

Starfruit (*Averrhoa carambola* L.) as a Sustainable Bioresource: Bioactive Phytochemicals, Functional Properties, and Emerging Food Applications

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Received: 27/08/2026

Accepted: 21/09/2026

Published: 30/09/2026

Abstract

Introduction: Starfruit (*Averrhoa carambola* L.), an underutilized tropical fruit of the family Oxalidaceae, has attracted scientific and industrial attention because of its nutritional contents, bioactive phytochemicals, functional attributes, and potential applications in sustainable food systems.

Materials and Methods: A literature search was conducted by Google Scholar, Web of Science, ScienceDirect, and Scopus to make a comprehensive review. Further analysis of the available studies was carried out to compile existing knowledge and to extract implications for further potential, limitations, and challenges.

Results: Starfruit contains high levels of dietary fibre, bioactive compounds, vitamins, and minerals. Its bioactive potential has been reported as antioxidant, antimicrobial, anti-inflammatory, antidiabetic, antihyperlipidemic, hepatoprotective, anticancer, and immunomodulatory. The research has identified new roles of starfruit in the form of functional foods, fermented beverages, nutraceutical products, edible coatings, and functional ingredients. Recent advances in the technology of drying fermentation microencapsulation, and other unit operations have set new directions in the development of new safe and stable products with the retention of bioactive compounds. Pectin, phenolic compounds and dietary fibre in the peels/residues may provide further resource recovery option in circular-bioeconomy.

Discussion: Despite its promising nutritional, functional, and technological potential, there are still some safety issues related to the presence of oxalates and caramboxin that should be taken into account in people with impaired renal function. Additional research like optimized processing methods, bioavailability, and toxicity studies, validation of biological effects and analysis of economic and environmental sustainability are needed. Strategies for integrated use of food processing and by-product valorization can promote the sustainable use of starfruit as a multi-purpose bioresource

Keywords: *Averrhoa carambola*; pharmacological actions; bioactive phytochemical compounds; functional foods; food processing, toxicity, caramboxin, nutraceuticals

Journal of Applied Pharmaceutical Sciences and Research, (2026);

DOI: 10.31069/japsr.v9i3.18

Introduction

Global food security and natural resource management are challenges faced by all developing countries, especially India. To satisfy global food demand, it should be ensured that the food provides nutrients at high density while reducing the input of resources, food losses, and waste. In this context, geographically or nutritionally restricted underutilised fruit crops are gaining renewed attention, as they may offer different nutrient combinations, phytochemicals, functional ingredients, and biomass for value-added use^[1,2,3]. Star fruit (*Averrhoa carambola* L.), a member of the Oxalidaceae family, most commonly known as 'carambola', is one such popular tropical fruit grown in many parts of the world, including Southeast Asian countries, India, Sri Lanka, Malaysia, Indonesia, the Philippines, and many other tropical and

subtropical areas. The fruit is often called 'starfruit' because of its distinctive five-ridged, star-shaped appearance, juicy texture, and characteristic sweet-to-acidic flavour, and it also has medicinal properties^[4,5].

In Asia, starfruit has traditionally been used to manage various ailments, including fever, cough, sore throat, inflammation, diabetes, digestive disorders, skin diseases, and hangovers^[6]. Different plant parts, including fruits, leaves, roots, flowers, and bark, contain diverse phytochemicals associated with potential therapeutic properties^[5,7]. Recent research has increasingly investigated the nutritional composition, phenolic and flavonoid contents, antioxidant activity, and potential metabolic effects of starfruit, while advances in analytical and food-processing technologies have expanded its potential applications in edible coatings,

pectin recovery, green extraction, and plant-mediated nanomaterial synthesis^[8,9,10,11]. On top of the edible pulp, leaves can also be a source of specialized metabolites, for example of dihydrochalcone C-glycosides, while phenolic and other related compounds found in bark and other non-edible tissues are also of scientific interest^[12,13]. The peel of starfruit, a major potential processing by-product, brings potential for pectin and other functional compound recovery, and microwave-assisted extraction of starfruit peel has recently shown promising results for pectin recovery^[11]. But, the use of starfruit must be evaluated about safety issues related to oxalates, which have been linked to renal injury and to the neurotoxic compound of concern in people with advanced or premature failure of the kidney, caramboxin^[14,15]. Because of this, before any health-related claims can be made, the health benefits of starfruit need to be balanced with its potential toxicity, using dosages, cultivars, and processing conditions, and chemical composition. While investigations of starfruit across nutritional science, phytochemistry pharmacology postharvest food processing, and materials science have proliferated, they are all numerous and disconnected. Discrepancies of plant organ, developmental stage cultivar extraction methods, and analysis methods also challenge comparison of the studies. An integrated review is this way demanded to systematically analyze the nutritional and functional properties, safety issues, novel use, and sustainable valorization prospect of *A. carambola*.

The current paper systematically investigated the potential applications of *A. carambola* as a multi-purpose bio-resource for the design of an integrated circular-bioeconomy. Advances were gained on its nutritional composition, phytodiversities, bio-compound, and its activities, novel applications as ingredients for food and nutraceuticals, safety issues during the processing, reutilization of its by-products towards other high value-added products, and onto the new emerging material applications. Special emphasize was given on the function-al safety dilemma and the transition from the conventionally used fruit towards the new concept of an integrated circular-bioeconomy, including current, knowledge, gaps, and future research needs for safe exploitation of the bio-resource.

Material and Methods

The present paper involves a comprehensive collection of published knowledge on starfruit (*Averrhoa carambola* L.), Most of all about its composition and functionality, including the chemical composition phytochemicals physiological roles, and its food use potential, sustainability, and safety issues. All related knowledge was collected, consolidated, and evaluated through searching of the relevant literature collection from several electronic databases (Scopus, Web of Science, ScienceDirect, and Google Scholar), from January 2015 to October 2026, when possible, selecting prior publication for better understanding of the starfruit. The keywords were "*Averrhoa carambola*", "starfruit",

"phytochemicals", "phenolic compounds", "flavonoids", "antioxidant activity", "functional foods", "food processing", "by-product utilization", "oxalate", and "caramboxin". The reference citations of those selected papers were also reviewed to find any other potentially relevant papers. All the identified records were initially screened by reading their titles and abstracts, and then, the full texts of the relevant papers were reviewed. The inclusion criteria were original research articles and review papers published in the English language, not duplicated papers, or publications not related to the scope of the study. Information on research objectives, research methods, major results, bioactive compounds, possible utilization, and safety aspects were extracted and categorized under several themes. A qualitative synthesis was conducted to compare the evidence available about the starfruit's nutraceutical functional technological, and sustainable utilization potential.

Botanical Description and potential

Averrhoa carambola or starfruit, is a tropical or sub-tropical fruit tree of the family Oxalidaceae. The plant is a small to medium-sized evergreen tree (Figure 1), cultivated extensively in Asia, including India, Bangladesh, Malaysia, Indonesia and southern China, and is also grown in parts of South and Central America and other tropical regions.

Its adaptability, attractive appearance and distinctive flavour have contributed to its use in both local markets and specialty fruit markets^[16]. The fruit is eaten at various stages of maturity. It is highly variable in quality, based on the cultivar, the degree of ripeness and the growing conditions and can be either sour or sweet. The plant other than the fruit, like the bark and leaves, brings phytochemicals that have been of interest in food and natural-product research^[5] (Luan et al., 2021). Fruits vary in shape, size, sweetness, acidity and colour according to the cultivar and environmental conditions^[17]. Ramadan et al.^[18] reported variations in the profile of nutrients and sensory metabolites with the country of origin and ripening stage.

Star fruit has additional resource potential as a source of compounds. Pulp can be dried and formulated into juices



Figure 1: Morphological characteristics of *Averrhoa carambola* L., showing a whole tree, bark, leaves, leaflets, flowers, mature fruit and seeds

beverages fruit leather, dried products, jams, and preserves, and peel potential includes pectin recovery and isolation of fibre- and phenolic-rich ingredients. Leaves and other plant components may provide sources of specialized metabolites. This integrated whole-plant vision encourages industry to develop processing technologies that recover edible products, functional ingredients, and materials from various fractions. Commercially, composition, seasonal availability, processing efficiency, and potential toxicity impact the potential for use in human food products and the market acceptance of these products.

Nutritional Composition and Phytochemical diversity

Starfruit contains about 132 isolated phytochemical compound in various parts of plant.^[5] It is a low-energy fruit with high water content and rich in vitamins C, minerals including potassium and magnesium, dietary fibres, antioxidants and bioactive compounds (Table 1). These nutrients contribute to hydration, digestive health, collagen synthesis and normal metabolic functions, although the amounts supplied vary by nutrient and serving size (USDA Agricultural Research Service, Food Data Central).

The fruit is marketed as a functional and nutraceutical food for its low-calorie content and high levels of valuable micronutrients and phytochemicals^[19]. The star fruit contains some valuable macro- and micro-nutrients including L-ascorbic acid, carotenoids, and natural sugars with a low total fat content^[20]. Published information on compositional and mineral levels in star fruit suggests considerable

variability in values^[14,20] due to growing conditions, cultivar maturation, handling, and analytical method. So, take into account the particular terms of the maturity of the crop and the nature of the reported values (fresh- or dry-weight basis)^[14]. The star fruit phytochemistry is chemically diverse, and includes phenolic acids, flavonoids, tannins, saponins, alkaloids, and dihydrochalcones, and these constituents may all contribute to the reports of antioxidant activity and other biological effects of star-fruit extracts. Recent advances in analytical capabilities using techniques such as UHPLC/Q-Orbitrap MS and molecular networking are helping to shed light on the chemical diversity of star fruit. Wang et al.^[21] reported 53 dihydrochalcones from 12 star-fruit cultivars and identified 3-hydroxyphloretin as a key thing. They also reported that the dihydrochalcones were more abundant in star-fruit leaves than in star-fruit fruits, which emphasizes the importance of plant-part selection in selecting star fruit as a source of bioactive compounds. Yang et al.^[12] characterized dihydrochalcone C-glycosides in *A. carambola* leaves, once again illustrating that non-fruit parts of the plant likely contain novel compounds to explore in the future. Such extensive chemical diversity is a gateway to natural ingredient candidates, functional foods, and developing uniform standardized botanical extracts.

Biological and Functional Properties

Biological activities, including antioxidant, glucose-, and lipid-modulating, anti-inflammatory, anti-microbial, liver-protective, and other properties, have been noted with star-fruit extracts or isolated constituents (Table 2). Antioxidant effects are most frequently evaluated by chemical assays, while the metabolic and protective effects are studied in cultured cells and animals. Song et al.^[22] found a number of fruit polyphenols reduced hyperlipidaemia, fatty liver and high blood sugar in obese mice, indicating possible effects on lipid and blood sugar regulation, but an obvious benefit to humans cannot be assumed. Cell-based studies suggest a biological response but cell cultures may expose cells to concentrations of compounds not reached with usual dietary intake. Animal studies have attempted to address issues related to physiological effects and mechanisms with the results to be verified in humans. Clinical effects in humans are required to determine efficacy, food intake and relevant outcomes.

Currently, the functional properties of star fruit appear to be mainly based on chemical, in-vitro, and animal studies while there is very little evidence from human trials^[5,14]. Another issue to be taken into account is the fruit's safety. Star fruit, includes, oxalates, and caramboxin, and ingestion has been linked to renal and neurological toxicity, in particular in subjects with compromised renal function. That means, the functional-food potential of this fruit should not be claimed as a proof that high doses or concentrates of extracts are safe. Complementing bioactivity testing with analysis of oxalate and caramboxin levels, as well as dose analysis, toxicological assessment, and vulnerable populations, should be performed.

Table 1: Nutritional Profile of *A. carambola* and its health significance per 100g edible portion.

Component	Amount (per 100g)	Significance
Energy	30-35kcal	Low-calorie fruit
Carbohydrates	6-7g	Energy Source
Protein	1g	Tissue Repair
Fat	0.3g	Very low fat
Dietary fiber	2-3g	Digestive help
Vitamin C	30-35mg	Anti-oxidants, Immunity
Potassium	120-130mg	Heart function
Magnesium	10 mg	muscle and nerve function
Phosphorus	12 mg	Helps in bone structure, energy metabolism
Calcium	3- 5 mg	Bone health
Water	91.4 g	Keep hydrating
Sugars	3-4g	Supplies energy
Thiamin (B1)	0.014 mg	Helps in the function of CNS
Riboflavin (B2)	0.016 mg	Energy metabolism and cellular function.
Others (trace): Niacin (B3), Pantothenic acid (B5), Vitamin B6, Folate		

Source: US Department of Agriculture, "Carambola (starfruit) <https://fdc.nal.usda.gov/>

Table 2: Phytochemicals, biological activities and safety considerations of star fruit

Component/resource	Applications	Reference
Phenolic acids and flavonoids	Antioxidant potential; possible anti-inflammatory effects observed in laboratory	[5]
Dihydrochalcones	Bioactive compounds; potential functional ingredients, reported in preclinical research	[23]
Fruit polyphenols	In an animal study, reported potential effects on lipid and glucose metabolism	[22]
Fruit pulp	Juices, beverages, fruit leather, and dried products	[24]
Peel and processing residues	Recovery of fibre and phenolic-rich ingredients; composting or bioconversion	[5]
Fruit extract and nanoparticles	Research reported antibacterial and UV-protective textile applications	[8]
Extract-based polymer films	Potential functional and packaging materials	[10]
Oxalates and caramboxin	Neurological toxicity potential renal and documented under safety concern	[15]

Food Processing and Application

The short postharvest life of starfruit can limit its market potential and causing losses during storage, handling, and transport. The processing of starfruit products; for instance, juices beverages, dried pieces and powders, fruit leather jams jellies, pickles, and jams can increase its period of usability and can bring value-added products. Processing parameters need to be optimized to balance changes in both sensory and nutritional quality factors. Edible coatings present a promising method for the shelf life extension of fresh starfruit by limiting water loss and quality decline. Edible coatings using gelatin–sodium alginate incorporated with green-tea extract for preservation of the quality of starfruit. Also the application of pectin coatings used to maintain fruit quality at ambient storage. Still, the practical application of edible coating needs consideration of food contact safety, sensory property cost food-grade quality and the storage condition in the supply chain in commercial application. A detail evaluation on microbial safety, retention of nutrients, storage time, packaging material, consumer acceptance and standard process should be investigated. Starfruit peels and other residues from processing are a potential source of pectin, a source of dietary fibre, and phenolic compounds. Pectin is beneficial for its gelling, thickening, and emulsifying effects in food products. Acid extraction, Microwave-Assisted extraction (MAE), and Ultrasound-Assisted extraction (UAE) are traditional extraction methods for retrieving pectin from fruit residues. Rahman et al. (2026) compared acid extraction and UAE and MAE for obtaining pectin from the peel of carambola and found the highest recovery (22.38%) with MAE. The pectin was characterized as high-methoxyl pectin, which look promising for food gelation and emulsion purposes^[11]. Extraction efficiency is highly dependent on raw-material makeup and processing parameters. Beyond traditional food applications, starfruit extracts and peel-based polymers are tested as potential functional materials. Porrawatkul et al.^[8] studied the microwave-assisted synthesis of silver/zinc oxide nanoparticles with starfruit extract and their potential use as cotton fabric with antibacterial and UV protective features. Similarly, Mandal et al.^[25] highlighting potential applications of starfruit extract in titanium dioxide nanoparticle-chitosan film formation. Although

plant-mediated nanoparticle synthesis may reduce the use of certain conventional chemical reagents, it does not automatically guarantee environmental sustainability or product safety. Further research is required to nanoparticle characterization, environmental fate, production costs, toxicity, migration, and life-cycle impacts.

Overall, integrating postharvest preservation, food processing, by-product recovery, and material development could improve starfruit utilization and reduce waste.

Safety, Toxicity and Responsible Utilization

Irrespective of its health benefits that include nutrition, phytochemicals, and other health aspects, food safety considerations tied to star fruit are significant. It is a rich source of oxalates and the neurotoxin caramboxin, and these have been connected to acute kidney injury, neurological symptoms, and potentially life-threatening toxicity, mainly in individuals with chronic kidney disease or compromised renal function^[15]. As a result, the development of concentrated juices, star-fruit-based functional foods and botanical extracts should be justified with accurate quantitative measurement of all relevant oxalates and toxic materials, with control over processing technology, dose-related safety testing and user information. Its use should be carried out with these considerations in a circular-bioeconomy mentality that considers the best utilization of peel, pulp, and other residues from the plant.

Innovative applications in edible films and plant-based nanomaterials are emerging, but their environmental and health safety, migration behaviour and potential toxicity and degradability needs to be verified before commercial implementation.

Research Gaps, Future Directions and Conclusions

Future studies should focus on cultivar-specific characterization of the nutritional and phytochemical composition with validated analytical techniques; standardized protocols for greener extraction and improved understanding of the effects of maturity, processing, and storage on product quality and safety; dose–response and toxicological studies; impact of processing on oxalates and caramboxin; life-cycle assessment; techno-economic

analysis; and pilot-scale investigation of pectin extraction, functional ingredients and new materials. It is a promising bioresource for a wider circular bioeconomy in food systems as bioactive-rich food development and consumption of star fruit pose some intriguing opportunities. The ability to guarantee consistent quality, safety, market viability, and observable ecological sustainability will ultimately determine the true value of star fruit, in addition to the discovery of new compounds or application areas. Star fruit's potential can be maximized within a larger circular food system through synergies through the smooth integration of scientific product development pathways, by-product valorization, and sustainable consumption practices.

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How to cite this article: Srivastava R, Singh AK, Pankaj U, Kushwaha S. Starfruit (*Averrhoa carambola* L.) as a Sustainable Bioresource: Bioactive Phytochemicals, Functional Properties, and Emerging Food Applications. *Journal of Applied Pharmaceutical Sciences and Research*. 2026; 9(3):112-117 Doi : 10.31069/japsr.v9i3.17