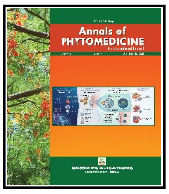
Annals of Phytomedicine 14(2): 127-139, 2025

DOI: http://dx.doi.org/10.54085/ap.2025.14.2.13

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885



Review Article : Open Access

A comprehensive review on technological advances in Red pepper (*Capsicum annuum* L.) derived carotenoids: An industrial perspective

K. Shalini*, M.S. Aneesa Rani◆, M. Mohanalakshmi*, R. Kalaiyarasi***, D. Amirtham**** and N. Bharathi*******

**Department of Plantation, Spices, Medicinal and Aromatic Crops, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641003, Tamil Nadu, India*
*** Horticultural College and Research Institute, Tamil Nadu Agricultural University, Paiyur-635112, Tamil Nadu, India*
**** Department of Oilseeds, Tamil Nadu Agricultural University, Coimbatore-641003, Tamil Nadu, India*
***** Department of Plant Biotechnology, Tamil Nadu Agricultural University, Coimbatore-641003, Tamil Nadu, India*
****** Department of Plant Molecular Biology and Bioinformatics, Tamil Nadu Agricultural University, Coimbatore-641003, Tamil Nadu, India*

Article Info

Article history
Received 8 November 2025
Revised 9 December 2025
Accepted 10 December 2025
Published Online 30 December 2025

Keywords
Bioactive compounds
Capsanthin
Natural colorants
Pharmaceuticals
Functional foods

Abstract

Red pepper (*Capsicum annuum* L.) is globally recognized for its bright red fruits. In recent years, red pepper is gaining attention for having health benefits, especially due to its high carotenoid content which is rich in colourants and has abundant industrial uses. These pigments are now emerging as functional ingredients with therapeutic potential which can be used in pharmaceuticals, cosmetics and nutraceuticals. Consumers are increasingly opting for products that use natural and sustainable ingredients and additives which are health boosting. Red pepper derived carotenoids seem to pose good substitutes for synthetic additives. Further, antioxidants, anti-inflammatory and disease preventing properties make carotenoids even more attractive on the market. Furthermore, remarkable progress towards improvements of extraction methods and bioavailability have broadened the application of these pigments across various fields. This review synthesizes current knowledge on the chemistry, processing innovations and industrial utilization of red pepper carotenoids. By addressing the technological challenges and exploring future prospects, the review aims to provide insights for researchers and industry professionals seeking to utilize the full potential of these compounds in product development based on health values while considering ecological concerns.

1. Introduction

Red pepper also known as paprika (*Capsicum annuum* L.), belongs to the Solanaceae family, is a globally cultivated crop of economic importance, used fresh, dried, or processed as a spice and colorant. Its nutritional and therapeutic value stems from bioactive compounds like carotenoids, capsaicinoids, flavonoids, and phenolics, enhancing sensory and health properties. Key carotenoids include capsanthin, capsorubin, cryptocapsin, cucurbitaxanthin A, β-cryptoxanthin, capsanthin epoxide, zeaxanthin, and β-carotene, with capsanthin and capsorubin as signature red pigments (Maeda *et al.,* 2021). Carotenoid content ranges from 0.1-1.3% dry weight, mainly capsorubin and β-cryptoxanthin for red hues, and β-carotene, zeaxanthin, violaxanthin, cryptoxanthin for yellow-orange. Major production occurs in Central Europe (Hungary, Spain, Serbia, Bulgaria), while India leads in consumption, export, and genetic diversity of cultivars. The global red pepper market, valued at USD (United States Dollar) 432.7 million in 2018, grows at a 5.3% CAGR through 2025 (Reddy and Ponnam, 2023). Figure 1 shows the global production of red pepper, highlighting the key producing regions and their relative contributions.

Corresponding author: Dr. M.S. Aneesa Rani
Nodal Officer, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Paiyur-635112, Tamil Nadu, India
E-mail: aneesarani@tnau.ac.in
Tel.: +91-9788923254

Copyright © 2025 Ukaaz Publications. All rights reserved.
Email: ukaaz@yahoo.com; Website: www.ukaazpublications.com

The application of plant-derived pigments in food systems faces considerable technical hurdles, principally owing to their susceptibility to degradation and limited bioavailability. Encapsulation has emerged as a promising strategy to improve bio accessibility, enhance digestive uptake and enable controlled release of these bioactive compounds. In food fortification applications, advanced encapsulation techniques are essential to mitigate pigment deterioration and maintain their functional integrity throughout gastrointestinal transit. This approach offers a viable pathway for innovating next-generation functional foods with enhanced nutritional value (Ghosh *et al.,* 2022). The industrial viability of red pepper derived carotenoids is fundamentally governed by their physicochemical characteristics, particularly thermal resilience and lipophilic affinity. These intrinsic parameters dictate both their compatibility with various food systems and their endurance against manufacturing stressors, including thermal processing and photolytic degradation (Zeiner *et al.,* 2023). Stabilization processes aimed at protecting the integrity of carotenoids during processing and storage are essential for the industrial use of red pepper as a natural colorant.

The carotenoids in red pepper, particularly β-carotene, lutein and zeaxanthin serve dual roles as both pigmentation agents and bioactive nutraceuticals. These phytochemicals demonstrate significant radical scavenging capacity, mitigating cellular damage induced by reactive oxygen species (Zeiner *et al.,* 2023). Emerging research further suggests their therapeutic potential in modulating inflammatory pathways, inhibiting carcinogenesis and supporting cardiovascular health. Such multifunctional attributes have driven the interest of the food sector in red pepper pigments as dual-purpose natural additives (Novais *et al.,* 2022). The strategic incorporation of bioactive carotenoids into functional foods and pharmaceutical preparations represents a critical advancement in preventive medicine and therapeutic interventions. These phytochemical formulations demonstrate significant potential for mitigating age-related physiological decline through their potent redox modulating and anti-inflammatory properties (Shanaida *et al.,* 2025). Inspite of these demonstrated physiological benefits, technical limitations including molecular instability, limited aqueous dispersion and degradation during processing, hinder commercial implementation. Contemporary innovations in microencapsulation, nano-scale dispersion systems and molecular stabilization approaches present viable strategies to augment their utility beyond conventional coloring applications. The paradigm shift toward clean label ingredients has accelerated the exploration of red pepper derived pigments as eco-friendly substitutes for artificial colorants. Nevertheless, economic viability and production scalability continue to pose substantial barriers to widespread industrial utilization. This comprehensive review synthesizes recent advancement in red pepper carotenoid stabilization, delivery systems and multifunctional applications, providing actionable insights for researchers and industry professionals seeking to expand the utilization of these bioactive compounds beyond conventional roles.

Figure 1: Global production of Red pepper (Prepared using mapchart.net).

2. Carotenoid chemistry

The characteristic red pigmentation of red pepper is attributed to its carotenoid content, a group of tetraterpenoid compounds composed of eight isoprenoid units. These pigments exhibit structural diversity through terminal cyclic or acyclic configurations, giving rise to various cis and trans geometric isomers, the trans forms being predominantly found in natural sources. Carotenoids are broadly categorized into two classes: hydrocarbon carotenes (*e.g.,* α-carotene, β-carotene, γ-carotene and lycopene), which demonstrate lipophilic characteristics and negligible solubility in aqueous media and oxygenated xanthophylls (*e.g.,* fucoxanthin, lutein and violaxanthin), which possess amphiphilic properties due to their hydroxyl, keto, or carboxyl functional groups. While carotenes dissolve readily in nonpolar organic solvents, xanthophylls exhibit dual solubility in both polar (*e.g.,* methanol) and nonpolar (*e.g.,* hexane) solvents (Ghosh *et al.,* 2022).

Carotenoids are inherently lipophilic compounds, exhibiting pronounced hydrophobicity and minimal aqueous solubility, which facilitates their localization in non-polar cellular environments. Structurally, these tetraterpenoid pigments ($C_{40}H_{56}$) comprise eight isoprenoid units linked in a head-to-tail arrangement, forming a central conjugated polyene system with alternating double and single bonds. Such conjugated electron systems govern their photochemical behavior and radical scavenging activity. The presence of configurational isomerism about C-C bonds generates both trans and cis stereoisomers, which exhibit distinct physicochemical properties including thermal stability, solvation characteristics and UV-Vis spectral profiles (Zeiner *et al.,* 2023). Table 1 summarizes the structural and physicochemical differences among major red pepper carotenoids. Carotenoids occur either as free molecules or as fatty acid esters (*e.g.,* palmitate, stearate esters), with their biological functionality being intrinsically linked to molecular architecture. The light absorbing conjugated chromophore, responsible for their vivid coloration (400–600 nm) and photoprotective capacity represents the key structural determinant of their optical and photochemical properties (Shanaida *et al.,* 2025).

Table 1: Properties of key carotenoids in Red pepper

Carotenoid	Molecular weight	Colour	Biological activities and benefits	References
Capsanthin ($C_{40}H_{56}O_3$)	584.9 g/mol	Red-orange pigment	Powerful antioxidant, anti-tumor activities, attenuates obesity-induced inflammation, raises HDL (High-density lipoprotein) cholesterol levels. Beneficial in pain relief, cardio protection, weight loss and body temperature regulation.	Shanmugham and Subban, 2022
Capsorubin ($C_{40}H_{56}O_4$)	600.9 g/mol	Bright red pigment	Potent antioxidative properties are attributable to their conjugated keto-polyene structure, which facilitates enhanced electron delocalization. While exhibiting reduced systemic absorption compared to β-carotene, they display superior free radical scavenging capacity and oxidative stress mitigation potential.	Murillo *et al.,* 2013; Abourashed, 2013
β-cryptoxanthin ($C_{40}H_{56}O$)	552.9 g/mol	Yellow-orange pigment	Acts as provitamin A (converted to retinol in the body). Antioxidant properties help prevent free radical damage and stimulate DNA (Deoxyribonucleic acid) repair.	Lorenzo *et al.,* 2009
β-carotene ($C_{40}H_{56}$)	536.888 g/mol	Red-orange pigment	β-Carotene can be converted into vitamin A in the human body, where it exerts oxidation resistance, anticancer activity and anti-cardiovascular properties. A major precursor of vitamin A, which is effective in the treatment of night blindness	Wang *et al.,* 2021
Zeaxanthin ($C_{40}H_{56}O_2$)	568.9 g/mol	Yellow-orange pigment	Important for eye health and protection against oxidative stress.	Sajilata *et al.,* 2008
Cucurbitaxanthin A($C_{40}H_{56}O_3$)	584.9 g/mol	Yellow-orange pigment	Inhibits the proliferation of cancer cells and induces apoptosis (programmed cell death). Its antioxidant properties also contribute to its chemo preventive effects.	Gagez *et al.,* 2012
Capsanthin epoxide ($C_{40}H_{56}O_4$)	600.9 g/mol	Red-orange pigment	Shields skin from UV (Ultraviolet)-induced damage and oxidative stress. Exhibits free radical scavenging and antioxidant properties, helping to reduce oxidative stress linked to chronic diseases	Maeda *et al.,* 2021; Kennedy *et al.,* 2021
Cryptocapsin ($C_{40}H_{56}O_3$)	568.9 g/mol	Red-orange pigment	Exhibits strong antioxidant properties. It can neutralize free radicals and reduce oxidative stress, which is linked to chronic diseases such as cancer, cardiovascular diseases and neurodegenerative disorders.	Kim *et al.,* 2022
Violaxanthin ($C_{40}H_{56}O_4$)	600.9 g/mol	Yellow-orange pigment	Helps neutralize harmful free radicals, reducing oxidative stress in cells. This protects against cellular damage linked to aging and chronic diseases. Exerts anticancer effects through apoptosis induction and oxidative DNA damage reduction.	Wang *et al.,* 2018;

2.1 Biosynthesis of Red pepper carotenoids

The carotenoid biosynthesis pathway in *C. annuum* begins with phytoene synthase (PSY) catalyzing the condensation of geranylgeranyl diphosphate to form phytoene, the first committed intermediate. Phytoene is desaturated and isomerized by phytoene desaturase (PDS) and β-carotene desaturase (ZDS) to produce lycopene, a linear red tetraterpene. Lycopene branching occurs *via* lycopene cyclases (LCY-B and LCY-E): LCY-B converts lycopene into β-carotene, while combined LCY-B and LCY-E activities yield α-carotene. Subsequent hydroxylation by β-carotene hydroxylase (BCH) and cytochrome P450 enzymes (CYP97A) forms β-cryptoxanthin and then zeaxanthin. Through the xanthophyll cycle, zeaxanthin is epoxidized by zeaxanthin epoxidase (ZEP) to antheraxanthin and violaxanthin, which are substrates for capsanthin and capsorubin formation *via* capsanthin-capsorubin synthase (CCS), giving red pepper its characteristic color. Lutein originates from β-carotene through a parallel xanthophyll pathway. The biosynthetic pathway of major red pepper carotenoids, including key enzymatic conversions from phytoene to capsanthin, is illustrated in Figure 2.

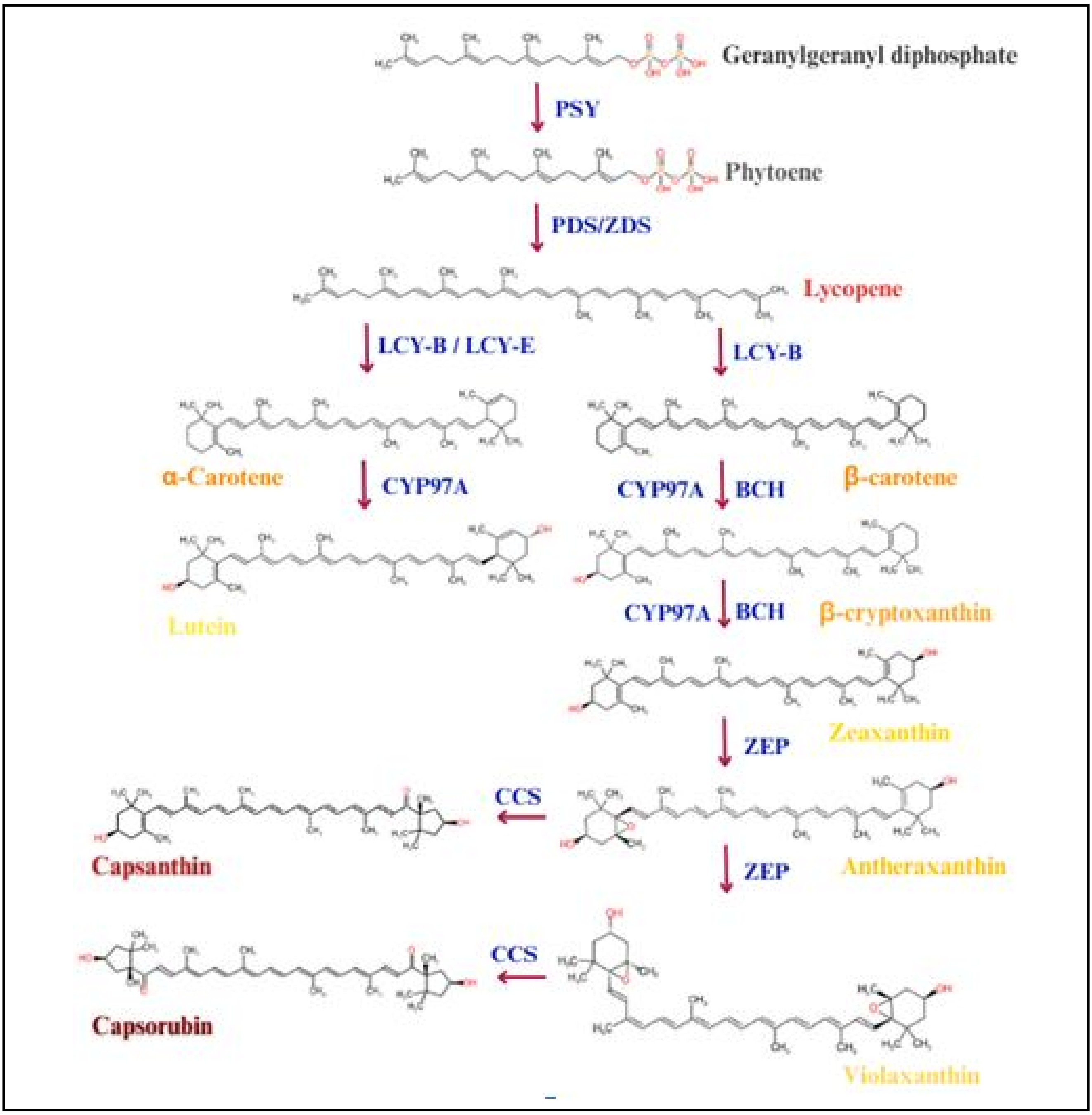


Figure 2: Biosynthetic pathway of carotenoids in Red pepper (Prepared using canva).

3. Extraction and processing

3.1 Extraction methods

Extraction of bioactive compounds from plant matrices involves various techniques such as maceration, infusion, digestion, decoction, percolation, Soxhlet extraction, microwave-assisted extraction (MAE), and ultrasound-assisted extraction (UAE) (Abubakar and Haque, 2020). In red pepper, conventional methods like Soxhlet extraction and maceration ensure adequate yield and simple operation but suffer from long processing times, high solvent use, and environmental drawbacks, limiting industrial application. In response, advanced techniques including supercritical fluid extraction (SFE), MAE, enzyme-assisted extraction (EAE), and UAE have emerged as superior alternatives. These methods enhance extraction speed, selectivity, and yield while minimizing solvent consumption and preserving thermolabile carotenoids (Baenas *et al.,* 2019; Ravindran *et al.,* 2025). The choice of technique depends on both technical parameters (compound stability, matrix complexity) and economic viability, with advanced methods offering distinct advantages for sensitive compounds like red pepper carotenoids through enhanced preservation, efficiency, and sustainability. Their superior mass transfer kinetics, environmental benefits and reproducibility make them increasingly indispensable for industrial-scale extraction of high value pigments. Driven by rising consumer preference for naturally derived ingredients, there is a noticeable shift toward innovative pigment extraction techniques that are recognized for their eco-efficiency and sustainability, offering a more environmentally responsible alternative to traditional methods (Sharma *et al.,* 2025). Table 2 provides a comparative analysis of conventional versus advanced carotenoid extraction methods from red pepper, evaluating critical parameters including processing duration, economic feasibility and extraction performance.

Supercritical carbon dioxide (SC-CO_2) extraction enables the production of premium red pepper extracts with enhanced concentrations of bioactive carotenoids and polyunsaturated fatty acids, ideal for pharmaceutical, cosmetic and functional food applications through precise modulation of extraction parameters like pressure and temperature (Kostrzewa *et al.,* 2023). The optimization of these processes has been revolutionized by response surface methodology (RSM), which statistically models extraction variables to maximize bioactive yield (Saha *et al.,* 2015). Accelerated solvent extraction (ASE) further advances extraction efficacy by operating under rigorously controlled pressure, temperature and solvent conditions while maintaining oxygen-free, light-protected environments to preserve compound integrity (Truong *et al.,* 2012). Comparative analyses highlight ASE's superiority over ME and UAE, yielding higher American spice trade association (ASTA) color and pungency values in red pepper oleoresins (Huang *et al.,* 2022).

Table 2: Comparison between traditional and modern extraction techniques (Saini and Keum, 2018)

Feature	Traditional extraction techniques	Modern extraction techniques
Examples	Maceration, Decoction, Soxhlet, Steam distillation, Cold pressing	Supercritical fluid extraction (SFE), Microwave-assisted extraction (MAE), Ultrasound-assisted extraction (UAE), Pressurized liquid extraction (PLE), Pulsed electric field (PEF)
Solvent used	Organic solvents (ethanol, methanol, hexane) or water	Green solvents (CO, , water, ionic liquids), or minimal solvent
Temperature	High (can degrade thermolabile compounds)	Controlled (low to moderate, preserving heat-sensitive compounds)
Time	Long extraction time (hours to days)	Faster (minutes to a few hours)
Energy consumption	High (due to prolonged heating/evaporation)	Lower (efficient energy use)
Yield and efficiency	Moderate to low (inefficient extraction)	Higher yield (better penetration and selectivity)
Selectivity	Less selective (co-extraction of impurities)	More selective (target-specific extraction)
Environmental impact	High (toxic solvent waste, pollution)	Eco-friendly (reduced waste, recyclable solvents)
Cost	Low initial cost, high operational cost	High initial investment, lower running cost
Automation	Manual or semi-automated	Fully automated and controlled

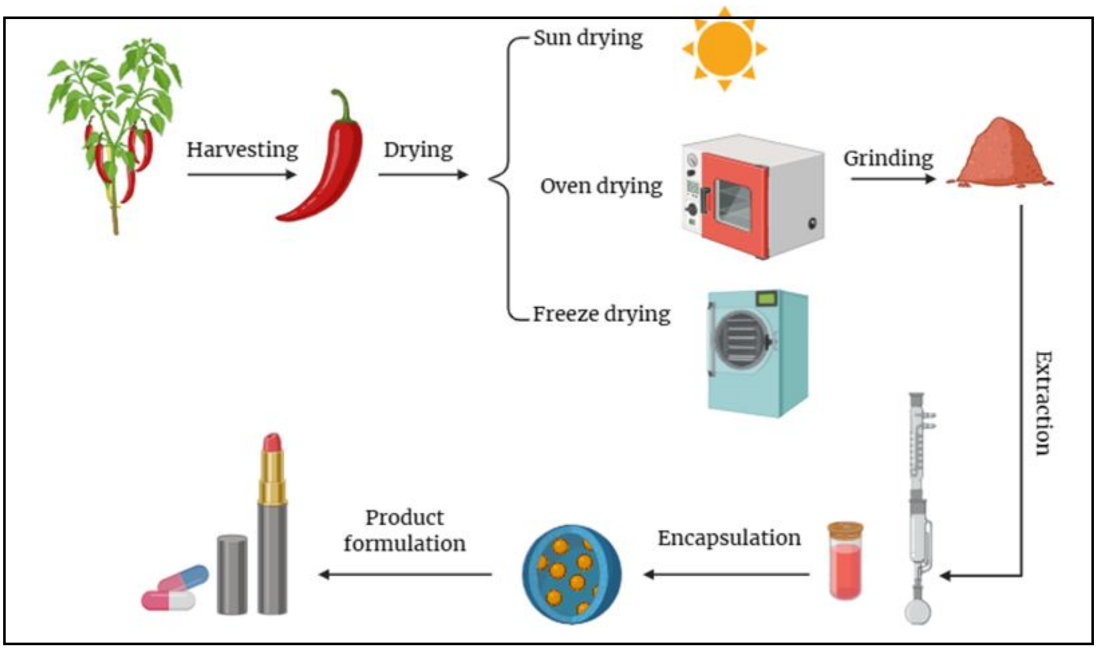


Figure 3: Processing of Red pepper carotenoids (Prepared using biorender).

3.2 Processing

The post-harvest treatment of Capsicum fruits significantly impacts capsaicinoid concentrations, with drying parameters and seed retention directly modulating pungency levels. Analytical comparisons reveal smoked red pepper exhibits superior carotenoid content relative to other preparations, suggesting thermal processing enhances phytochemical accessibility (Elvira-Torales *et al*., 2019). This phenomenon mirrors the carotenoid bioaccessibility improvements observed in other high-temperature treatments. Xanthophyll profiles in powdered red pepper products demonstrate drying-method dependence, with smoking protocols notably elevating cryptoxanthin and β-cryptoxanthin concentrations. Quantitative analyses document a 1.5-fold augmentation in both zeaxanthin and cis-zeaxanthin isomers in smoked variants compared to conventional preparations (Ponder *et al*., 2021).

Conventional sun-drying techniques, while historically prevalent for red pepper processing, present significant limitations including extended duration (up to 10 days to achieve 9.9% moisture content wet basis) and elevated risk of microbial contamination. The prolonged exposure inherent to this method creates optimal conditions for fungal growth and subsequent mycotoxin production, compromising product safety and quality. To address these challenges, modern drying technologies including Freeze drying (FD), Oven drying (OD), Natural convective drying (NCD) and Refractance window drying (RWD) have been implemented as alternatives. Comparative analyses reveal that while FD, OD and RWD processing of red pepper puree yields visually appealing products, these methods result in measurable reductions of both carotenoid and capsaicinoid content. In contrast, the NCD approach utilizing sliced raw material demonstrates superior bioactive retention, maintaining higher concentrations of most carotenoid species and all capsaicinoid derivatives (Topuz *et al*., 2011). Figure 3 outlines the processing stages such as drying, grinding, extraction and purification, that turn fresh red pepper into concentrated carotenoids.

3.3 Encapsulation approaches to improve stability

Carotenoids exhibit significant vulnerability to degradation during food processing and storage, with oxidative breakdown and light-induced isomerization representing primary degradation pathways that compromise both color stability and nutritional value. These heat- and photo-labile compounds undergo structural transformations when exposed to thermal processing (yielding both volatile and non-volatile derivatives) or light exposure, with trans-to-cis isomerization being particularly influenced by environmental factors including temperature, pH and light intensity (Lu *et al.,* 2020). Despite their inherent instability, carotenoids demonstrate potent antioxidant capacity and associated health benefits, though their efficacy ultimately depends on bioaccessibility (release from food matrices) and subsequent bioavailability (absorption and utilization) (Lu *et al.,* 2021). Critical factors modulating carotenoid assimilation include dietary components (particularly lipid composition and fibre content) as well as physiological variables (age, gender, and metabolic status), with lipid co-consumption proving especially important for optimal absorption kinetics (Shilpa *et al.,* 2020).

Natural pigments represent a class of safe, bioactive food additives that not only impart color but also demonstrate significant therapeutic potential for disease prevention and health promotion. The encapsulation of these phytochemicals has emerged as a transformative approach to enhance their stability and functional applications, with microencapsulation and nanoencapsulation techniques providing effective protection against environmental degradation while enabling controlled release kinetics. Originally developed as a protective coating technology for various physical states, modern encapsulation methods now offer precise delivery systems that shield sensitive compounds from oxidative, thermal, and photolytic damage. Particularly in functional food applications, nanoencapsulation techniques including emulsification, molecular inclusion, coacervation and nanoprecipitation have revolutionized the delivery of bioactive pigments, significantly improving their bioavailability and enabling targeted release to maximize health benefits for broader consumer populations (Ghosh *et al.,* 2022).

Spray drying has emerged as a leading technique for carotenoid encapsulation, effectively protecting these sensitive compounds through protein-polysaccharide matrices while optimizing stability and bioavailability. By precisely controlling processing parameters, this method achieves high encapsulation efficiency and enables tailored release properties for diverse applications in functional foods and nutraceuticals. Its scalability and cost-effectiveness make it particularly valuable for industrial-scale production of stable carotenoid formulations. With encapsulation efficiencies exceeding 90% for sensitive compounds like capsanthin and â-carotene, spray drying continues to evolve as a scalable and cost-effective solution for industrial carotenoid stabilization, opening new possibilities for their incorporation into value-added products while overcoming inherent challenges related to light, heat and oxygen sensitivity (Griep *et al.,* 2025).

4. Industrial applications

Red pepper serves as a dual-purpose ingredient, valued both as a culinary spice and a medicinal component, with particular importance in Asian and Central American food and pharmaceutical industries (Liu *et al.,* 2021). The carotenoid compounds derived from red pepper demonstrate exceptional versatility across multiple industrial sectors due to their distinctive bioactive characteristics and chemical stability, finding applications in pharmaceutical formulations, nutraceutical products, food additives, cosmetic preparations and fine chemical production (Baenas *et al.,* 2019). Compared to alternative pigments such as lycopene, red pepper-derived carotenoids offer superior economic advantages, including enhanced cost-efficiency, greater stability and comparable color properties (Mortensen, 2006). These high-value phytochemicals occupy a unique market position, serving both mass-market and premium segments due to their multifunctional capacity to enhance product color, flavor profiles and nutritional value. The broad industrial utility of red pepper carotenoids is comprehensively illustrated in Figure 4, highlighting their cross-sectoral applications in food technology, cosmetic science, and pharmaceutical development.

4.1 Food colorant

Visual appearance serves as a primary determinant of food quality assessment, profoundly influencing consumer appetite and purchasing decisions. Colorants play a pivotal role in enhancing food attractiveness, palatability, and product identification. While synthetic colorants have been widely utilized for their vibrant hues and cost-effectiveness, growing concerns over their potential toxicity have driven a global shift toward natural alternatives. These plant-derived pigments have gained substantial market traction due to their dual functionality imparting desirable coloration while offering demonstrated therapeutic benefits. The increasing consumer demand for clean-label products has further accelerated the replacement of artificial colorants with natural pigment sources, many of which exhibit significant bioactive potential alongside their chromatic properties (Lu *et al.,* 2021; Juriæ *et al.,* 2022).

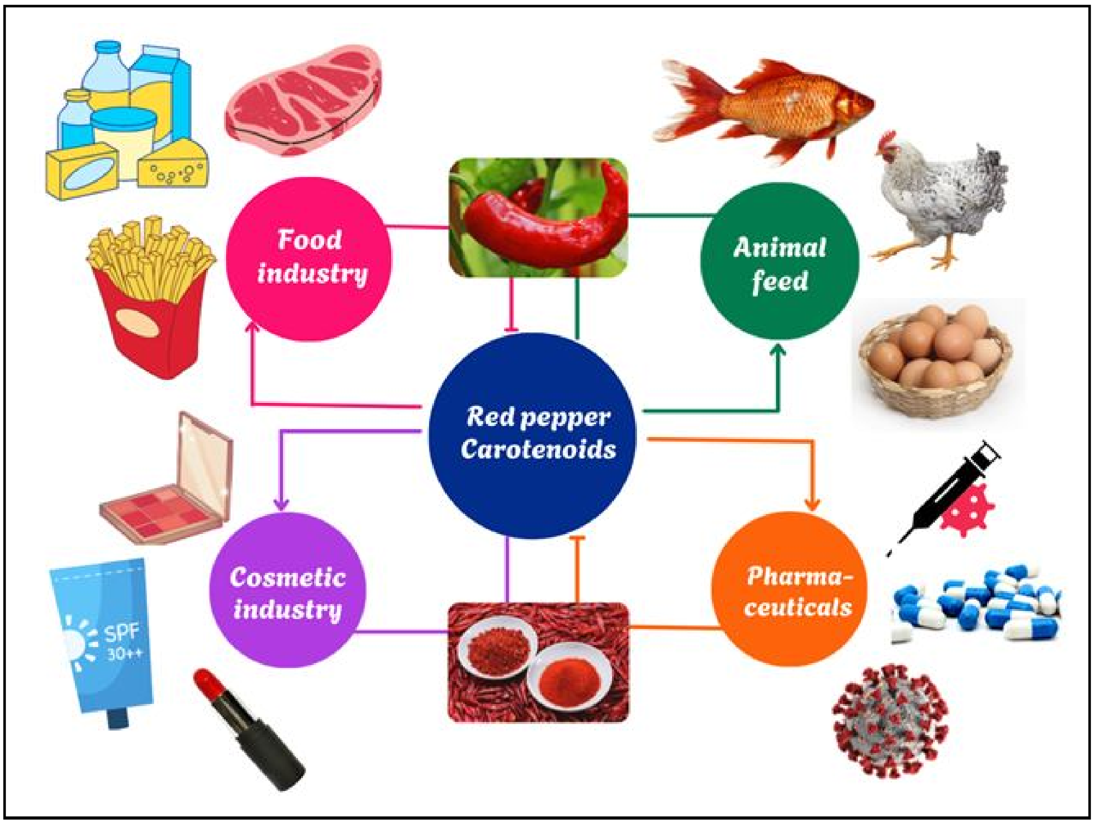


Figure 4: Industrial applications of Red pepper carotenoids (Prepared using canva).

Carotenoids have been widely employed as natural pigments in the food industry, valued for their ability to produce vibrant yellow-orange to red hues in various applications. These bioactive compounds are commercially formulated as oil-based extracts, water-dispersible emulsions, and stable dried powders to accommodate different processing requirements. Major botanical sources including red pepper (*Capsicum annuum*), annatto (*Bixa orellana*), marigold (*Tagetes erecta*), and tomato (*Solanum lycopersicum*) provide carotenoids for both direct food coloring and indirect applications such as poultry feed supplementation to enhance egg yolk pigmentation. The regulatory status of carotenoids varies significantly across international markets, with certain pigments approved for general food use while others are restricted to specific applications like animal feed additives. Among red colorants, red pepper derived products particularly red pepper powder and oleoresins have become indispensable in food manufacturing due to their dual functionality as both colorants and flavor enhancers (Juriæ *et al.,* 2022).

Red pepper derived colorants are commercially available in two primary formulations such as powdered form and oleoresin extracts, the latter comprising a complex mixture of pigments, lipids, and waxes. These natural colorants find widespread application across various food categories including spice blends, processed meats, and sauce systems (Delgado-Vargas and Paredes-López, 2003. While both forms are approved for general food use in the United States, their characteristic pungency may limit applications in products requiring milder flavor profiles. The vibrant red-orange coloration primarily stems from the keto-carotenoids capsanthin and capsorubin (designated as E160c in oleoresin form), which are extensively used in dairy products, processed meats, preserves, and convenience foods (Food Info Foundation 2020). In contrast, β-carotene serves as the predominant yellow-orange pigment in food applications. Regional regulatory variations exist, as evidenced by the EU's approval of zeaxanthin oleoresin for animal feed applications while permitting purified forms in human foods such as pasta, baked goods and fat-based products (Delgado-Vargas and Paredes-López, 2003). This regulatory landscape reflects the growing importance of natural colorants in meeting both technological and consumer demands for clean-label ingredients.

4.2 Animal feed

Carotenoids serve as essential phytochemicals in animal husbandry, significantly influencing growth performance, product quality, and visual characteristics of animal-derived foods. These bioactive pigments, either obtained from natural dietary sources or through specialized supplementation, have become integral components of optimized feed formulations (Langi *et al.,* 2018). The animal nutrition industry has developed sophisticated strategies to incorporate these compounds cost-effectively while meeting specific physiological requirements across different species. The functional benefits of carotenoids in animal production can be categorized into three primary aspects such as metabolic functions, biological actions, and nutrient interactions. Commonly utilized carotenoids in feed formulations include astaxanthin, β-carotene, lutein, zeaxanthin, and capsanthin, each selected for their distinct properties. Among these, zeaxanthin demonstrates particular efficacy in providing uniform pigmentation for both muscle tissue and egg yolks, making it a preferred choice for quality enhancement (Lee and Küçükata, 2023). Capsanthin-rich red pepper extracts excel in poultry for skin and egg yolk coloration (EFSA FEEDAP Panel, 2020).

Production methods includes chemical synthesis for purity, natural extraction from plants/algae, and microbial biosynthesis for sustainability supporting reliable, customized feeds that boost animal health and consumer-preferred product traits (Lee and Küçükata, 2023). Modern feed technology has advanced considerably from traditional fresh feed systems, which frequently contained insufficient micronutrient levels. Today, feed-grade carotenoids are produced through three primary industrial methods including chemical synthesis, which offers precise control over molecular structure and purity; natural extraction processes, which utilize plant or algal sources to obtain bioavailable forms of carotenoids; and microbial biosynthesis, an emerging approach that employs engineered microorganisms for sustainable, high-yield production. These diverse manufacturing techniques ensure reliable carotenoid supply chains while enabling customized feed formulations tailored to specific livestock requirements, ultimately supporting both animal health and the quality of derived food products (Amaya and Nickell, 2015). This diversified production approach ensures a consistent supply while allowing formulation of species-specific diets that support both animal health and end-product quality characteristics valued by consumers. The strategic inclusion of carotenoids in animal nutrition represents a convergence of biological science and food technology, addressing both physiological needs and market demands for high-quality animal products.

Dietary supplementation with red pepper extract at 5% inclusion levels has demonstrated significant efficacy in enhancing coloration, as evidenced by a 4.71-unit increase in chromatic intensity values for comet fish (Haetami *et al.,* 2021). While capsanthin serves as a functional feed additive for aquatic species, its pigmentation efficacy in rainbow trout remains comparatively lower than synthetic alternatives like astaxanthin and canthaxanthin. Nevertheless, both capsanthin and capsorubin effectively enhance pigmentation in salmonids, white shrimp, and poultry products particularly in broiler skin and egg yolk coloration while concurrently improving growth performance in broilers and reproductive outcomes in yellowtail species (Pasarin and Rovinaru, 2018). Zeaxanthin has emerged as a versatile carotenoid in animal nutrition, imparting golden-yellow pigmentation to poultry skin and egg yolks while enhancing skin coloration in swine and aquatic species. In aquaculture systems, strategic incorporation of zeaxanthin into feed formulations represents an effective approach for improving product quality through enhanced red-orange pigmentation in crustaceans and finfish (Zakynthinos and Varzakas, 2016).

4.3 Cosmetic industry

The cosmetic industry has witnessed a paradigm shift toward natural ingredients, driven by growing safety concerns regarding synthetic colorants and increasing consumer demand for clean-label products (Mahanthesh *et al.,* 2020; Pandit *et al.,* 2022). Carotenoids from red pepper have emerged as particularly valuable ingredients for cosmetic formulations due to their remarkable multifunctional properties in dermatological applications. These natural pigments serve as effective photoprotective agents by absorbing harmful UV radiation, thereby helping to mitigate photoaging effects and reduce the risk of skin cancer development. Beyond UV protection, carotenoids also function as skin-brightening compounds that can prevent unwanted discoloration while simultaneously enhancing natural skin pigmentation for a healthier complexion (Sathasivam and Ki, 2018). The dermatological benefits of red pepper carotenoids extend to their regulatory effects on skin physiology. These bioactive compounds help normalize sebum production in oily skin types, unclog hair follicles to prevent acne formation, and promote epidermal renewal processes for improved skin texture. Such multifaceted actions make them particularly valuable for addressing various skin concerns ranging from acne to age-related changes.

In commercial applications, red pepper derived carotenoids, especially zeaxanthin and lutein, have been successfully incorporated into various skincare products. Antioxidant serums and nutricosmetic supplements increasingly feature these compounds to capitalize on their ability to reduce oxidative stress in skin cells (Baenas *et al.,* 2019). This combination of aesthetic and functional properties positions red pepper carotenoids as ideal ingredients for the growing market of cosmeceutical products that bridge the gap between cosmetics and dermatological treatments. The ability to offer both immediate color payoff and long-term skin improvement makes them particularly valuable in product formulations that cater to health-conscious consumers seeking multifunctional beauty solutions.

4.3.1 Mechanisms of Dermatological Action

Extensive research has characterized several key mechanisms through which red pepper carotenoids exert their skin benefits. As potent photoprotective agents, these compounds demonstrate broad-spectrum UV absorption capabilities, significantly reducing oxidative stress and DNA damage in epidermal cells. β-cryptoxanthin has shown particular efficacy in regulating melanogenesis, with oral administration suppressing UVB-induced skin pigmentation in murine models by up to 40% (Shimoda *et al.,* 2012). Red pepper xanthophylls, including zeaxanthin and lutein, enhance cutaneous hydration through dual mechanisms: upregulation of aquaporin-3 expression and improved stratum corneum barrier function (Yatsuhashi *et al.,* 2022). Lutein containing formulations defend skin from photo-aging and skin damage. National Cancer Institute human observational study revealed that high dietary intake of lutein significantly decreases (44%) the melanoma risks (Millen *et al.,* 2004).

4.3.2 Commercial Formulation Strategies

The cosmetic industry has developed innovative delivery systems to maximize the efficacy of red pepper carotenoids. Capsicum oleoresins have been successfully incorporated into long-wear lipstick formulations, providing stable coloration while delivering antioxidant protection. The safety, compatibility and efficacy of the natural dyes used in present lipstick formulations make them more suitable candidates in colourant cosmetics than their synthetic counterparts (Mate *et al.,* 2023). Dietary supplementation of lutein helps thickening of the skin (epidermal hyperplasia) and skin sunburn (apoptotic cell) formation. Beta-carotene cosmetics enhances skin turn-over the rate and skin regeneration. Skin tone is also improved as it adds glowing pigment upon topical application. Beta Carotene due to its tinting ability, is used in suntan creams and lotions. It heals skin scratches, protects against scarring and reduces skin irritation and itchiness (Bin-Jumah *et al.,* 2021).

Beta-carotene protects skin from sunburn caused by exposure to sunlight. It is well-known that wrinkle formation and skin sagging are due to increased metalloproteinase-9 contents in skin. â-carotene consumption prohibits metalloproteinase-9 activation and increases 5-α-hydroperoxide synthesis thus inhibiting skin sagging and wrinkle formation. It also protects from photosensitive disease, *i.e.* erythropoietic protoporphyria and sunburn diseases (Bin-Jumah *et al.,* 2021). Topically applied cosmetic sunscreens contain beta carotene due to its property of improving skin health and providing long-term protection against the phenomenon of sunburn reaction (Stahl and Krutmann, 2006). These applications highlight the versatility of red pepper carotenoids in addressing multiple consumer needs through different administration routes.

4.3.3 Emerging Applications and Future Directions

Current research explores novel applications leveraging the unique properties of red pepper carotenoids. These natural extracts provide vibrant coloration alongside additional skincare benefits, representing a significant advancement in multifunctional cosmetic development. These natural pigments are being increasingly utilized as sustainable colorants in makeup products, particularly in lipsticks and blushes, where they provide vibrant chromatic effects while delivering skin health benefits (Adeel *et al.,* 2024). Advanced delivery systems, including nanoemulsions and liposomal carriers, are being developed to overcome formulation challenges associated with carotenoid stability and skin penetration. The successful incorporation of red pepper derived carotenoids in various product categories from sunscreens to color cosmetics demonstrates their versatility and positions them as key ingredients in the next generation of cosmeceutical formulations. As encapsulation technologies advance, the market is expected to see increased incorporation of red pepper carotenoids in water-based formulations, opening new opportunities in serums and toners.

4.4 Pharmaceutical industry

Carotenoids derived from red pepper exhibit significant therapeutic potential due to their potent antioxidant capacity, effectively neutralizing reactive oxygen species (ROS) and protecting cellular integrity (Jimenez-Escobar *et al.,* 2020). The growing preference for sustainable, plant-based bioactive compounds has driven substantial pharmaceutical interest in these pigments, particularly for their multifaceted health benefits. Provitamin A carotenoids such as β-carotene and β-cryptoxanthin, characterized by their unsubstituted β-ionone rings, serve as crucial precursors for retinal synthesis in humans and animals. Capsanthin demonstrates remarkable metabolic regulatory properties, modulating hepatic gene expression to enhance glucose metabolism and low density lipoprotein (LDL) receptor activity while inhibiting cholesterol catabolism pathways. These mechanisms contribute to improved lipid profile management, including elevated HDL cholesterol levels associated with cardiovascular risk reduction (Amaya and Nickell, 2015). Similarly, β-cryptoxanthin exhibits pronounced anti-inflammatory effects, with epidemiological evidence supporting its protective role against chronic conditions like arthritis.

Zeaxanthin emerges as a particularly versatile carotenoid, displaying immunomodulatory, antiviral and neuroprotective activities through antioxidant, anti-apoptotic and anti-inflammatory pathways (Zafar *et al.,* 2021). Its therapeutic applications extend to dermatological protection against UV-induced erythema and scalp disorders, as well as cognitive enhancement and neurological disorder prevention. When combined with lutein, these xanthophylls demonstrate synergistic benefits for ocular health and brain function. Zeaxanthin exhibited anti-inflammatory and anti-allergenic properties (Yu *et al.,* 2018). The expanding recognition of these physiological benefits underscores the growing commercial value of red pepper carotenoids across pharmaceutical, nutraceutical, and cosmeceutical sectors. Their ability to address multiple health concerns from metabolic disorders to chronic inflammation and neurodegeneration, positions them as high-value ingredients in preventive healthcare formulations.

4.4.1 Antioxidant

Red pepper derived carotenoids exhibit varying degrees of antioxidant capacity, with capsorubin showing the highest activity followed by cucurbitaxanthin A, capsanthin, astaxanthin, cryptocapsin, and zeaxanthin (Nishino *et al.,* 2016). These compounds play crucial roles in cellular protection, particularly through their ability to neutralize reactive oxygen species. Among them, capsanthin, capsorubin, β-carotene and lutein have been shown to provide significant dermal photoprotection by effectively quenching singlet oxygen and scavenging peroxyl radicals, thereby complementing the natural defense system of the skin against UV-induced damage (Fernández-García *et al.,* 2016; Stahl and Sies, 2012). The health benefits of these carotenoids extend beyond their antioxidant properties. β-carotene serves dual functions as both a provitamin A precursor and a cellular protectant, contributing to the characteristic orange pigmentation of red pepper while helping to prevent oxidative damage to cells. Similarly, β-cryptoxanthin has gained increasing attention for its metabolic benefits, particularly in reducing risk factors associated with lifestyle-related diseases such as non-alcoholic fatty liver disease (NAFLD), through its conversion to biologically active vitamin A metabolites (Zafar *et al.,* 2021). Zeaxanthin emerges as a particularly versatile carotenoid with wide-ranging therapeutic applications. Its potent antioxidant capabilities contribute to protection against chronic diseases, while emerging evidence suggests additional benefits for bone health through potential protective effects against osteoporosis. Furthermore, the combined anti-inflammatory and antioxidant properties of zeaxanthin may offer protective benefits against conditions such as Acquired immune deficiency syndrome (AIDS), highlighting its potential in immunomodulatory applications (El-Akabawy and El-Sherif, 2019; Gao *et al.,* 2016). The diverse biological activities of these red pepper derived carotenoids underscore their significant potential as functional ingredients in nutraceuticals.

4.4.2 Foetal development

Zeaxanthin plays a vital role in foetal neurodevelopment, particularly during later pregnancy stages. Research shows that maternal intake significantly supports foetal brain maturation, with the compound accumulating in developing neural tissues. Studies link higher prenatal zeaxanthin and lutein exposure to improved childhood cognitive function and behavioural outcomes, likely through neuroprotective mechanisms. Current guidelines emphasize increased zeaxanthin consumption during pregnancy, especially after mid-gestation when brain growth peaks, highlighting its importance for optimal neurodevelopment (Mahmassani *et al.,* 2021).

4.4.3 Against COVID-19

Oxidative stress plays a central role in COVID-19 and Long-COVID by interacting with inflammation in a destructive cycle. This oxidative-inflammatory cascade drives disease progression, causing systemic hyperinflammation, coagulopathy, and multi-organ damage through endothelial injury and immunothrombosis. The persistent redox imbalance highlights oxidative stress as a crucial therapeutic target for both acute and chronic phases of the disease (Vollbracht and Kraft, 2022). Dietary carotenoids effectively neutralize reactive oxygen species (ROS) like singlet oxygen within cellular membranes. Studies show high intake of á-carotene, â-carotene and lutein/zeaxanthin correlates with reduced oxidative stress and inflammation markers. These fat-soluble compounds localize in lipid bilayers, where their molecular structures enable potent antioxidant and anti-inflammatory activity, offering protection against oxidative damage (Zafar *et al.,* 2021).

4.4.4 Anticarcinogenic

Red pepper derived carotenoids, including capsanthin, β-cryptoxanthin, lutein, zeaxanthin, and β-carotene exhibit well-documented chemo preventive potential against various malignancies (Tanaka *et al.,* 2012; Nishino *et al.,* 2002). Capsanthin demonstrates particular promise in oncology by modulating the tumor microenvironment and disrupting critical oncogenic pathways, showing significant efficacy against aggressive triple-negative breast cancer (TNBC) brain metastases. Beyond direct tumor suppression, capsanthin enhances host antitumor immunity while inducing selective cytotoxicity through ROS-mediated apoptosis in malignant cells (Chien *et al.,* 2025; Shanmugham and Subban, 2022). Zeaxanthin emerges as another potent anticancer agent, demonstrating superior efficacy to β-carotene in preventing lipid peroxidation and oxidative cellular damage key processes in carcinogenesis. Epidemiological data reveal a striking 79% reduction in ovarian cancer risk associated with high lutein/zeaxanthin intake (Sakai *et al.,* 2009). Mechanistic studies illustrate the ability of zeaxanthin to activate multiple apoptotic pathways in gastric cancer cells through ROS-dependent modulation of mitogen-activated protein kinase (MAPK), protein kinase B, nuclear factor-κB, and signal transducer and activator of transcription 3 (STAT3) signaling cascades (Sheng *et al.,* 2020). These multimodal mechanisms position red pepper carotenoids as promising candidates for both cancer prevention and adjunctive therapy.

4.4.5 Antidiabetic

Emerging research highlights the therapeutic benefits of red pepper derived carotenoids in diabetes management. Non-acylated capsanthin-capsorubin complexes demonstrate significant efficacy in ameliorating obesity-associated insulin resistance through their modulatory effects on metabolic pathways (Hassan *et al.,* 2019). These purified pigments show particular promise for addressing the root metabolic dysfunctions in type 2 diabetes.

The visual complications of diabetes may be mitigated by lutein and zeaxanthin supplementation, as these xanthophylls enhance multiple aspects of ocular function. Clinical evidence supports their ability to improve visual acuity, contrast sensitivity, and macular edema, making them valuable candidates for preventing diabetic retinopathy progression. β-carotene exhibits a protective role against diabetes development, with epidemiological studies revealing an inverse correlation between plasma β-carotene levels and both fasting glucose concentrations and insulin resistance markers. This association suggests the potential of β-carotene as both a preventive agent and adjunct therapy in diabetes management across populations (Hu *et al.,* 2011).

4.4.6 Antiobesity

Red pepper carotenoids exhibit significant potential in managing obesity and related metabolic disorders through multiple complementary mechanisms. Both capsanthin and β-cryptoxanthin demonstrate potent anti-obesity effects by ameliorating obesity-induced inflammatory changes in adipocytes while improving key metabolic parameters (Maeda *et al.,* 2013; Takayanagi, 2011). Capsanthin-enriched formulations have been shown to reduce body mass gain, increase adiponectin secretion, and decrease leptin, free fatty acid, and insulin concentrations without adverse effects at therapeutic doses (Shanmugham and Subban, 2022). Similarly, β-cryptoxanthin administration (0.8 mg/kg body weight daily) in murine models significantly reduced visceral adiposity, adipocyte hypertrophy, and serum lipid levels (Takayanagi, 2011). These consistent findings across different carotenoids highlight their shared ability to modulate adipocyte function and systemic metabolic regulation. The dual action of the compounds on both inflammatory pathways and metabolic manifestations of obesity, combined with their favorable safety profiles, positions them as promising candidates for developing functional foods and nutraceutical interventions targeting weight management and metabolic syndrome. The demonstrated efficacy in improving multiple obesity-related parameters suggests red pepper carotenoids could serve as valuable components in comprehensive strategies for preventing and managing obesity and its complications.

5. Future prospects

Red pepper carotenoids are promising multifunctional bioactive ingredients with potential for sustainable and health-promoting uses beyond traditional colorants. Future research should focus on scalable, eco-friendly biosynthetic production through metabolic engineering and microbial fermentation (*e.g.,* yeast, algae), while Clustered regularly interspaced short palindromic repeats (CRISPR) gene editing could boost carotenoid yields in Capsicum. Advanced extraction methods like pulsed electric field and subcritical water extraction may improve efficiency and sustainability. Nano-encapsulation technologies could enhance bioavailability for functional foods and nutraceuticals. Exploring synergistic combinations with polyphenols, omega-3s, or probiotics may open new applications for metabolic and age-related conditions, while carotenoid-loaded nanocosmeceuticals offer potential in UV protection and antiageing skincare. Finally, unifying global regulations and increasing consumer awareness of health benefits such as vision support and anti-inflammatory effects are vital for expanding market adoption into therapeutic domains. These advances align with current trends emphasizing natural, sustainable, and health-enhancing ingredients.

6. Conclusion

Red pepper derived carotenoids have evolved into multifunctional bioactive compounds with applications extending far beyond their traditional use as natural pigments, demonstrating significant antioxidant, anti-inflammatory and health-promoting properties that make them valuable across food, pharmaceutical, and cosmetic industries. Growing consumer demand for natural ingredients is driving market expansion, though challenges related to stability, bioavailability, and production costs currently limit wider adoption. Overcoming these barriers through innovative stabilization technologies, enhanced delivery systems and cost-effective production methods will unlock their full potential for developing health-focused products that meet global demands for sustainable wellness solutions.

Acknowledgements

The authors gratefully acknowledge Tamil Nadu Agricultural University (TNAU) for providing the necessary academic support and research environment for this review. Sincere thanks are also extended to the Department of Spices and Plantation Crops for their guidance and encouragement. The authors further express their appreciation to the researchers whose original studies have been cited in this review, as their contributions form the scientific basis of the work presented. The authors did not receive support from any organization for the submitted work. No funding was received for conducting this study or assisting with the preparation of this manuscript.

Author contributions

K.Shalini : writing original draft, Visualization, Resources data curation, conceptualization. M.S. Aneesa Rani: writing review and editing, Visualization, Validation, Supervision. M.Mohonalakshmi: Visualization, Validation, Supervision. R. Kalaiyarasi: Formal analysis, Editing. D. Amirtham: Conceptualization, Literature compilation, Reference management. N. Bharathi: Conceptualization, Formal analysis

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

References

Abourashed, E.A. (2013). Bioavailability of plant-derived antioxidants. Antioxidants, **2**(4):309-325.

Abubakar, A.R. and Haque, M. (2020). Preparation of medicinal plants: Basic extraction and fractionation procedures for experimental purposes. Journal of Pharmacy and Bioallied Sciences, **12**(1):1-10.

Adeel, S.; Abrar, S.; Ozomay, M.; Hussaan, M. and Batool, F. (2024). Evolving role of plant pigments in the cosmetic industry. Renewable Dyes and Pigments, pp:307-319.

Amaya, E. and Nickell, D. (2015). Using feed to enhance the color quality of fish and crustaceans. Feed and Feeding Practices in Aquaculture, pp. 269–298.

Baenas, N.; Beloviæ, M.; Ilic, N.; Moreno, D. A. and García-Viguera, C. (2019). Industrial use of pepper (*Capsicum annum* L.) derived products: Technological benefits and biological advantages. Food Chemistry, **274**:872-885.

Bin-Jumah, M.; Alwakeel, S. S.; Moga, M.; Buvnariu, L.; Bigiu, N. and Zia-Ul-Haq, M. (2021). Application of carotenoids in cosmetics. In Carotenoids: Structure and function in the human body, pp. 747-756. Cham: Springer International Publishing.

Chien, Y. C.; Wu, J. Y.; Liu, L. C. and Yu, Y. L. (2025). Capsanthin inhibits migration and reduces N-linked glycosylation of PD-L1 *via* the EZH2-PD-L1 axis in triple-negative breast cancer brain metastasis. Cell Death Discovery, **11**(1):85.

del Rocío Gómez-García, M. and Ochoa-Alejo, N. (2013). Biochemistry and molecular biology of carotenoid biosynthesis in chili peppers (*Capsicum* spp.). International Journal of Molecular Sciences, **14**(9):19025-19053.

Delgado-Vargas, F. and Paredes-López, O. (2003) Pigments as food colorants. Natural Colorants for Food and Nutraceutical Uses. Boca Raton, pp. 31–61.

EFSA Panel on Additives and Products or Substances used in Animal Feed (FEEDAP), Bampidis, V.; Azimonti, G.; Bastos, M. D. L.; Christensen, H.; Dusemund, B. and Kouba, M. (2020). Safety and efficacy of saponified paprika extract, containing capsanthin as main carotenoid source, for poultry for fattening and laying (except turkeys). EFSA Journal, **18**(2), e06023.

El-Akabawy, G. and El-Sherif, N.M. (2019). Zeaxanthin exerts protective effects on acetic acid-induced colitis in rats *via* modulation of pro-inflammatory cytokines and oxidative stress. Biomedicine & Pharmacotherapy, **111**:841–851.

Elvira-Torales, L.I.; J. García-Alonso, and M.J. Periago-Castón. (2019). Nutritional importance of carotenoids and their effect on liver health: A review. Antioxidants, **8**(7):229.

Fernández-García, E.; Carvajal-Lérida, I. and Pérez-Gálvez, A. (2016). Carotenoids exclusively synthesized in red pepper (capsanthin and capsorubin) protect human dermal fibroblasts against UVB induced DNA damage. Photochemical & Photobiological Sciences, **15**:1204-1211.

Gagez, A. L.; Thiery, V.; Pasquet, V.; Cadoret, J. P. and Picot, L. (2012). Epoxycarotenoids and cancer. Review. Current Bioactive Compounds, **8**(2):109-141.

Gao, Y. Y.; Jin, L.; Ji, J.; Sun, B. L.; Xu, L. H.; Wang, Q. X. and Bi §, Y. Z. (2016). Xanthophyll supplementation reduced inflammatory mediators and apoptosis in hens and chicks. Journal of Animal Science, **94**(5):2014-2023.

Ghosh, S.; Sarkar, T.; Das, A. and Chakraborty, R. (2022). Natural colorants from plant pigments and their encapsulation: An emerging window for the food industry. Lwt, **153**:112527.

Griep, P.; Gayeski, L.; Colet, R.; Zeni, J. and Valduga, E. (2025). Recent updates of carotenoid encapsulation by spray-drying technique. Journal of Microencapsulation, **42**(1):26-46.

Haetami, K.; Lili, W.; Grandiosa, R. and Destiyantara, F. A. (2021). The effect of Red Paprika Extract (*Capsicum Annuum*) in Feed on the Color Intensity Level of Comet Fish (*Carassius auratus*). Asian Journal of Fisheries and Aquatic Research, **13**(2):37-45.

Hu, B. J.; Hu, Y. N.; Lin, S.; Ma, W. J. and Li, X. R. (2011). Application of Lutein and Zeaxanthin in nonproliferative diabetic retinopathy. International Journal of Ophthalmology, **4**(3):303.

Huang, P.; Yu, Q.; Feng, X.; Ma, C. and Kan, J. (2022). Optimization of accelerated solvent extraction of paprika oleoresin and its effect on capsaicinoid and carotenoid composition. Journal of Food Composition and Analysis, **110**:104589.

Jimenez-Escobar, M. P.; Pascual-Mathey, L. I.; Beristain, C. I.; Flores-Andrade, E.; Jiménez, M. and Pascual-Pineda, L. A. (2020). In vitro and In vivo antioxidant properties of paprika carotenoids nanoemulsions. Lwt, **118**:108694.

Juriæ, S.; Juriæ, M.; Król-Kiliñska.; Vlahovièek-Kahlina, K.; Vincekoviæ, M.; Dragoviæ-Uzelac, V. and Donsì, F. (2022). Sources, stability, encapsulation and application of natural pigments in foods. Food Reviews International, **38**(8):1735-1790.

Kennedy, L. E.; Abraham, A.; Kulkarni, G.; Shettigar, N.; Dave, T. and Kulkarni, M. (2021). Capsanthin, a plant-derived xanthophyll: A review of pharmacology and delivery strategies. AAPS pharmscitech, **22**(5):203.

Kim, J. K.; Kim, D. W.; Gebru, Y. A.; Choi, H. S.; Kim, Y. H. and Kim, M. K. (2022). The Identification and Quantitative Analysis of Unusual Keto-Carotenoids in Ripe Fruits of Maclura tricuspidate and Its Potential as a Valuable Source of Cryptocapsin. Molecules, **27**(23):8317.

Kostrzewa, D.; Mazurek, B.; Kostrzewa, M. and JóŸwik, E. (2023). Carotenoids and Fatty Acids Obtained from Paprika *Capsicum annuum* by Supercritical Carbon Dioxide and Ethanol as Co-Extractant. Molecules, **28**(14):5438.

Langi, P.; Kiokias, S.; Varzakas, T. and Proestos, C. (2018). Carotenoids: From plants to food and feed industries. Microbial carotenoids: Methods and protocols, pp:57-71.

Lee, C.C. and Küçükata. Y.A. (2023). Microbial production of zeaxanthin, in Microbial Production of Food Bioactive Compounds. Springer, pp. 1-38.

Liu, X.; Fan, Y.; Chang, C. P.; Lo, C. K. and Wang, X. (2021). High-throughput screening and quantification of pesticides in paprika by UHPLC-Q-TOF/MS. Food Analytical Methods, **14**(10):2186-2198.

Lorenzo, Y.; Azqueta, A.; Luna, L.; Bonilla, F.; Domínguez, G. and Collins, A. R. (2009). The carotenoid β-cryptoxanthin stimulates the repair of DNA oxidation damage in addition to acting as an antioxidant in human cells. Carcinogenesis, **30**(2):308-314.

Lu, W., V.A. Maidannyk, and Lim. A.S. (2020). Carotenoids degradation and precautions during processing, in Carotenoids: Properties, Processing and Applications. Elsevier, pp:223-258.

Lu, Y.; Wang, J.; Soladoye, O. P.; Aluko, R. E.; Fu, Y. and Zhang, Y. (2021). Preparation, receptors, bioactivity and bioavailability of ã-glutamyl peptides: A comprehensive review. Trends in Food Science & Technology, **113**:301-314.

Maeda, H.; Saito, S.; Nakamura, N. and Maoka, T. (2013). Paprika pigments attenuate obesity induced inflammation in 3T3 L1 adipocytes. International Scholarly Research Notices, **2013**(1):763758.

Maeda, H.; Nishino, A. and Maoka, T. (2006). Biological activities of paprika carotenoids, capsanthin and capsorubin. In Carotenoids: Biosynthetic and Biofunctional Approaches, pp:285-293.

Mahanthesh, M. C.; Manjappa, A. S.; Shinde, M. V.; Sherikar, A. S.; Disouza, J. I.; Namrata, B. U. and Ajija, W. C. (2020). Design, development and assessment of herbal lipstick from natural pigments. Int. J. Pharm. Sci. Rev. Res, **61**(1):59-64.

Mahmassani, H. A.; Switkowski, K. M.; Scott, T. M.; Johnson, E. J.; Rifas-Shiman, S. L.; Oken, E. and Jacques, P. F. (2021). Maternal intake of lutein and zeaxanthin during pregnancy is positively associated with offspring verbal intelligence and behavior regulation in mid-childhood in the project viva cohort. The Journal of Nutrition, **151**(3):615-627.

Mate, D.; Ramlunalanaglu, K.; Pimple, B.; Vadge, S.; Kuchekar, M.; Nipate, S. and Baheti, D. (2023). Comparative evaluation of lipsticks developed using isolated pigments of *Capsicum annuum* and *Lycopersicon esculentum* fruits and various natural bases. Int. J. Exp. Res. Rev., **30**:352-358.

Millen, A. E.; Tucker, M. A.; Hartge, P.; Halpern, A.; Elder, D. E.; Guerry IV, D. and Potischman, N. (2004). Diet and melanoma in a case-control study. Cancer Epidemiology Biomarkers and Prevention, **13**(6), 1042-1051.

Mohd Hassan, N.; Yusof, N. A.; Yahaya, A. F.; Mohd Rozali, N. N. and Othman, R. (2019). Carotenoids of capsicum fruits: Pigment profile and health-promoting functional attributes. Antioxidants, **8**(10):469.

Mortensen, A. (2006). Carotenoids and other pigments as natural colorants. Pure and Applied Chemistry, **78**(8):1477-1491.

Murillo, E.; Nagy, V.; Agócs, A. and Deli, J. (2013). Carotenoids with ê-end group. Carotenoids: Food Sources, Production and Health Benefits, pp:49-77.

Nishino, A.; Yasui, H. and Maoka, T. (2016). Reaction of paprika carotenoids, capsanthin and capsorubin, with reactive oxygen species. Journal of Agricultural and Food Chemistry, **64**(23):4786-4792.

Nishino, H.; Murakoshi, M.; Ii, T.; Takemura, M.; Kuchide, M.; Kanazawa, M. and Jinno, K. (2002). Carotenoids in cancer chemoprevention. Cancer and Metastasis Reviews, **21**(3):257-264.

Novais, C.; Molina, A. K.; Abreu, R. M.; Santo-Buelga, C.; Ferreira, I. C.; Pereira, C. and Barros, L. (2022). Natural food colorants and preservatives: A review, a demand, and a challenge. Journal of agricultural and food chemistry, **70**(9):2789-2805.

Pandit, P.; Singha, K.; Maity, S. and Ahmed, S. (Eds.). (2022). Textile Dyes and Pigments: A Green Chemistry Approach. John Wiley and Sons.

Pasarin, D. and Rovinaru, C. (2018). Sources of carotenoids and their uses as animal feed additives-a review.

Ponder, A.; Kulik, K. and Hallmann, E. (2021). Occurrence and determination of carotenoids and polyphenols in different paprika powders from organic and conventional production. Molecules, **26**(10):2980.

Ravindran, A.; Jayashree, E. and Anees, K. (2025). Recent Advances in the Extraction of Spice Essential Oil and Oleoresin: A Review. Agricultural Reviews, **46**(1).

Reddy, M. and Ponnam, N. (2023). Chilli farming for Indian health and wealth. Indian Horticulture, **68**(2):87-89.

Saha, S.; Choi, G.-D. and Cho, Y.-H. (2015). Optimal rotor shape design of LSPM with efficiency and power factor improvement using response surface methodology. IEEE Transactions on Magnetics, **51**(11):1-4.

Saini, R.K. and Keum, Y.-S. (2018). Carotenoid extraction methods: A review of recent developments. Food Chemistry, **240**:90-103.

Sajilata, M.; Singhal, R. and Kamat, M. (2008). The carotenoid pigment zeaxanthin-a review. Comprehensive Reviews in Food Science and Food Safety, **7**(1):29-49.

Sakai, S.; Sugawara, T.; Matsubara, K. and Hirata, T. (2009). Inhibitory effect of carotenoids on the degranulation of mast cells *via* suppression of antigen-induced aggregation of high affinity IgE receptors. Journal of Biological Chemistry, **284**(41):28172-28179.

Sathasivam, R. and Ki, J.-S. (2018). A review of the biological activities of microalgal carotenoids and their potential use in healthcare and cosmetic industries. Marine Drugs, **16**(1): 26.

Shanaida, M.; Mykhailenko, O.; Lysiuk, R., Hudz, N.; Balwierz, R.; Shulhai, A. and Bjørklund, G. (2025). Carotenoids for Antiaging: Nutraceutical, Pharmaceutical, and Cosmeceutical Applications. Pharmaceuticals, **18**(3):403-415.

Shanmugham, V. and Subban, R. (2022). Capsanthin-loaded micelles: Preparation, characterization and *in vitro* evaluation of cytotoxicity using MDA-MB-231 breast cancer cell line. Food Technology and Biotechnology, **60**(3):350-360.

Shanmugham, V. and Subban, R. (2022). Comparison of the anti-obesity effect of enriched capsanthin and capsaicin from *Capsicum annuum* L. fruit in obesity-induced C57BL/6J mouse model. Food Technology and Biotechnology, **60**(2):202-212.

Shanmugham, V. and Subban, R. (2022). Capsanthin from Capsicum annum fruits exerts anti glaucoma, antioxidant, anti inflammatory activity, and corneal pro inflammatory cytokine gene expression in a benzalkonium chloride induced rat dry eye model. Journal of Food Biochemistry, **46**(10):e14352.

Sharma, S.; Dedha, A.; Gupta, M. M.; Singh, N.; Gautam, A. and Kumari, A. (2025). Green and sustainable technologies for extraction of carotenoids from natural sources: A comprehensive review. Preparative Biochemistry and Biotechnology, **55**(3):245-277.

Sheng, Y. N.; Luo, Y. H.; Liu, S. B.; Xu, W. T.; Zhang, Y.; Zhang, T. and Jin, C. H. (2020). Zeaxanthin induces apoptosis *via* ROS-regulated MAPK and AKT signaling pathway in human gastric cancer cells. OncoTargets and therapy, pp:10995-11006.

Shilpa, S.; Shwetha, H. J.; Raju, M. and Lakshminarayana, R. (2020). Factors affecting bioaccessibility and bio-efficacy of carotenoids. In Carotenoids: Properties, processing and applications, pp:41-73. Academic Press.

Shimoda, H.; Terazawa, S.; Hitoe, S.; Tanaka, J.; Nakamura, S.; Matsuda, H. and Yoshikawa, M. (2012). Changes in ceramides and glucosylceramides in mouse skin and human epidermal equivalents by rice-derived glucosylceramide. Journal of Medicinal Food, **15**(12):1064-1072.

Stahl, W. and Krutmann, J. (2006). Systemic photoprotection through carotenoids. Der Hautarzt, **57**:281-285.

Stahl, W. and Sies, H. (2012). β-Carotene and other carotenoids in protection from sunlight. The American Journal of Clinical Nutrition **96**(5):1179S-1184S.

Takayanagi, K. (2011). Prevention of adiposity by the oral administration of β-cryptoxanthin. Frontiers in Neurology, 2:67.

Tanaka, T.; Shnimizu, M. and Moriwaki, H. (2012). Cancer chemoprevention by carotenoids. Molecules, **17**(3):3202-3242.

Topuz, A.; Dincer, C.; Özdemir, K. S.; Feng, H. and Kushad, M. (2011). Influence of different drying methods on carotenoids and capsaicinoids of paprika (Cv., Jalapeno). Food Chemistry, **129**(3):860-865.

Vollbracht, C. and Kraft, K. (2022). Oxidative stress and hyper-inflammation as major drivers of severe COVID-19 and long COVID: implications for the benefit of high-dose intravenous vitamin C. Frontiers in Pharmacology, **13**:899198.

Wang, F.; Huang, L.; Gao, B. and Zhang, C. (2018). Optimum production conditions, purification, identification, and antioxidant activity of violaxanthin from microalga Eustigmatos cf. polyphem (Eustigmatophyceae). Marine Drugs, **16**(6):190.

Wang, L.; Liu, Z.; Jiang, H. and Mao, X. (2021). Biotechnology advances in β-carotene production by microorganisms. Trends in Food Science and Technology, **111**:322-332.

Yatsuhashi, H.; Takumi, H.; Terada, Y. and Kuriki, T. (2022). Effects of oral supplementation with paprika xanthophylls on human skin moisture. Journal of Oleo Science, **71**(5):735-745.

Yu, M., Yan, W. and Beight, C. (2018). Lutein and zeaxanthin isomers protect against light-induced retinopathy *via* decreasing oxidative and endoplasmic reticulum stress in BALB/cJ mice. Nutrients, **10**(7):842.

Zafar, J.; Aqeel, A.; Shah, F. I.; Ehsan, N.; Gohar, U. F.; Moga, M. A. and Chicea, R. (2021). Biochemical and immunological implications of lutein and zeaxanthin. International Journal of Molecular Sciences, **22**(20):10910.

Zakynthinos, G. and Varzakas, T. (2016). Carotenoids: From plants to food industry. Current Research in Nutrition and Food Science, **4**(1):38–51.

Zeiner, M.; Fiedler, H.; Juranoviæ Cindriæ, I.; Nemet, I.; Toma, D. and Habinovec, I. (2023). Preliminary study of Pepper types based on Multielement Content combined with Chemometrics. Foods, **12**(16):3132.

Citation **K. Shalini, M.S. Aneesa Rani, M. Mohanalakshmi, R. Kalaiyarasi, D. Amirtham and N. Bharathi (2025). A comprehensive review on technological advances in Red pepper (*Capsicum annuum* L.) derived carotenoids: An industrial perspective. Ann. Phytomed., 14(2):127-139. http://dx.doi.org/10.54085/ap.2025.14.2.13.**