Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
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Cite this: DOI: 10.1039/d5fb00643k

Valorization of custard apple (*Annona squamosa*) seeds and peels: composition, extraction technologies, and food applications

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Received 1st October 2025
Accepted 15th April 2026

DOI: 10.1039/d5fb00643k

rsc.li/susfoodtech

Custard apple processing generates significant by-products, particularly seeds and peels, which are rich in bioactive compounds with potential application in food and nutraceutical industries. This review examines the composition of these by-products and the conventional and emerging extraction technologies used to recover valuable compounds, including phenolics, lipids, and proteins. The potential applications of these components as natural preservatives, functional ingredients, edible coatings/films, oil and protein isolates are also discussed. Despite their promising potential, several challenges limit their use, including the presence of toxic compounds, the scalability of extraction techniques, seasonal availability of raw materials, and sensory limitations that affect consumer acceptance. In addition, regulatory and safety considerations remain critical for their successful incorporation into food systems. Future research should focus on developing safe, sustainable, and scalable processing technologies to fully unlock the valorization potential of custard apple by-products and support their industrial application.

Sustainability spotlight

The fruit processing industry generates substantial waste in the form of seeds and peels, raising environmental and economic concerns and underutilizing valuable bioactive compounds. This review highlights the potential of custard apple by-products as sustainable sources of value-added products through the application of efficient extraction technologies. Their valorization into food applications supports waste reduction, resource efficiency, and the development of health-promoting products. This approach aligns with the UN Sustainable Development Goals, particularly SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), and SDG 12 (Responsible Consumption and Production).

1. Introduction

Fruit production accounted for 17 percent of the overall value in 2022,[1] resulting in the generation of substantial amounts of by-products. During processing, nearly half of each fruit is discarded as waste, comprising seeds, peels, rinds, husks, rags, roots, pomace, and more.[2,3] Notably, these by-products often possess higher concentrations of nutrients and bioactive compounds than the pulp,[4,5] highlighting their potential for value-added utilization.

Custard apple (*Annona squamosa* L.), part of the Annonaceae family, is a tropical fruit cultivated in the regions of the West Indies, South and Central America, Ecuador, Peru, Brazil, India, Mexico, the Bahamas, Bermuda, and Egypt.[6] Commonly known as sugar apple or sweetsop,[7,8] characterized by its tough green exterior and sweet, creamy pulp.[8] It is widely used in the production of juice, ice cream, confectionery, and milk products.[9] However, processing generates a significant portion of waste, primarily seeds and peels.[10] These by-products are rich in bioactive compounds, including phenolic acids, flavonoids, and procyanidins[11] and have been reported with antitumor, anti-inflammatory, and antioxidant activities.[12,13] Such properties indicate strong potential for their valorization into nutritious and functional food products.[2]

The fruit processing sector needs solutions for handling by-products to not only reduce food waste but also to implement strategies that enhance their reuse for economic benefit.[14] Conventional extraction techniques are often associated with high solvent consumption, long processing times, and significant energy requirements, which limit their efficiency. As a result, emerging technologies have gained increasing attention in food, pharmaceutical, and medicinal industries due to their reduced solvent usage, shorter extraction times, and higher extraction efficiency. These approaches have demonstrated the ability to produce high-quality extracts with economic and environmental advantages; however, most have been evaluated only at the laboratory scale, highlighting the need for further development and scale-up for industrial applications.[15,16]

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In addition to their nutritional and functional potential, plant-derived ingredients are often associated with sensory challenges that can limit consumer acceptance. Recent studies have reported that plant-based foods frequently exhibit negative sensory perceptions, including astringency, bitterness, undesirable textures, and various off-flavors,[17] which are largely attributed to polyphenols and other compounds.[18] Moreover, plant proteins can influence texture and mouthfeel by increasing viscosity, causing grittiness, and exhibiting poor solubility, particularly in beverage applications.[19] These limitations are relevant to custard apple by-products, as seed-derived proteins and phenolic-rich peel extracts may influence the sensory quality of formulated products.

Although several reviews have examined the phytochemical composition or biological activity of custard apple, an integrated evaluation focusing specifically on the valorization of its by-products (seeds and peels) remains limited. In particular, there is a lack of consolidated analysis linking composition, extraction technologies, safety concerns, and industrial food applications. Therefore, this review aims to address this gap by providing a comparative assessment of conventional and emerging extraction methods, a focused discussion on scalable food applications and industrial relevance, and a critical evaluation of toxicity and safety challenges.

2. Nutritional and phytochemical composition of custard apple seeds and peels

Custard apple has been traditionally utilized in natural medicine and various food applications.[6,20] Its nutritional value is primarily attributed to its carbohydrates, proteins, amino acids, and vitamins.[21] Nonetheless, recent research has revealed that custard apple by-products, particularly seeds and peels, also contain valuable nutrients. These include significant levels of protein, fat, carbohydrates, fiber, ash, and vital minerals[22] (Table 1).

Custard apple by-products are not only nutritionally valuable but also rich in phytochemicals that contribute to various health benefits. Table 2 shows the key phytochemicals found in custard apple seeds and peels. According to Leite *et al.*,[23] the seeds are rich in phenolic compounds (32.53 ± 2.13 μg GAE per mg) and flavonoids (893.30 ± 6.66 μg QE per g), and they also contain vitamin C (0.57 ± 0.07 mg AA/100 g) and carotenoids (0.45 ± 0.01 μg of β-carotene/10 mg). Similarly, the peels have been reported to contain significant levels of phenolic compounds (28.771 ± 0.008 μg GAE per mg), and flavonoids (81.27 ± 1.74 μg QE per g).[10,22]

Recent studies emphasize the potential of custard apple by-products, such as seeds, peels, and leaves, as valuable sources of flavonoids, phenolic acids, and phytosterols, among other compounds.[11,25] These bioactive compounds are associated with diverse biological activities. For instance, custard apple seeds have been reported to exhibit anticancer properties,[26] as well as antibacterial, hepatoprotective, antioxidant, and antitumor properties.[27] In addition, the peels contain bioactive components such as tannins, acetogenins, and alkaloids, which contribute to their antioxidant and antimicrobial properties.[28]

Overall, the abundance of bioactive compounds in custard apple by-products highlights their potential in developing value-added products, particularly in functional foods and nutraceutical applications.

3. Extraction technologies for custard apple seeds and peels

Fruit by-products are rich sources of bioactive compounds, such as dietary fiber, flavonoids, phenolic compounds, antioxidants, polysaccharides, and other nutrients and phytochemicals with health-promoting properties.[29] These compounds can be

Table 1 Nutritional composition of custard apple species' seeds and peels[22a]

Component	Seed	Peel
Proximate (%)		
Protein	1.90 ± 0.56 to 2.25 ± 0.28	2.99 ± 0.47 to 3.30 ± 0.16
Fat	24.83 ± 1.21 to 29.21 ± 1.12	6.83 ± 0.20 to 7.78 ± 0.46
Carbohydrate	66.64 ± 3.92 to 70.91 ± 3.82	86.75 ± 1.94 to 87.33 ± 1.91
Fiber	32.64 ± 1.87 to 34.10 ± 1.32	8.50 ± 0.45 to 9.17 ± 0.61
Ash	1.90 ± 0.50 to 2.36 ± 0.44	2.17 ± 0.15 to 2.85 ± 0.24
Minerals (mg kg^{-1})		
Calcium	46.90 to 75.11	29.31 to 51.22
Copper	0.28 to 0.30	0.12 to 0.20
Iron	1.21 to 6.74	1.05 to 1.41
Potassium	56.21 to 56.47	108.30 to 115.78
Magnesium	16.78 to 20.36	27.92 to 38.60
Manganese	0.25 to 0.28	0.18 to 0.19
Sodium	7.85 to 9.29	29.54 to 32.18
Phosphorus	33.30 to 33.49	33.32 to 47.67
Zinc	0.43 to 0.64	0.22 to 0.27

[a] Abbreviations: %, proximate composition expressed as percentages, mg kg^{-1}, milligrams of a mineral in one kilogram of the sample.

Table 2 Phytochemical content of custard apple seeds and peels[a]

Component	Seed	Reference	Peel	Reference
Total phenolics	32.53 ± 2.13 μg GAE per mg	23	28.771 ± 0.008 μg GAE per mg	24
Total flavonoids	893.30 ± 6.66 μg QE per g	23	81.27 ± 1.74 μg QE per g	22
Vitamin C	0.57 ± 0.07 mg AA/100 g	23		
Carotenoids	0.45 ± 0.01 μg of β-carotene/10 mg	23		

[a] Abbreviations: μg GAE per mg, micrograms of gallic acid equivalents (GAE) per milligram of the extract; μg QE per g, micrograms of quercetin equivalent per gram of extract; mg AA per 100 g, milligrams of ascorbic acid per 100 grams; μg of β-carotene/10 mg, micrograms of β-carotene within every 10 milligrams (mg) of a substance; mg GAE per g, milligrams of gallic acid equivalent per gram of extract.

recovered using a range of extraction technologies, which can be utilized in the development of value-added products, such as functional foods or dietary supplements, while also contributing to the reduction of environmental waste.[30]

Extraction methods are classified based on their efficiency, cost-effectiveness, and sustainability. The bioactive compounds can be isolated, identified, and characterized for use in multiple sectors, including food, pharmaceuticals, cosmetics, or textiles.[30–32] Fig. 1 presents the overall valorization pathway of custard apple by-products, while Table 3 summarizes the extraction techniques applied, along with their conditions and outcomes.

3.1. Conventional methods

Conventional methods are typically based on the solvent extraction power, often involving heat or a combination of heat and other methods.[43,44]

3.1.1. Solvent extraction. Solvent extraction is a conventional method that primarily involves solid–liquid extraction, where organic solvents are used to break down the plant matrix to facilitate the recovery of bioactive compounds. Commonly used solvents include ethanol, acetone, and methanol. The quality of the bioactive compounds obtained and the efficiency of the extraction process depend on the solvent used.[45] In addition, other factors such as temperature, extraction period, and solid-to-liquid ratio significantly affect the solvent extraction performance, which requires optimization to achieve the maximum yield.[45,46]

Several studies have demonstrated the effectiveness of solvent extraction for recovering valuable compounds from custard apple by-products. For instance, Deng *et al.*[33] reported that 30% acetone–water mixture, combined with ultrasound assistance, achieved optimal recovery of total phenolic content from custard apple peel, yielding 26.81 mg GAE per g. The use of aqueous acetone enhanced the solubility of phenolic compounds, while ultrasound further improved mass transfer, highlighting the importance of solvent selection and process integration.

Similarly, García-Villegas *et al.*[10] used ethanol extraction for analyzing the total phenolic content of custard apple by-products, reporting 30.4 ± 0.7 and 28.771 ± 0.008 mg GAE per g for seeds and peels, respectively. The use of ethanol is advantageous in food applications due to its low toxicity and regulatory acceptance, making it suitable for developing functional food ingredients.

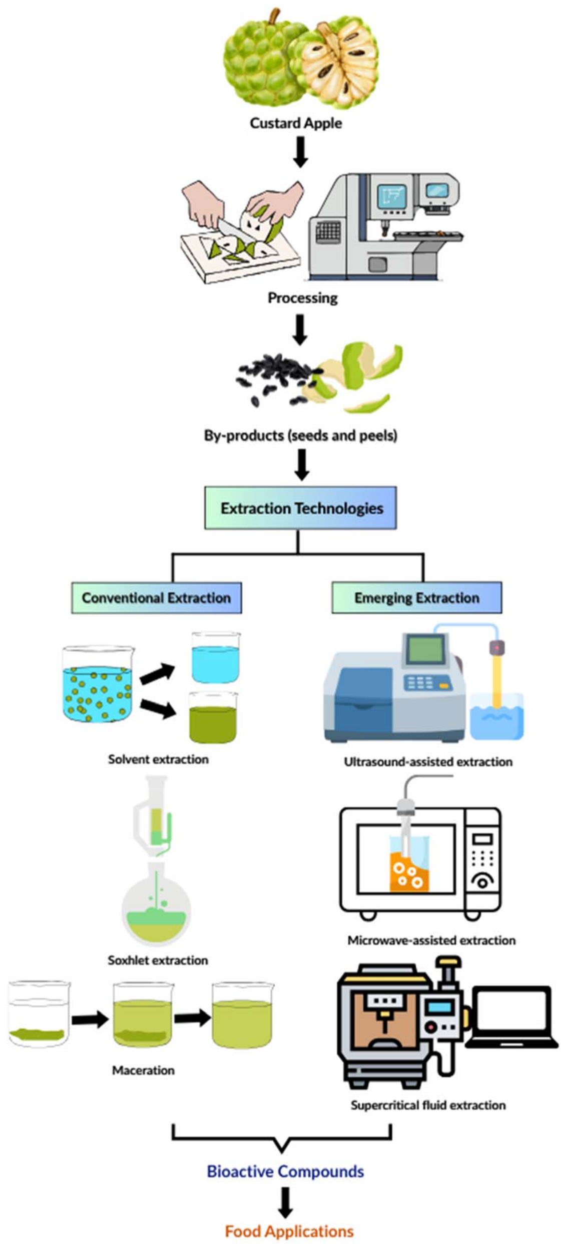

Fig. 1 Schematic diagram of the custard apple by-product valorization pathway. Seeds and peels produced during processing can undergo pre-treatment and extraction methods to recover bioactive compounds, which are then used in value-added food applications.

Table 3 Extraction of bioactive compounds from custard apple by-products[a]

Method	By-product	Target compound/s	Key conditions	Yield/result	Advantage	Reference
Solvent extraction	Peel	Phenolic	30% acetone; paired with UAE	26.81 (mg GAE per g)	Simple, effective for phenolic recovery	33
	Seed	Fatty acids	Methanol, 65 °C	Oleic acid (39.72%), linoleic acid (29.17%), palmitic acid (17.79%), stearic acid (4.29%)	Efficient for lipid profiling	34
	Seed and peel	Total phenolic content	Ethanol	30.4 ± 0.7 mg GAE per g (seeds) 28.771 ± 0.008 mg GAE per g (peels)	Food-grade solvent, suitable for bioactive compounds	10
Soxhlet extraction	Seed	Fatty acids	Petroleum ether (b. p. 60–80 °C)	Oleic (50.5%), linoleic (22.7%), palmitic (15.2%), and stearic (9.6%)	High extraction efficiency for lipid-soluble compounds and secondary metabolites	35
		Tocopherol		15.55 mg/100 g oil		
		Amino acids		7.266 g/100 g protein		
	Seed	Cyclopeptides and acetogenins	Methanol	—		36
	Seed	Oil/fatty acids	Hexane and methanol	10.5–19%		37
Maceration	Peel	Total phenolic content	52% ethanol, 51 min-extraction, 60 °C, solvent-to-solid ratio (26 mL g^{-1})	94.08 mg GAE per g	Simple and cost-effective technique suitable for thermolabile compounds	38
Ultrasound-assisted extraction	Peel	Pectin	Liquid-solid ratio (23.52 mL g^{-1}), 18.04 min, 63.22 °C, 2.3 pH	8.93%	Improving yield and reducing extraction time	39
	Seed	Oil/fatty acids	150 s, 30 W, 75% duty cycle	33.6%		40
Microwave-assisted extraction	Peel	Total phenolic content	60% ethanol, 5 min-extraction, solvent-solid ratio (25 mL g^{-1}), 214 W	96–98 mg GAE per g	Rapid extraction efficiency	41
Supercritical fluid extraction	Seed	Oil	15–25 MPa, 308–318 K, and 1.5–2.5 mL min^{-1}	22–31%	Produces high-purity bioactive compounds	40
	Peel	Total phenolic content	12% ethanol, 54 min, 52 °C, and 261 bar	109.38 mg GAE per g		42

[a] Abbreviations: mg GAE per g, milligrams of gallic acid equivalents per gram; s, seconds; W, watts; MPa, mega pascal; K, Kelvin.

In addition to phenolic compounds, solvent extraction has also been effectively used for lipid profiling of custard apple seeds. Prasad *et al.*[34] used methanol at 65 °C for the extraction of fatty acid composition from custard apple seed oil, reporting high levels of oleic acid (39.72%), linoleic acid (29.17%), along with palmitic acid (17.79%), and stearic acid (4.29%). These findings indicate that solvent extraction can efficiently recover valuable lipids, supporting its potential application in edible oil production.

Despite its effectiveness, solvent extraction has several drawbacks that may hinder its large-scale application. These include high solvent consumption, prolonged extraction time, and potential degradation of heat-sensitive compounds. Additionally, the use of organic solvents raises environmental and safety concerns, particularly in food applications, underscoring the need for greener, more sustainable extraction methods. However, food-grade solvents such as ethanol offer a safer and more sustainable alternative, highlighting the importance of solvent selection in optimizing extraction processes.

3.1.2. Soxhlet extraction. Soxhlet extraction is a widely used conventional technique for recovering bioactive compounds from various plant materials, although it was initially designed for lipid extraction.[47,48] This method involves continuous extraction of compounds from solid matrices using a solvent that is heated and condensed in a Soxhlet apparatus. The selection of an appropriate solvent is critical as it must effectively extract the target components. The effectiveness of Soxhlet extraction is influenced by factors, including solubility, mass transfer, and the properties of the solid material.[49,50]

This technique has been widely used for oil recovery from custard apple seeds. For instance, Mariod *et al.*[35] reported high oil yield with significant levels of oleic (50.5%), linoleic (22.7%), palmitic (15.2%), and stearic (9.6%) using petroleum ether (60–80 °C), along with seed's tocopherol content (15.55 mg/100 g oil) and the total amount of amino acids (7.266 g/100 g protein), demonstrating its effectiveness in lipid extraction. Pathak[36] extracted oil from the seeds using methanol as the solvent. Several compounds were identified *via* APCILC-MS, including cyclopeptides and acetogenins, which were reported to have anti-diabetic, anticancer, and anti-inflammatory agents and exhibited insecticidal properties. Another study reported oil yields ranging from 19% with hexane to 10.5% with methanol, depending on seed quality and solvent polarity.[37]

Despite its high extraction efficiency, this method is associated with significant energy consumption due to continuous solvent heating and reflux, as well as the risk of thermal degradation of heat-sensitive compounds. These factors may limit its suitability for processing temperature-sensitive bioactive compounds and raise operational costs. Consequently, there is growing research interest in alternative or hybrid extraction techniques that can achieve comparable yields under milder, more energy-efficient conditions.

3.1.3. Maceration. Maceration involves reducing the sample into fine particles to increase its surface area and improve solvent penetration. The ground materials are mixed with the solvent with continuous stirring, followed by filtration to separate extracts from solid residues. Although maceration is a relatively straightforward extraction method, it has drawbacks such as requiring a long extraction time and limited extraction efficiency.[51,52]

Despite its simplicity, maceration can be effective for extracting thermolabile compounds, as it generally operates under mild conditions. For example, Nguyen and Phan[38] investigated the extraction of phenolic compounds from custard apple peels and reported a total phenolic content of 94.08 mg GAE per g under optimized conditions (52% ethanol, 51 min extraction time, 60 °C, and a solvent-to-solid ratio of 26 mL g^{-1}). The relatively high phenolic yield demonstrates that maceration can be a viable method for recovering antioxidant compounds when appropriate extraction parameters are applied.

However, this method is limited by its extended extraction times and lower efficiency compared to emerging methods, which may restrict its large-scale industrial use. Despite these issues, it remains a cost-effective and accessible method, particularly for extracting thermolabile compounds, and can be improved through process optimization or integration with advanced extraction technologies.

3.2. Emerging/green technologies

Conventional extraction methods require substantial time, energy, and solvent, which present limitations. As a result, emerging technologies are increasingly being adopted across the pharmaceutical, food, and medical sectors. These new methods use less solvent, require shorter extraction times, and exhibit higher extraction efficiency compared to conventional techniques.[30,53] Several studies have demonstrated that these eco-friendly approaches can produce high-quality extracts, providing both economic and environmental advantages, highlighting their importance for industrial and commercial applications.[53,54]

In recent years, green extraction technologies have been integrated with optimization and scale-up strategies to recover bioactive compounds from tropical fruit by-products. This integration employs mathematical modelling and artificial intelligence tools to enhance precision and reproducibility at an industrial scale.[54–56]

3.2.1. Ultrasound-assisted extraction. Ultrasound-assisted extraction (UAE) utilizes ultrasonic energy along with solvents to extract desired compounds from various plant materials.[57,58] This technique enables rapid extraction at low temperatures while reducing solvent and energy requirements. As a non-thermal method, UAE is advantageous for preserving the functionality of bioactive compounds. However, its effectiveness depends on the optimization of operational parameters, including frequency, power, duty cycle, temperature, time, solvent type, and liquid–solid ratio for each specific by-product.[58]

Previous studies have demonstrated the use of UAE in extracting valuable compounds from custard apple by-products. For instance, Shivamathi *et al.*[39] reported the extraction of pectin from custard apple peel, yielding 8.93% under optimized conditions (liquid–solid ratio of 23.52 mL g^{-1}, extraction time of 18.04 min, temperature of 63.22 °C, and pH 2.3). The enhanced yield was attributed to cavitation-induced cell disruption, which improved the release of pectic substances from the plant matrix.

Similarly, Panadare *et al.*[59] investigated the extraction of the custard apple seed oil using ultrasound-assisted three-phase partitioning (TPP). Under optimized conditions (150 s ultrasound pre-treatment, 30 W power, and 75% duty cycle), an oil yield of 33.6% (w/w) was achieved. The study demonstrated that ultrasound pre-treatment significantly improved extraction efficiency compared to conventional TPP by enhancing phase separation and mass transfer.

These findings show the effectiveness of UAE in improving extraction efficiency through enhanced mass transfer and cell disruption, highlighting its potential for recovering valuable compounds from custard apple by-products. Despite its advantages, most studies on UAE of custard apple by-products have been conducted at a laboratory scale. Further investigation is needed to evaluate its scalability, energy efficiency, and process uniformity in large-scale systems.

3.2.2. Microwave-assisted extraction. Microwave-assisted extraction (MAE) is an automated and environmentally friendly method that offers several advantages, including reduced extraction time and solvent use, the ability to extract multiple samples simultaneously, and a significant increase in sample throughput. It is widely recognized as an effective alternative to conventional methods for extracting organic and organometallic compounds from various matrices.[60] Numerous factors influence the efficiency of MAE, such as power, frequency, extraction duration and temperature, moisture content of the sample, particle size, pressure, solvent type, and solid-to-liquid ratio.[61,62]

Thi and Tai[41] investigated the extraction of polyphenols from custard apple peel under different aqueous ethanol compositions, extraction irradiation durations, solvent-to-solid ratios, and microwave power levels. Using response surface methodology, the optimal conditions were determined to be 60% ethanol, 5 minutes of extraction time, a solvent-to-solid ratio of 25 mL g^{-1}, and a microwave power of 214 W. Under these conditions, the total phenolic content reached 96.12 ± 0.21 to

98.63 ± 1.05 mg GAE per g. The extracts also exhibited strong antioxidant activity, with DPPH values ranging from 589.46 ± 17.39 to 617.35 ± 15.54 μmol TE per g and ABTS values from 1242.98 ± 21.79 to 1361.38 ± 19.91 μmol TE per g. These findings highlight the effectiveness of MAE in rapidly recovering high-value bioactive compounds from custard apple by-products.

Despite the promising results obtained using MAE, studies specifically focusing on custard apple by-products remain limited. Current research is limited to a few investigations and laboratory-scale experiments, underscoring the need for further studies to optimize process parameters and assess their scalability for industrial applications.

3.2.3. Supercritical fluid extraction. Supercritical fluid extraction (SFE) is an effective technique for the valorization of food by-products, offering efficient recovery of bioactive compounds while addressing concerns related to food loss and waste.[63] This is a novel technology for extracting soluble materials from diverse sources into a fluid under supercritical conditions. SFE involves isolating one component (the matrix) from another (the extractant) using supercritical fluids. Carbon dioxide (CO_2) is the most commonly used fluid due to its non-toxic, inexpensive, and non-flammable nature.[64] The efficacy of the application of SFE is dependent on several parameters, such as flow rate, time, temperature, and pressure, that enhance the permeability of the solvent (CO_2) and the extraction yields.[40]

Recent studies have demonstrated the use of SFE to extract valuable compounds from custard apple by-products. Panadare *et al.*[40] extracted volatile and non-volatile oils from custard apple seeds, yielding 22–31%. The optimized conditions for non-volatile components were identified at 25 MPa pressure, 318 K temperature, and 2.5 mL min^{-1} flow rate, whereas for volatile oils at 15 MPa pressure, 308 K temperature, and 1.5 mL min^{-1}. The extracted oils were rich in fatty acids such as palmitic, stearic acids, oleic, and linoleic acids, which exhibited notable antibacterial and antifungal properties.

Similarly, Tai *et al.*[42] extracted custard apple peel combined with ethanol as a cosolvent. The optimal conditions (12% ethanol, 54 min, 52 °C, and 261 bar) yielded a total phenolic content of 109.38 mg GAE per g and strong antioxidant activity (1197.79 μmol TE per g for the DPPH assay and 1396.42 μmol TE per g for the ABTS assay). These findings highlight the effectiveness of SFE, particularly when combined with co-solvents, enhancing the extraction of bioactive compounds from plant matrices.

Although SFE shows strong potential for industrial application due to its ability to produce high-purity extracts, its scalability is constrained by high operational costs and equipment requirements. Further research on cost reduction and process optimization is necessary to enhance its commercial feasibility.

3.3. Comparative analysis of extraction techniques

Table 4 presents a comparative analysis of conventional and emerging extraction techniques based on key parameters, including efficiency, processing time, solvent consumption, energy requirements, and cost. These comparisons are based on previously reported studies summarized in Table 3.

Conventional methods such as solvent, maceration, and Soxhlet extraction generally exhibit low to high extraction efficiency; however, they are associated with longer processing times and higher solvent and energy consumption. In contrast, emerging techniques, including ultrasound-assisted extraction and microwave-assisted extraction, demonstrate higher efficiency with significantly reduced extraction time and lower solvent usage, making them more suitable for rapid and sustainable processing.

Furthermore, supercritical fluid extraction offers very high extraction efficiency and produces high-purity extracts with minimal solvent residues, highlighting its potential for high-value applications. However, its high operational cost and energy requirements may limit its widespread industrial adoption. Overall, emerging extraction technologies present clear advantages over conventional methods in terms of efficiency, sustainability, and processing time, although considerations related to cost and scalability remain important for industrial implementation.

4. Potential food applications

The growing research on sustainability and waste valorization in the food industry has driven interest in using fruit by-products as value-added ingredients. Custard apple by-products, such as seeds and peels, are often regarded as agricultural and industrial waste. However, these by-products show promising potential for use in various food products due to their rich sources of bioactive compounds, fatty acids, vitamins, minerals, and proteins. Exploring their potential food applications not only reduces environmental concerns but also contributes to the development of innovative, health-promoting, and economically viable food solutions.

Recent studies have demonstrated that custard apple by-products can be applied as natural preservatives, functional ingredients, edible coatings and films, and sources of essential oils and proteins (Fig. 2). These applications highlight their versatility and potential for incorporation into a wide range of food products. Table 5 further summarizes the specific by-products, application types, functional compounds, and their corresponding technological benefits.

4.1. Natural preservatives

Custard apple by-products, particularly seeds and peels, are rich in phenolic compounds, flavonoids, and tocopherols, which exhibit strong antioxidant and antimicrobial properties. These bioactive compounds enable their application as natural preservatives by inhibiting lipid oxidation and microbial growth in food systems.

For instance, Bheemagani *et al.*[65] reported that the extracts from custard apple seeds have demonstrated antibacterial activity against microorganisms, while Kumari *et al.*[27] reported the presence of tannins, vitamins, amino acids, and fatty acids contributing to their bioactivity. These findings highlight the

Table 4 Comparative analysis of extraction techniques

Method	Efficiency	Time	Solvent use	Energy use	Cost	Key strength	Limitation
Solvent extraction	Low to moderate	Long	High	Moderate	Low	Simple	Solvent-intensive
Maceration extraction	Low to moderate	Long	High	Moderate	Low	Simple	Solvent-intensive
Soxhlet	High	Very long	High	High	Low	Exhaustive	Heat damage
UAE	High	Short	Low	Low	Moderate	Fast	Scale-up issues
MAE	Very high	Very short	Low	Moderate	Moderate	Rapid	Overheating
SFE	Very high	Moderate	Very low	High	High	High purity	Expensive

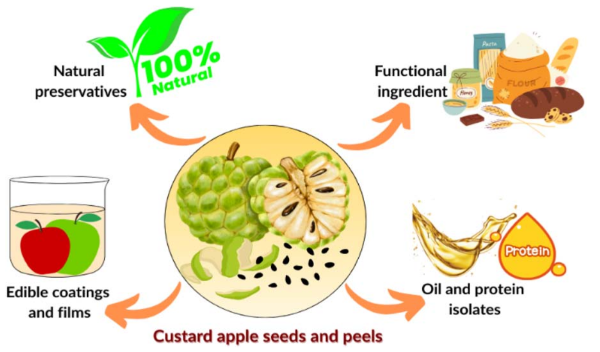

Fig. 2 Potential food applications of custard apple seeds and peels.

potential of custard apple by-products as plant-based alternatives to synthetic preservatives. This application supports the valorization of agro-industrial waste by converting underutilized materials into functional and clean-label food additives.

4.2. Functional ingredients

Custard apple peel-derived flour represents a functional ingredient due to its high nutrients and phenolic compounds. Incorporation of peel flour into food formulations can enhance the nutritional value while maintaining acceptable sensory properties. Souza *et al.*[66] demonstrated that the inclusion of custard apple bagasse flour (5–50%) in cookies can significantly increase the phenolic content, with good consumer acceptability. The flour also contributed essential minerals such as Fe, Zn, and Ca, supporting its role in nutrient enrichment.

Moreover, it was also highlighted that custard apple peels possess strong antioxidant properties. According to Hussain *et al.*,[67] fruit peels are a rich source of biologically active natural compounds, offering considerable benefits for both human and animal health. These findings indicate that custard apple peel can be effectively utilized in bakery and snack products, contributing to value addition and waste reduction in fruit processing industries.

4.3. Edible coatings and films

Bioactive extracts from custard apple peels can be incorporated into edible coatings/films to enhance food preservation. These extracts provide antioxidant and antimicrobial functions while improving barrier properties against moisture and oxygen.

Table 5 Valorization and food applications of custard apple by-products[a]

By-product	Application	Product type	Level used	Key compounds	Functional effect	Reference
Seed	Extract/oil	Natural preservatives	—	Tannins, vitamins, amino acids, fatty acids	Antibacterial, hepatoprotective, antioxidant, and anticancer	27 and 65
Peel	Flour	Cookies	5–50%	Minerals and phenolic compounds	Increased antioxidant activity, high acceptability	66
Peel	Edible coating	Shrimp preservation	300 mg GAE per L	Phenolics	Antioxidant and antimicrobial properties, reduced lipid oxidation, and extended shelf life	68
Peel	Film	Potential in bioplastics	—	—	Good structural integrity, controlled water solubility, and significant biodegradability (∼59%)	69
Seed	Oil	Potential in edible fat blend or as an ingredient in emulsified foods	18–28.8%	—	—	40, 70 and 71
Seed	Flour and protein isolate	Potential in acid foods, milk analogues, and protein-rich beverages	—	—	—	72

[a] Abbreviations: mg GAE per L, milligrams of gallic acid equivalents per liter.

Thi *et al.*[68] reported that chitosan coatings enriched with custard apple peel extract significantly improved the shelf life and quality of shrimp during refrigerated storage. The treatment reduced lipid oxidation, microbial spoilage, and physicochemical deterioration compared to untreated samples.

In addition, the peel has potential as a film, for example, Ravinder *et al.*[69] developed starch-based films from custard apple peel, and the films showed good structural integrity, controlled water solubility, and significant biodegradability (∼59%). This indicates that custard apple peel is a viable raw material for biodegradable films/packaging.

Overall, the findings demonstrate the potential of custard apple by-products in developing active packaging systems, contributing to sustainable food preservation strategies.

4.4. Oil and protein isolates for food formulations

Custard apple seeds are a valuable source of lipids and proteins, making them suitable for food and nutraceutical applications. Reported oil content ranges from approximately 18 to 28%,[40,70,71] with a fatty acid profile rich in oleic and linoleic acids, indicating potential as an edible oil source.

Seed-derived protein isolates exhibit favourable functional properties, including solubility across a wide pH range, supporting application in emulsified foods, bakery products, and protein-enriched formulations.[72] However, further research is needed to address safety concerns, particularly the removal of antinutritional and toxic compounds, to enable safe incorporation into food systems.

In addition, incorporating plant-derived proteins into food systems such as beverages may pose sensory challenges, including undesirable flavours, limited solubility, and textural issues, which can affect consumer acceptance. This highlights the need for formulation strategies such as flavour masking, enzymatic modification, or microencapsulation to improve acceptability. Addressing these sensory limitations is essential for the successful development of food products derived from the by-products.

Overall, the utilization of seed-derived oils and proteins represents a promising pathway for the valorization of custard apple by-products into high-value food ingredients.

5. Toxicity, food safety, and regulatory considerations

In addition to the functional potential of custard apple by-products, their safe utilization in food systems requires a comprehensive evaluation of toxicity, food safety, and regulatory considerations.

5.1. Toxicity of custard apple by-products

Custard apple (*Annona squamosa* L.) is recognized as an essential medicinal plant with various health applications in traditional healing practices.[73] Extracts obtained from different parts of the custard apple plant, including its bark, roots, leaves, stems, fruit, peel, and seeds, have been employed in traditional medicine across several countries to treat various diseases such as dysentery, epilepsy, hemorrhage, fever, and tumors.[6,74] This is due to their anti-inflammatory, antimicrobial, antioxidant, and anticancer properties, making them a potential candidate for various health-related uses. Furthermore, their abundant nutritional profile positions them as a viable alternative food source in areas facing food insecurity.[75] However, recent studies have reported that custard apple seeds contain toxic substances that can have adverse health effects when consumed in excess.

Custard apple seeds are known to contain substances like anonaine and other alkaloids, which can be harmful in large amounts. These compounds have been found to have neurotoxic effects, and consuming significant quantities of the seeds may result in symptoms such as dizziness, nausea, and, in severe cases, seizures. It is crucial to refrain from eating the seeds raw or in large doses.[75]

Nagaraja *et al.*[76] documented six patients who developed toxic keratoconjunctivitis 6–12 hours after ocular exposure to custard apple seeds. Similar findings were observed by Devi Nivean *et al.*[77] Other studies have reported that certain extracts of active compounds from the leaves and seeds, when applied in four organic solvents, caused conjunctival redness, chemosis, a rough cornea, skin erythema, and edema.[27,78] These studies indicate that further research is needed regarding its toxicity to determine safe consumption levels and detoxification methods.

5.2. Food safety considerations and regulatory aspects

Beyond toxicity concerns, the safe utilization of custard apple by-products in food systems requires careful consideration of food safety and regulatory aspects. Extraction processes may introduce safety risks associated with residual solvents. Particularly, the use of conventional solvents like alcohols (methanol, ethanol), acetone, diethyl ether, and ethyl acetate, often mixed with different proportions of water. The disadvantage is a possible hazardous effect on human health, as the residues of the solvents may also remain in the final products.[79] Therefore, the selection of food-grade solvents is crucial to ensure consumer safety and regulatory compliance.

Furthermore, the incorporation of custard apple by-products into food formulations requires evaluation of microbial safety, stability, and potential antinutritional factors. Processing techniques, such as heat treatments, can mitigate these risks. Food hygiene and processing conditions must be controlled to ensure product safety as outlined by food safety frameworks.

From a regulatory perspective, food ingredients derived from plant by-products must comply with established safety assessment systems. For example, Codex Alimentarius provides internationally recognized standards for pesticide residues, contaminants, food additives, and hygiene requirements.[80] Similarly, in the United States, ingredients intended for food use must meet the criteria for Generally Recognized as Safe (GRAS) status.[81] However, specific regulatory approval for custard apple seed and peel-derived ingredients remains limited, which may hinder their large-scale commercialization and highlights the need for further toxicological and regulatory evaluation.

6. Challenges and future prospects

Despite the promising potential of custard apple by-products, several challenges limit their effective valorization, particularly in industrial applications.

One of the primary concerns is the presence of toxic compounds in custard apple seeds, including alkaloids such as anonaine, which restrict their direct incorporation into food products. To address this limitation, future research should focus on developing effective detoxification strategies, such as solvent purification, thermal treatment, fermentation, or enzymatic degradation, to reduce or eliminate toxic compounds while preserving functional components. In addition, comprehensive toxicological evaluations and the establishment of safe consumption limits are necessary to support their use in food systems.

Another significant limitation is the seasonal availability and inconsistent supply of custard apple, which can affect the continuous industrial processing. To overcome this challenge, the development of efficient storage and stabilization techniques, such as drying, freeze-drying, or controlled-atmosphere storage, is crucial to extend shelf life and ensure a stable supply of raw materials. Furthermore, establishing organized supply chains and contract farming systems with local producers could improve the consistency and availability of feedstock.

In terms of processing, the scalability of extraction technologies remains a critical barrier. While emerging techniques have demonstrated high efficiency at the laboratory scale, their industrial implementation requires further optimization to reduce energy consumption, operational costs, and equipment complexity. Further studies should focus on process intensification, hybrid extraction systems, and techno-economic analysis to evaluate their feasibility for large-scale applications. Additionally, sensory limitations associated with plant-derived ingredients may affect consumer acceptance, highlighting the need for further product optimization and formulation strategies.

From a regulatory and commercial perspective, the lack of established safety approvals for custard apple by-product-derived ingredients presents an additional challenge. Further work should aim to develop standardized safety data and support regulatory submissions to facilitate their acceptance in food and nutraceutical markets. Addressing these challenges through integrated research approaches will be essential to unlock the full valorization potential of custard apple by-products.

7. Conclusion

This review highlights the potential of custard apple seeds and peels as valuable sources of bioactive compounds for food and nutraceutical applications. Various conventional and emerging extraction techniques have demonstrated effectiveness in recovering phenolics, lipids, and other functional compounds, supporting the valorization of these by-products. In addition, their application as natural preservatives, functional ingredients, edible coatings/films, and oil and protein isolates underscores their potential for developing sustainable value-added products.

However, several challenges remain, including the presence of toxic compounds in seeds, limitations in large-scale extraction, seasonal availability of raw materials, and sensory issues affecting consumer acceptance. Furthermore, regulatory constraints and the lack of standardized safety assessments continue to hinder their industrial application.

Future research should focus on developing efficient detoxification strategies, optimizing scalable, cost-effective extraction technologies, and improving sensory properties through advanced formulation approaches. Addressing these challenges will be essential to enable the safe, sustainable, and industrial-scale utilization of custard apple by-products, thereby contributing to waste reduction and the advancement of circular economy practices.

Author contributions

Mary Ann B. Mamayabay: conceptualization, validation, writing – original draft, investigation, data curation, formal analysis, review, and editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software, or code have been included, and no new data were generated or analysed as part of this review.

Acknowledgements

The author sincerely thanks the Department of Science and Technology-Science Education Institute Science and Technology Regional Alliance of Universities for National Development (DOST-SEI STRAND) for the scholarship grant.

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