Letters in Food Research 2(3): e26126
Journal homepage: https://www.lettersinfoodresearch.com

LETTERS IN FOOD RESEARCH

REVIEW

Bioavailability and health impacts of plant-derived carotenoids in Sri Lankan cuisine

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Article history:
Received: 4 March 2026
Received in revised form: 30 March 2026
Accepted: 2 April 2026
Available Online: 7 April 2026

Keywords:
Dietary carotenoids,
Sri Lankan cuisine,
Bioavailability,
Provitamin A,
Traditional cooking methods,
Health impact

OPEN ACCESS
Citation: Gamage, C.U. and Ratnayake, J.T. (2026). Bioavailability and health impacts of plant-derived carotenoids in Sri Lankan cuisine. *Letters in Food Research*, 2(3), e26126. https://doi.org/10.26656/lfr.2.e26126

Abstract

Carotenoids are essential bioactive pigments with significant health-promoting properties. Due to its rich biodiversity and culinary practices, Sri Lanka offers a variety of carotenoid -rich food ranging from green, non-green vegetables, and fruits like mango, papaya and jackfruit. The review aims to investigate the bioavailability, metabolism, and health impacts of plant-derived carotenoids in Sri Lankan diets, focusing on alleviating micronutrient deficiencies and preventing chronic diseases, including cardiovascular conditions, diabetes, neurodegenerative disorders and cancer. Despite their abundance in local produce, carotenoid intake and absorption are influenced by regional variability in carotenoid profiles, bioavailability constraints, and lack of localised data. Advances in nanostructured delivery systems and personalised nutrition are highlighted as innovative approaches optimising carotenoid absorption and efficacy. Therefore, the current review underscores the importance of promoting carotenoid-rich traditional foods in Sri Lanka to address malnutrition and foster long-term health resilience.

1. Introduction

Sri Lanka, a tropical island renowned for its biodiversity and agricultural heritage, offers an ideal environment for carotenoid biosynthesis due to its diverse climate characterised by variations in rainfall, altitude, temperature, and soil composition (Gunatilleke *et al.*, 2017). This unique setting has fostered the growth of a wide variety of carotenoid-rich plants that significantly contribute to the nation's cuisine and public health. Carotenoids, natural pigments found in the chloroplasts and chromoplasts of plants and photosynthetic organisms, are responsible for the vibrant orange, yellow, and red hues in many foods (Henry *et al.*, 1998; Dutta *et al.*, 2005). Humans cannot synthesise their own carotenoid requirements, so they have to obtain them through carotenoid-rich foods and supplements (Sy *et al.*, 2013). These bioactive compounds play vital roles in human health, including supporting vision, boosting the immune system, promoting cell growth, and maintaining epithelial integrity. Additionally, carotenoids possess antioxidant properties that combat oxidative stress, a major contributor to chronic diseases such as cardiovascular conditions, diabetes, and cancer (Sui *et al.*, 2024; Li *et al.*, 2025).

Although approximately 500–600 carotenoids are identified, only about 40 are regularly consumed by humans through food sources (Sy *et al.*, 2013). In Sri Lankan diets, carotenoids such as β-carotene, α-carotene, lutein, lycopene, and zeaxanthin are abundant in staples like Gotukola (*Centella asiatica),* pumpkin (*Cucurbita maxima*), and papaya (*Carica papaya*) (Chandrika *et al.*, 2011; Schweiggert *et al.*, 2011) . These compounds are critical for preventing vitamin A deficiency and reducing the risk of age-related macular degeneration and enhancing skin health (Melendez-Martinez *et al.*, 2019; Michalak *et al.*, 2021). Recent studies have linked carotenoid intake with decreased risks of degenerative diseases, improved immune responses, and the mitigation of harmful free radicals and reactive oxygen species (Cho *et al.*, 2018; Baeza-Morales *et al.*, 2024).

Sri Lankan cuisine promotes carotenoid bioavailability through traditional cooking practices,

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eISSN: 3093-7361 /
Published by Rynnye Lyan Resources

including dietary fats essential for absorbing of these fat-soluble compounds. While traditional dietary practices maximise carotenoid benefits, modern dietary shifts toward processed foods and reduced dietary diversity threaten optimal intake, necessitating the preservation and promotion of traditional food systems. Carotenoids are not only vital in nutrition but also significant in broader applications. For example, carotenoids can absorb light in the visible spectrum and protect against photooxidation (Gómez-Sagasti *et al.*, 2023). In photosynthesis, carotenoids absorb blue and green light, transferring energy to chlorophylls and preventing the formation of reactive oxygen species such as singlet oxygen. In addition, carotenoids are used in the food, cosmetic and renewable energy industries (Li *et al.*, 2024; Razz, 2024). For example, their use as natural dyes in dye-sensitised solar cells (DSSC) exemplifies their versatility in technological innovation (Alwis *et al.*, 2021).

This review explores the bioavailability, health impacts, and broader applications of carotenoids, emphasising their role in Sri Lankan cuisine and public health. Furthermore, this review highlights the critical need for localised carotenoid databases to guide dietary interventions by integrating data from original research, conference proceedings, and local studies. Finally, it underscores the importance of preserving traditional culinary practices to harness the full health potential of carotenoids, while exploring innovations in carotenoid extraction, fortification, and application.

2. Major sources of carotenoids in Sri Lankan cuisine

2.1 Leafy vegetables

Sri Lankan cuisine is abundant in carotenoid-rich foods, with green leafy vegetables (GLVs), non-leafy vegetables, and various fruits serving as major sources. GLVs are critical for human health due to their high levels of provitamin A carotenoids like lutein and β-carotene, which provide protection against vitamin A deficiency and age-related macular degeneration (AMD) (Chandrika, 2023). Among the GLVs studied, sweet potato (*Ipomoea batatas*) leaves were identified as the richest source of β-carotene (743.9 ± 35.0 µg/g DW), while *Syngonium angustatum* leaves exhibited the highest lutein content (1,728.2 ± 168.3 µg/g DW) (Chandrika *et al.*, 2006). Cooking methods significantly influence the bioavailability of these carotenoids, with stir-fried dishes, particularly those prepared with coconut fat, demonstrating superior bio accessibility compared to raw or boiled preparations (Chandrika *et al.*, 2006).

2.2 Non-leafy vegetables

Non-leafy vegetables such as carrots, pumpkins, and squashes are also excellent sources of provitamin A carotenoids, particularly β-carotene and α-carotene. For example, carrots contain β-carotene levels ranging from 406.7 to 456.3 µg/g DW, while pumpkins show significant variation in carotenoid content, with lutein often being the predominant compound (Priyadarshani and Jansz, 2014). Studies conducted by our research group utilised high-performance liquid chromatography (HPLC) to determine carotenoid content across various cooking methods, simulating human intestinal conditions *in vitro*. The analysis revealed that carrot preparations contained mean β-carotene levels ranging from 406.7 to 456.3 µg/g DW, α-carotene levels between 183.7 and 213.5 µg/g DW, and lutein levels from 29.0 to 39.6 µg/g DW. Similarly, pumpkin preparations showed carotenoid levels ranging from 282.1 to 294.4 µg/g DW (Priyadarshani and Jansz, 2014).

2.3 Fruits

Fruits play a significant role in carotenoid intake within Sri Lankan diets, offering diverse sources of these bioactive compounds. Jackfruit (*Artocarpus heterophyllus*) contains six carotenoids, including β-carotene and α-carotene, providing 141.6 retinol equivalents (RE) per 100 g and demonstrating satisfactory bioavailability as a source of provitamin A (Chandrika *et al.*, 2003). Papaya (*Carica papaya*) varieties such as Rathna and Red Lady are notable for their provitamin A carotenoids, with Rathna containing high levels of all-trans-β-carotene (15.58 ± 1.00 µg/g FW) and β-cryptoxanthin (25.90 ± 2.9 µg/g FW), while Red Lady is distinguished by its lycopene content (10.39 ± 2.1 µg/g FW) (Chandrika *et al.*, 2003). Mangoes (*Mangifera indica*), such as the *Karuthacolamban* variety, provide β-carotene (2.7 ± 0.3 µg/g FW), violaxanthin, and neoxanthin, enriching local diets (Wansapala, 2010). Guava (*Psidium guajava*) and watermelon (*Citrullus lanatus*) are vital sources of lycopene, with Horana Red guava showing superior bioavailability (73%) compared to Sugar Baby watermelon (25.8%). Avocado (*Persea americana*) varieties, including *Monrece* and *Reed*, offer β-carotene and lutein, contributing to macular health and vitamin A status.

Rata Lavalu (*Pouteria campechiana*), although modest in β-carotene levels, is dominated by neoxanthin, enhancing its potential as a natural antioxidant and food colourant. Despite popular belief and recommendations by some Sri Lankan communities and healthcare practitioners that Rata Lavalu is beneficial for vitamin A deficiency, scientific findings indicate that it is not a suitable source for addressing this deficiency. Instead, its nutritional value lies in its antioxidant properties and potential as a functional food ingredient (Chandrika *et al.*, 2003; Chandrika *et al.*, 2011). Palmyrah (*Borassus*

https://doi.org/10.26656/lfr.2.e26126

flabellifer), with its vibrant yellow-orange fruit pulp, is a source of carotenoids such as α-carotene, lycopene, ζ-carotene, and β-zeacarotene. Bioconversion trials in Wistar rats revealed that provitamin A carotenoids are bioavailable, underscoring their potential utility in addressing vitamin A deficiency. A study from Hambantota district further highlighted the dominance of hydrocarbon carotenoids, such as phytofluene and phytoene, albeit with limited provitamin A activity, reflecting geographical and morphological influences on its carotenoid profile (Priyadarshani and Jansz, 2014). These findings underscore the need to raise awareness among consumers about the true availability of provitamin A carotenoids in Palmyrah. The common misconception that yellow-colored fruits and vegetables inherently address vitamin A deficiency should be corrected to prevent reliance on inadequate dietary sources. Cantaloupe melon (*Cucumis melo*) is an exceptional dietary source of β-carotene, with levels of 26 ± 8 µg/g FW and high in vitro bio-accessibility (71 ± 11%). For example, a 100 g serving provides approximately 240% of the Recommended Daily Allowance (RDA) for Vitamin A, making it an excellent option for addressing vitamin A deficiency (Chandrika *et al.*, 2006). These findings underscore the potential of cantaloupe melon as a highly effective source of vitamin A, and it is recommended for cultivation and consumption in Sri Lanka and other regions affected by vitamin A deficiency to alleviate this critical public health issue. Underutilised fruits such as Ambarella fruit (*Spondias dulcis*) and Passion fruit (*Passiflora edulis*) contribute modestly to carotenoid intake but offer notable health benefits. Ambarella fruits, including tall (*Spondias dulcis*) and dwarf (*Spondias centred*) varieties, offer modest carotenoid contributions. *Spondias dulcis* serves as a key source of β-carotene (2.1 ± 0.2 µg/g), while *Spondias ceytherea* contains both β-carotene (0.7 ± 0.2 µg/g) and lutein (0.9 ± 0.7 µg/g), with potential provitamin A and anti-carcinogenic benefit. Yellow passion fruit (*Passiflora edulis*) boasts diverse carotenoids, including β-carotene (304.6 ± 24.5 µg/100 g FW) and β-cryptoxanthin (74.4 ± 28.5 µg/100 g FW). In addition to being a rich source of provitamin A, its anti-cancer properties, attributed to its carotenoid and polyphenol content, underscore its value as a bioactive and nutritionally significant fruit (Chandrika *et al.*, 2003).

3. Factors affecting the bioavailability of carotenoids

Carotenoids, essential bioactive compounds for human health, must be effectively absorbed to exert their nutritional and functional benefits, yet their bioavailability is influenced by dietary, preparation, and physiological factors (Bas, 2024). The food matrix and cooking methods are pivotal in carotenoid release and absorption. Carotenoids are embedded in complex plant structures and become more bio-accessible through cooking techniques such as boiling, steaming, and frying, which disrupt cell walls and break down the matrix (Shahidi and Pan, 2022). For instance, thermal processing significantly enhances the bio-accessibility of β-carotene in pumpkin and butternut squash, with deep-frying increasing bio-accessibility to 68.7% in pumpkin compared to raw samples at 10.6% (Shahidi and Pan, 2022). However, excessive heat can degrade carotenoids, necessitating optimised cooking methods to balance nutrient preservation and bioavailability. Dietary fats are crucial for carotenoid absorption, given their fat-soluble nature. Even minimal fat intake (3–5 g per meal) improves uptake, as demonstrated in traditional Sri Lankan dishes like *malluma* (stir-fried greens), where coconut fat enhances the bioavailability of β-carotene and lutein (Chandrika *et al.*, 2006; Chandrika *et al.*, 2011). Nevertheless, interactions among carotenoids within mixed meals and unabsorbable fat-soluble compounds can complicate absorption dynamics.

Advancements in analytical methods, such as in vitro models using differentiated human colon cancer cell (Caco-2 cells) assays simulating intestinal digestion, have refined our understanding of carotenoid bio-accessibility. Yet discrepancies between laboratory results call for standardised protocols (Rodrigues and Failla, 2021). Existing assays often underestimate carotenoid antioxidant capacity, highlighting the need for improved techniques to measure biological relevance (Cassotta *et al.*, 2024). Traditional Sri Lankan cooking practices, including stir-frying and the use of dietary fats like coconut oil, significantly enhance carotenoid bioavailability compared to raw or boiled preparations (Chandrika *et al.*, 2006). For example, stir-fried *Centella asiatica* and *Cucurbita maxima* demonstrate superior carotenoid release, underscoring the importance of culturally embedded culinary techniques in maximising intake (Chandrika *et al.*, 2006).

Additionally, traditional cooking methods are critical in enhancing nutrient bio-accessibility and overall food functionality. For example, a study on yellow-fleshed manioc (YFM) in Sri Lanka examined the effects of boiling in water and cooking in coconut milk on the *in vitro* bioaccessibility of β-carotene and starch. High-performance liquid chromatography with photodiode-array detection (HPLC-DAD) revealed that cooking with coconut milk resulted in vigorous cell disruption, facilitating the release of starch and β-carotene through broken cell walls. The raw YFM 'Swarna' variety had a β-carotene content of 1.04 µg/g dry weight (DW), while boiled YFM and YFM curry prepared with coconut milk contained 0.34 and 1.07 µg/g DW, respectively.

However, *in vitro* accessible β-carotene content was undetectable, suggesting limited potential as a vitamin A source (Wickramasinghe *et al.*, 2018). The estimated glycemic index (EGI) of YFM curry (50.3) was higher than boiled YFM (24.6), indicating that boiled YFM may be a better option for individuals with obesity or diabetes. Collectively, these findings emphasise the importance of integrating traditional knowledge with modern scientific advancements to enhance carotenoid bioavailability while addressing diverse nutritional needs (Wickramasinghe *et al.*, 2018).

However, challenges remain in optimising carotenoid bioavailability. High fibre content, unabsorbable fat-soluble compounds, certain isomeric forms of carotenoids, and variations in absorption efficiency due to host factors such as age, gender, and genetics limit carotenoid utilisation. Innovations in nanostructured delivery systems, including lipid-based and biopolymeric nanocarriers, offer promising solutions by enhancing solubility, stability, and absorption. By leveraging these technologies, carotenoid therapies can be optimised to meet individual health needs, offering a multifaceted approach to improving quality of life and addressing age-related health challenges. Nevertheless, further research is needed to establish their safety and efficacy for long-term dietary use.

4. Metabolism and conversion of carotenoids in the human body

Carotenoids, essential tetraterpene pigments in the human diet, are widely recognised for their diverse roles in promoting health and preventing chronic diseases (Bhatt and Patel, 2020). Their metabolism and conversion within the body are central to their biological activity, enabling antioxidant, cytoprotective, and photoprotective functions that help combat conditions such as cancer, diabetes, cardiovascular diseases, obesity, and neurodegenerative disorders (Milani *et al.*, 2017; Kabir *et al.*, 2022). The absorption of carotenoids occurs in the small intestine, where they undergo enzymatic breakdown and are incorporated into chylomicrons for transport via the lymphatic system. β-Carotene, the most extensively studied provitamin A carotenoid, is metabolised primarily by β-carotene oxygenase 1 (BCO1), which converts it into retinal. Retinal can further oxidise to retinoic acid, a transcriptional regulator influencing gene expression through nuclear hormone receptors like retinoic acid receptor (RAR) and retinoid X receptor (RXR) (Harrison, 2022). Variability in carotenoid metabolism arises from factors such as interindividual differences in bioavailability, bioactivity, and enzyme expression, as well as phase 2 metabolism processes like oxidation and excretion of carotenoid metabolites (Desmarchelier and Borel, 2017). Retinoids derived from carotenoids can also be stored as esters in the liver, providing a reserve for future use (Bohn *et al.*, 2023b).

Emerging evidence links carotenoids and their derivatives to adipose tissue biology and the regulation of body fat (Bonet *et al.*, 2016). They have been shown to influence adipocyte differentiation and promote the browning of white adipose tissue, which enhances thermogenesis and fatty acid oxidation (Mukherjee and Yun, 2022). Higher dietary intake and serum levels of carotenoids are associated with reduced adiposity and preventing abdominal obesity. Human intervention studies, though limited, suggest that carotenoid supplementation may reduce abdominal fat accumulation and improve metabolic health, positioning carotenoids as potential nutritional regulators for obesity and related disorders like diabetes and cardiovascular disease (Bonet *et al.*, 2020).

The biological effects of carotenoids are largely mediated through their conversion to retinoids, which act on nuclear receptors to regulate gene expression (Milani *et al.*, 2017). Retinoid signalling pathways contribute to antioxidant activity by quenching singlet oxygen and scavenging free radicals, thereby offering cellular protection (Alvarez *et al.*, 2014). They also regulate cell growth, differentiation, and apoptosis, playing crucial roles in disease prevention (Bhatt and Patel, 2020). Emerging research suggests alternative regulatory mechanisms in retinoid-mediated signalling, challenging the traditional understanding of a linear relationship between carotenoid intake and health outcomes (Flieger *et al.*, 2024). Despite their significant benefits, the metabolism of carotenoids presents challenges, including variability in absorption and bioactivity (Moran *et al.*, 2018). Factors such as the food matrix, dietary fat, fibre content, and carotenoid interactions further complicate their utilisation (Saini *et al.*, 2022; Shahidi and Pan, 2022). The metabolic conversion of carotenoids and their specific roles in disease prevention remain areas of active investigation, with many unanswered questions about the interplay between diet, metabolism, and genetic factors (Rodriguez-Concepcion *et al.*, 2018).

5. Health impacts of carotenoids

Carotenoids are versatile bioactive compounds with profound health-promoting properties, playing vital roles in preventing and managing chronic diseases, supporting eye and immune health, and enhancing overall well-being. As natural antioxidants, carotenoids counteract oxidative stress, a primary contributor to age-related disorders, cardiovascular diseases, diabetes, neurodegenerative conditions, and liver diseases (Bakac *et al.*, 2023). By quenching singlet oxygen and scavenging reactive oxygen species (ROS), carotenoids

https://doi.org/10.26656/lfr.2.e26126

protect cellular components such as DNA, proteins, and lipids, thereby reducing the risk of chronic degenerative diseases. In cardiovascular health, they mitigate oxidative damage to blood vessels, improve lipid metabolism, and exhibit anti-inflammatory effects that address systemic inflammation—a key factor in metabolic and neurodegenerative disorders (Gandla *et al.*, 2023). Furthermore, carotenoids contribute to diabetes management by lowering glycated haemoglobin levels and fasting plasma glucose, enhancing overall metabolic health (Coyne *et al.*, 2005). Eye health is particularly influenced by carotenoids like lutein and zeaxanthin, which are concentrated in the macula of the retina (Ma and Lin, 2010). These compounds protect against oxidative stress and light-induced damage, significantly reducing the risk of age-related macular degeneration (AMD), a leading cause of vision loss among older adults (Johra *et al.*, 2020; Mrowicka *et al.*, 2022). Additionally, they alleviate eye fatigue, mitigate dry eye disease, and improve visual function (Kan *et al.*, 2020). Carotenoids also play a critical role in immune function, enhancing immune responses by supporting the development of key immune cells and reducing oxidative stress, which can impair immune efficacy (Pechinskii and Kuregyan, 2014; Milani *et al.*, 2017). As a precursor to vitamin A, β-carotene is integral to maintaining mucosal barrier integrity and promoting white blood cell production, strengthening the body's defences against infections (Mitra *et al.*, 2022; Chęcińska-Maciejewska *et al.*, 2024).

Carotenoids also demonstrate notable potential in cancer prevention and skin health (Darvin *et al.*, 2011). Compounds such as lycopene regulate cellular signalling pathways, reduce oxidative damage, and exhibit anti-inflammatory properties, thereby lowering the risks of prostate, lung, and skin cancers (Przybylska, 2020; Imran *et al.*, 2020; Puah *et al.*, 2021; Ozkan *et al.*, 2023). In skin health, carotenoids protect against UV-induced erythema, improve elasticity, and enhance hydration, making them valuable in anti-ageing formulations. They further address age-related conditions by combating oxidative stress and supporting metabolic health (Di Carlo and Sorrentino, 2024). In animal studies, carotenoids have been shown to reduce adiposity, enhance thermogenesis, and improve liver health by alleviating liver fibrosis and mitigating fatty liver conditions (Zakaria *et al.*, 2023; Tattoli *et al.*, 2024).

Structurally, carotenoids like β-carotene, α-carotene, and β-cryptoxanthin are recognised for their provitamin A activity, essential for vitamin A synthesis. These compounds contain a β-ionone ring with an 11-carbon polyene chain, enabling their conversion to vitamin A, an essential nutrient for vision, growth, and immune function. β-carotene is the most potent provitamin A carotenoid, capable of yielding two vitamin A molecules upon cleavage. In contrast, α-carotene and β-cryptoxanthin produce a single vitamin A molecule, providing approximately 50% of the activity of β-carotene. Lycopene, although a powerful antioxidant, lacks the β-ionone ring and does not exhibit provitamin A activity.

The antioxidant properties of carotenoids are integral to their health benefits, enabling them to neutralise harmful free radicals and singlet oxygen species. This protective mechanism is particularly critical in mitigating oxidative stress-related conditions such as cancer, cardiovascular diseases, and macular degeneration. Among the 700 naturally occurring carotenoids, lutein, β-carotene, and lycopene are particularly effective in quenching free radicals and preventing cellular damage.

6. Nutritional challenges and knowledge gaps

Carotenoids are crucial for addressing micronutrient deficiencies and preventing chronic diseases. However, several nutritional challenges and knowledge gaps hinder their effective utilisation in dietary interventions, particularly in developing countries like Sri Lanka. One major issue is the significant variation in carotenoid bioavailability across plant sources, influenced by factors such as the food matrix, carotenoid species, and preparation methods. For example, carotenoids embedded in fibrous matrices, such as green leafy vegetables, are less bioavailable than those found in lipid-rich matrices (Tattoli *et al.*, 2024). Variability in dietary diversity and food preparation practices further complicates carotenoid absorption, while a limited understanding of their metabolism and synergistic interactions in diverse diets presents additional knowledge gaps.

Micronutrient malnutrition is a persistent public health concern in Sri Lanka, exacerbated by monotonous, cereal-based diets lacking diversity, reducing consumption of traditional carotenoid-rich foods such as pumpkin, green leafy vegetables, and papaya. Urbanisation has further widened the gap, with surveys showing that 83% of women in urban areas fail to meet the Minimum Dietary Diversity for Women (MDD-W), compared to 63% in rural regions (Weerasekara *et al.*, 2020). The loss of traditional food systems due to agro-commercialisation, shrinking cultivation lands, and erosion of food culture has diminished the availability of carotenoid-rich foods, particularly in marginalised areas. These challenges underscore the urgent need for interventions to promote dietary diversity, enhance nutritional education, and preserve traditional food systems to ensure adequate carotenoid intake.

Carotenoid deficiencies are associated with

https://doi.org/10.26656/lfr.2.e26126

numerous health risks, including a heightened vulnerability to chronic diseases such as cardiovascular diseases, type 2 diabetes, obesity, and cancer. However, trials with isolated carotenoid supplements have yielded inconsistent outcomes, highlighting gaps in understanding their mechanisms of action. Carotenoids act as antioxidants by activating transcription factors such as NRF2 and NF-κB, reducing oxidative stress and inflammation (Ba *et al.*, 2023). Their metabolites also interact with nuclear hormone receptors like RAR, RXR, and PPARs, influencing gene expression and metabolic pathways. Despite these insights, there is a need for deeper exploration of the synergistic effects of carotenoids, optimal dosing, and genetic factors that shape their efficacy in preventing chronic diseases (Bohn *et al.*, 2023a).

The ongoing nutrition transition in Sri Lanka, marked by a shift from home-grown food to market-based diets, has aggravated micronutrient deficiencies, including those of carotenoids. Low dietary diversity remains a critical contributor to poor nutritional status, especially among women of reproductive age (Weerasekara *et al.*, 2020). Inappropriate food policies and governance have further hindered efforts to promote sustainable, carotenoid-rich diets in marginalised communities. To address these challenges, targeted interventions must focus on socioeconomic disparities, enhance education on nutrition, and preserve traditional food systems (Weerasekara *et al.*, 2020). By adopting a comprehensive approach, it is possible to overcome these barriers and improve carotenoid intake, ultimately contributing to better public health outcomes in Sri Lanka.

7. Research gaps and future directions

Despite the significant health potential of carotenoids and the abundant natural sources available in Sri Lanka, critical research gaps hinder their optimal utilisation in public health and nutrition strategies. A notable limitation is the lack of comprehensive and region-specific data on the carotenoid content of Sri Lankan foods. Geographic variability in soil, climate, and agricultural practices significantly influence carotenoid profiles in crops, yet existing databases often exclude local food sources or rely on generalised data that do not capture regional diversity. This highlights the pressing need for detailed food composition studies and the development of a robust, standardised carotenoid database tailored to Sri Lanka's unique agricultural and dietary landscape.

Enhancing carotenoid bioavailability remains another vital focus area, particularly for traditional Sri Lankan diets. While many local dishes inherently promote carotenoid absorption using dietary fats, further optimisation is possible. Investigating the effects of various cooking methods, such as stir-frying, steaming, and slow cooking, alongside the strategic combination of carotenoid-rich foods with fat-containing ingredients like coconut milk, scraped coconut, and coconut oil, could enhance nutrient uptake. Modern food processing technologies, including microencapsulation and nanotechnology, offer promising solutions for preserving carotenoid stability and improving absorption (Bera *et al.*, 2024). These advancements could provide practical recommendations for maximising bioavailability while maintaining the authenticity of traditional culinary practices.

Sri Lanka's rich indigenous culinary heritage provides a valuable foundation for enhancing carotenoid intake naturally. Indigenous plants such as Gotukola (*Centella asiatica*), Kathurumurunga (*Sesbania grandiflora*) and Mukunuwanna (*Alternanthera sessilis*) are notable carotenoid sources, and research into their traditional preparation methods can further increase their nutritional potential. Techniques such as Maluma (stir-fried green leafy vegetables with coconut) are already known to enhance carotenoid bioavailability, and scientific validation of these practices could promote their integration into modern nutrition programs (Weerasekara *et al.*, 2020). Additionally, preserving and documenting traditional knowledge related to carotenoid-rich foods and their preparation methods is essential for safeguarding culinary heritage while advancing sustainable dietary practices.

Potential applications of carotenoid research extend beyond individual health, with significant implications for public health and industrial innovation. Public health strategies must prioritise integrating carotenoid-rich foods into dietary interventions aimed at addressing vitamin A deficiency and other micronutrient-related health challenges. Educational campaigns are critical for raising awareness about the benefits of carotenoids and how to optimise their intake through diet. Policy development should focus on supporting the cultivation and accessibility of carotenoid-rich crops, particularly in underserved regions, while fortification of staple foods can offer a targeted approach to combatting deficiencies in at-risk populations.

Future research should delve deeper into under-studied carotenoids and less-explored food sources to expand the knowledge base. Additionally, standardised methodologies for analysing carotenoid content and bioavailability must be established to ensure consistent and reliable data (Chandrika, 2023). Exploring personalised dietary interventions based on genetic, lifestyle, and regional factors could also amplify the effectiveness of carotenoid-based strategies. By addressing these research gaps and leveraging both traditional knowledge and modern advancements, Sri Lanka can harness the full potential of its carotenoid resources to enhance public health and nutrition outcomes, while also exploring industrial applications of these bioactive compounds.

Conclusion

The current review highlights the critical role of plant-derived carotenoids in Sri Lankan cuisine, emphasising their significance in addressing micronutrient deficiencies and reducing the risk of chronic diseases, while promising for future functional foods and nutraceuticals. Although leafy and non-leafy vegetables, fruits, and underutilised varieties offer varying carotenoid profiles with distinct health benefits, challenges such as limited bioavailability, gaps in comprehensive food composition databases, and misconceptions about carotenoid-rich foods remain. Traditional Sri Lankan cooking practices, which often enhance carotenoid bioavailability using dietary fats and specific preparation techniques, remain an invaluable asset for maximising the nutritional potential of these compounds. Although advances in analytical methods and emerging technologies, such as nanostructured delivery systems, present new opportunities to improve carotenoid absorption and utilisation, future research should prioritise developing region-specific databases, exploring innovative approaches to enhance carotenoid stability and bioavailability, and validating the health impacts of traditional dietary practices. Integrating these findings into public health strategies, such as crop fortification and nutritional education, can play a transformative role in combating vitamin A deficiency and related health issues in Sri Lanka and similar settings. Bridging research gaps, preserving traditional knowledge, and fostering sustainable practices will ensure these natural resources are optimally utilised to improve public health outcomes and dietary diversity.

Conflict of interest

The authors declare no conflict of interest.

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