challenges in post-harvest management due to its short shelf life and perishability. The review also highlights recent advancements in processing techniques and preservation strategies such as drying, modified atmosphere storage, natural preservatives, and emerging non-thermal technologies like high-pressure processing and nano-coatings. Furthermore, the potential of custard apple in developing functional foods, value-added products, and nutraceuticals is emphasized. However, gaps remain in large-scale processing infrastructure, storage protocols, and clinical validation of its health benefits, indicating a strong need for further interdisciplinary research to fully realize its commercial and health potential.

Keywords: Custard apple (*Annona squamosa*), phytochemicals, nutritional composition, acetogenins, functional foods, antioxidant activity, processing technologies

1. Introduction
Custard apple (*Annona squamosa* L.), a member of the Annonaceae family, is a tropical fruit tree widely cultivated for its sweet, creamy pulp and medicinal properties. Native to the West Indies and tropical America, it has spread across Central and South America and was later introduced to Asia and Africa by colonial traders (Hiwale, 2015) [9]. Today, it thrives in tropical and subtropical climates, with India being one of the largest producers. The tree typically grows between 3 to 8 meters tall and bears globular fruits with knobby green skin and white segmented pulp, rich in sugars, vitamin C, potassium, and dietary fiber (Gautam *et al.*, 2024) [7].

1.1 Global distribution and significance
Globally, A. squamosa is cultivated in countries such as Brazil, Mexico, Egypt, Thailand, Indonesia, and the Philippines, and has gained commercial significance in dryland horticulture due to its drought tolerance and adaptability to marginal soils (Xu *et al.*, 2024) [37]. In India, it is grown extensively in states like Maharashtra, Gujarat, Madhya Pradesh, Rajasthan, and Tamil Nadu, covering over 40,000 hectares (Kumar *et al.*, 2021) [14]. Its economic importance stems not only from fresh fruit consumption but also from its use in processed products like ice creams, jams, syrups, and fermented beverages. Additionally, various plant parts—leaves, seeds, bark—are used in traditional medicine systems such as Ayurveda and Unani for treating ailments like dysentery, ulcers, and tumours (Gautam *et al.*, 2024; Moussa *et al.*, 2024) [7, 19].

1.2 Objective and scope of the review
The objective of this review is to consolidate and critically examine the nutritional, phytochemical, and pharmacological attributes of *Annona squamosa*, with a particular focus on its leaves and fruit pulp. The plant is known to contain bioactive compounds such as acetogenins, flavonoids, alkaloids, and phenolics, which contribute to its antioxidant, antidiabetic, anticancer, and anti-inflammatory activities (Kumar *et al.*, 2021; Moussa *et al.*, 2024) [15, 19]. While numerous *in vitro* and *in vivo* studies have demonstrated promising therapeutic effects, there remains a gap in clinical research, underscoring the need for further investigation into its potential applications in nutraceuticals and functional foods (Gautam *et al.*, 2024; Xu *et al.*, 2024) [7, 37].

2. Historical development of custard apple
Custard apple (*Annona squamosa* L.) has a rich and complex historical development that intertwines botanical origins, archaeological evidence, and cultural diffusion. Traditionally, it is believed to be native to the tropical Americas, particularly the West Indies and Central America, and was introduced to India by Portuguese traders during the 16th century (Hiwale, 2015) [9]. This theory is supported by its widespread cultivation in tropical and subtropical regions globally, including Australia, Brazil, and Egypt.
However, archaeobotanical discoveries challenge this narrative. Bala *et al.*, (2017) [1] reported the presence of custard apple seeds at the Neolithic site of Tokwa in Mirzapur District, India, dated to approximately 1520-1740 BCE using accelerator mass spectrometry (AMS) and liquid scintillation counting (LSC). The radiocarbon dating of custard apple seed remains from the Neolithic site of Tokwa suggests its presence in India as early as 1520-1740 cal BC, thereby challenging the belief that the fruit was introduced by the Portuguese in the 16th century (Sekar, 2015) [31]. These findings suggest that custard apple may have existed in India long before European contact, supporting hypotheses of pre-Columbian transoceanic exchanges. The seeds were identified as *Annona squamosa* based on morphological comparisons with extant species, and the fruit coat characteristics matched those of modern custard apples.
In India, custard apple has adapted remarkably well to semi-arid and dryland conditions, growing spontaneously in forests and wastelands across states like Maharashtra, Andhra Pradesh, Madhya Pradesh, and Rajasthan (Hiwale, 2015) [9]. Its resilience and minimal input requirements made it a popular fruit among rural communities, often referred to as “Sitaphal” or “Sharifa.” Over time, selective breeding and hybridization led to the development of improved varieties such as Balanagar, Mammoth, and Arka Sahan, which offer better yield, fruit size, and shelf life (Hiwale, 2015) [9].
The fruit also holds cultural and medicinal significance. It is mentioned in ancient Indian texts and used in Ayurvedic and Unani systems for its therapeutic properties. Its seeds, leaves, and roots have been employed in traditional remedies for skin ailments, digestive issues, and even as natural insecticides.

3. Botanical Description and Taxonomy
Custard apple (*Annona squamosa* L.) belongs to the family Annonaceae, which comprises over 2,100 species across 120 genera, making it one of the largest families in the order Magnoliales (Pirie *et al.*, 2005) [25]. The taxonomic classification of A. squamosa is as follows: Kingdom Plantae, Division Magnoliophyta, Class Magnoliopsida, Order Magnoliales, Family Annonaceae, Genus Annona, Species A. squamosa, it is commonly known as sugar apple, sweetsop, or sitaphal in India and is native to the tropical Americas, particularly the West Indies (Hiwale, 2015) [9].

3.1 Morphological characteristics of fruit, seed, leaves, etc.
Morphologically, A. squamosa is a small, semi-deciduous tree reaching 3-8 meters in height, with an irregular branching pattern and light brown bark (Darsimbe & Gawande, 2023) [4]. The leaves are simple, alternate, oblong to lanceolate, measuring 8-14 cm in length, and are glabrous when mature but pubescent when young (Gaurha *et al.*, 2024) [6]. Flowers are solitary or in clusters, actinomorphic, bisexual, and trimerous, with three green sepals and three fleshy, pale-yellow petals arranged in a valvate aestivation (Darsimbe & Gawande, 2023) [4]. The fruit is an aggregate of berries, typically globular or heart-shaped, with a knobby green surface and creamy white pulp. Each fruit contains 60-80 shiny black seeds embedded in the pulp, which is rich in sugars and aromatic compounds (Gajera, 2018; Rana *et al.*, 2025) [5, 28].

3.2 Major cultivated varieties
Several major cultivated varieties of custard apple have been developed for improved yield, fruit quality, and adaptability. Balanagar, a widely grown variety in India, produces fruits weighing 137-264 g with a pulp percentage of 44.9% and TSS of 20.7 °Brix (Hiwale, 2015; Rajadurai *et al.*, 2022) [9, 27]. Arka Sahan, a hybrid developed by IIHR Bangalore, is known for its sweet, fragrant, low-seeded fruits with a TSS of 30.8 °Brix and a shelf life of 4 days (Jalikop & Sampatkumar, 1998; Hiwale, 2015) [12, 9]. APK (Ca)-1, developed by TNAU, Tirunelveli, is a high-yielding clonal selection with a fruit weight of 207 g and a yield potential 30.7% higher than Balanagar (Rajadurai *et al.*, 2022) [27]. Other notable varieties include Mammoth, Red Sitaphal, and Washington P.I. 98797, each with distinct morphological and biochemical traits suited to different agro-climatic zones (Hiwale, 2015; Meghana *et al.*, 2020) [9, 18].

4. Nutritional Composition
Custard apple (*Annona squamosa*. L) contains a high proportion of carbohydrates, primarily in the form of natural sugars like glucose and fructose, contributing to its energy-dense profile—approximately 23.9 g of carbohydrates per 100 g of pulp (Nair & Agrawal, 2017) [21]. The protein content is modest, around 1.6 g/100 g, while fat levels are low, typically 0.18 g/100 g, making it suitable for low-fat diets (Bala *et al.*, 2017) [1]. Additionally, the fruit is a good source of dietary fiber, with values ranging from 3.1% to 11 g/100 g, aiding digestion, and promoting satiety (Kumar *et al.*, 2021) [14].

4.1 Micronutrients: vitamins (C, B-complex), minerals (Ca, K, Mg, Fe)
Micronutrient-wise, custard apple is particularly rich in vitamin C, with concentrations between 35-91 mg/100 g, which supports immune function and acts as a potent antioxidant (Gautam *et al.*, 2024) [8]. It also contains B-

complex vitamins such as thiamine (275 mcg), riboflavin (283 mcg), niacin (2.2 mg), and vitamin B6 (500 mcg), which are essential for energy metabolism and neurological health (Nair & Agrawal, 2017) [21]. Among minerals, it provides significant amounts of calcium (17.6-27 mg), potassium (382 mg), magnesium (21 mg), and iron (0.42-1.14 mg), contributing to bone strength, cardiovascular health, and oxygen transport (Rathod *et al.*, 2023; Kumar *et al.*, 2021) [29, 15].

When compared to other tropical fruits, custard apple stands out for its higher calorific value—about 104-235 kcal per 100 g, nearly double that of fruits like peach, orange, or apple (Nair & Agrawal, 2017) [21]. Its sugar content (12.4-18.15%) and TSS (Total Soluble Solids) levels (up to 26.4 °Brix) surpass many other fruits, making it ideal for desserts and processed products (Bala *et al.*, 2017). Moreover, its vitamin C content is comparable to guava and higher than mango, while its potassium and magnesium levels rival those found in banana and papaya (Kumar *et al.*, 2021) [15]. These attributes position custard apple as a valuable fruit for both nutritional and therapeutic applications.

5. Medicinal and Pharmacological Properties

Custard apple (*Annona squamosa* L.) has garnered significant attention for its diverse medicinal and pharmacological properties, owing to its rich phytochemical profile. The fruit, leaves, seeds, and bark contain bioactive compounds such as acetogenins, flavonoids, alkaloids, and phenolics, which contribute to its therapeutic potential (Gautam *et al.*, 2024; Kumar *et al.*, 2021) [8, 15].

5.1 Antioxidant Activity

The antioxidant potential of A. squamosa is primarily attributed to its high content of polyphenols and flavonoids. Jagtap & Bapat, (2012) [10]. Demonstrated that ethanol extracts of the fruit pulp exhibited strong free radical scavenging activity, with IC_{50} values of 134.76 µg/ml (DPPH assay) and 62.63 µg/ml (ABTS assay). These effects are linked to the presence of compounds like quercetin and gallic acid equivalents, which neutralize oxidative stress and prevent cellular damage.

5.2 Antimicrobial and Antifungal Effects

The antimicrobial efficacy of A. squamosa has been validated against various bacterial and fungal strains. Kalpana *et al.*, (2024) [13] reported that leaf and seed extracts possess broad-spectrum antimicrobial activity due to phytochemicals such as alkaloids, saponins, and flavonoids.

6. Processing and Preservation Technologies

Custard apple (*Annona squamosa* L.) is a climacteric fruit with a short shelf life due to high respiration and ethylene production, leading to rapid ripening and spoilage (Jain *et al.*, 2019) [11]. Postharvest handling is critical, as fruits become soft and unmarketable within 3-4 days of harvest. Lahane and Khandare (2015) [16] demonstrated that treatments such as wax coating (6%) and chitosan (1%) significantly extended shelf life by reducing physiological loss in weight, respiration rate, and ethylene evolution. Modified atmosphere packaging and controlled temperature (15-20 °C with 85-90% RH) are recommended to delay ripening and minimize chilling injuries (Chen, 1999; Broughton & Guat, 1979) [3, 2].

6.1 Processing technique

Processing techniques have evolved to reduce postharvest losses and add value. Pulp extraction is a primary step, often mechanized to separate seeds and rind efficiently (Mudgal *et al.*, 2021) [20]. The extracted pulp is used to prepare juice, puree, jam, squash, nectar, and frozen products, which are popular due to the fruit's high sugar and TSS content (Soni *et al.*, 2021) [35]. Drying methods such as solar drying, tray drying, and freeze-drying are employed to preserve pulp and extend shelf life. Shrivastava *et al.*, (2021) [33] optimized spray drying parameters using maltodextrin as a carrier, achieving stable custard apple pulp powder with retained phytonutrients and low moisture content.

6.2 Preservation strategies

Preservation strategies include cold storage, which maintains sensory and nutritional quality for up to 12 days at 10 °C (Solanke *et al.*, 2019) [34]. However, freezing beyond −18 °C may cause discoloration due to polyphenol oxidase activity (Pardede *et al.*, 1994) [23]. To prevent enzymatic browning and microbial spoilage, natural preservatives like citric acid, honey, and ascorbic acid are used. Sastry *et al.*, (1961) [30] found that 1% citric acid combined with 0.1% sodium benzoate effectively preserved pulp, while 100 ppm sulphur dioxide inhibited enzymatic discoloration. Emerging technologies such as High-Pressure Processing (HPP), ultrasound-assisted preservation, and nano-coatings are being explored for their ability to retain flavor, inhibit microbial growth, and extend shelf life without compromising quality (Shrivastava *et al.*, 2021; Patidar *et al.*, 2021) [33, 24].

7. Value-Added Products

Custard apple (*Annona squamosa*) offers a wide range of value-added applications across food, cosmetic, and health industries. Its pulp is widely used in the development of frozen desserts such as ice cream, kulfi, and yogurt due to its creamy texture and naturally sweet flavor. According to Kumar *et al.*, (2021) [15], the pulp is rich in sugars, vitamin C, and minerals, making it ideal for use in sweets and beverages. Spray-dried custard apple powder is also gaining popularity in baking and confectionery, offering convenience and extended shelf life (Kumar *et al.*, 2021) [14].

7.1 Custard apple seed oil and its uses

The seeds of custard apple, though inedible, are a source of potent oil with diverse applications. Custard apple seed oil is extracted via cold-pressing and contains essential fatty acids, linoleic acid, and antioxidants. As noted by PainAssist Team (2023) [22], this oil is used in skincare for its moisturizing and anti-aging properties, and in haircare to promote shine and reduce dandruff. Additionally, Shejwal *et al.*, (2023) [32] highlight its pesticidal properties due to the presence of acetogenins, which act as natural bio-inhibitors against pests like aphids and termites.

7.2 Potential in nutraceuticals and functional foods

In the realm of nutraceuticals and functional foods, custard apple shows promising potential. Gautam *et al.*, (2024) [7] emphasize its bioactive compounds—acetogenins, flavonoids, and alkaloids—which contribute to anti-inflammatory, antidiabetic, and anticancer properties. The fruit's high vitamin C and fiber content support immune and digestive health, while its low glycemic index makes it suitable for diabetic-friendly formulations. Kumar *et al.*, (2021) [14] further suggest that extracts from leaves and seeds can be incorporated into functional foods and supplements aimed at cardiovascular and metabolic health.

8. Challenges and Research Gaps

Custard apple (*Annona squamosa*) faces several challenges that hinder its full commercial potential. One major issue is its seasonal availability and high perishability, which restricts year-round supply and leads to significant post-harvest losses. The fruit ripens rapidly due to high respiration and ethylene production, becoming soft and unmarketable within a few days of harvest (Jain *et al.*, 2019) [11]. This short shelf life complicates transportation and storage, especially in regions lacking cold chain infrastructure. According to Sravanthi (2004) [36], pulp preservation using potassium metabisulphite can extend usability for up to six months, but such methods are not widely adopted due to cost and scalability concerns.

8.1 Lack of commercial-scale processing infrastructure

Another critical gap is the lack of commercial-scale processing infrastructure. Despite growing interest in custard apple-based products like pulp, ice cream, and beverages, most processing remains limited to cottage or small-scale units. Jain *et al.*, (2019) [11] emphasize that the absence of mechanized pulp extraction and preservation systems contributes to inefficiencies and low product consistency. Moreover, the fruit's delicate texture and susceptibility to enzymatic browning pose technical challenges during processing (Solanke *et al.*, 2019) [34].

8.2 Limited studies on storage and preservation

Storage and preservation studies are also limited. While some research has explored modified atmosphere packaging and low-temperature storage, comprehensive protocols for long-term preservation are still lacking. Prasanna *et al.*, (2000) [26] found that storage at 15 °C maximized shelf life, but chilling injuries below this temperature and fungal susceptibility above its complicate storage decisions. Additionally, heat treatments and chemical preservatives like citric acid and sodium benzoate have shown promise, but their effects on sensory quality and nutritional value require further investigation (Jain *et al.*, 2019; Sravanthi, 2004) [11, 36].

8.3 Future directions for research

Looking ahead, future research directions should focus on developing integrated post-harvest management systems, including optimized harvesting, packaging, and cold storage techniques. Genetic improvement for delayed ripening and disease resistance is another promising area. Madhavi *et al.*, (2024) [17] suggest that biochemical characterization of genotypes can aid in selecting varieties with better shelf stability and processing suitability. Furthermore, exploring novel applications in nutraceuticals and functional foods could unlock new markets, provided that bioactive compounds are systematically studied and standardized.

9. Summary and Conclusion

Custard apple (*Annona squamosa* L.) is a nutritionally dense and phytochemically rich tropical fruit with broad applications across food, pharmaceutical, and traditional medicine sectors. Its sweet, creamy pulp is a valuable source of natural sugars, vitamin C, potassium, and dietary fiber, while its seeds, leaves, and bark contain potent bioactive compounds like acetogenins, flavonoids, and alkaloids. These constituents contribute to a wide range of pharmacological activities, including antioxidant, antimicrobial, antidiabetic, and anticancer effects, which have been validated in various *in vitro* and *in vivo* studies.

Despite its nutritional and therapeutic appeal, custard apple remains underutilized due to challenges in postharvest handling, storage, and large-scale processing. The fruit's high perishability and rapid ripening limit its shelf life and marketability. Traditional preservation methods like cold storage and chemical preservatives offer limited benefits, while emerging technologies such as high-pressure processing and spray drying show promise but require further optimization and investment.

Value addition through pulp-based products, seed oil extraction, and functional food development presents a significant opportunity for economic upliftment and waste utilization. However, major gaps persist in commercial processing infrastructure, varietal improvement, and clinical research. To overcome these challenges, future efforts should focus on integrated post-harvest solutions, advanced preservation techniques, and systematic validation of its health-promoting properties. With coordinated research and industrial collaboration, custard apple can evolve from a seasonal delicacy into a nutraceutical-rich, commercially viable crop with global appeal.

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