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β-carotene as a functional bioactive compound: Chemical characteristics, biological functions, nutritional sources, health benefits and pharmaceutical and industrial applications

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Abstract

β-carotene, a major member of the carotenoid family, is a multifunctional bioactive compound with significant relevance in nutrition, human health, pharmaceutical formulations and industrial applications. Structurally characterized by a highly conjugated polyene chain with two β-ionone rings, β-carotene functions as the most efficient provitamin A carotenoid and plays a critical role in maintaining physiological functions. This review comprehensively discusses the chemical characteristics, biological functions, nutritional sources, health benefits, and pharmaceutical and industrial applications of β-carotene. Naturally abundant in fruits, vegetables and microalgae, β-carotene serves as a primary dietary source of vitamin A, particularly in populations dependent on plant-based foods. Biologically, β-carotene exhibits strong antioxidant activity by scavenging reactive oxygen species and quenching singlet oxygen, thereby protecting cellular components from oxidative stress. Through its enzymatic conversion into retinoids, it contributes to visual function, immune regulation, epithelial tissue maintenance and gene expression. Increasing scientific evidence suggests its potential protective role against various chronic diseases, including cardiovascular disorders, metabolic diseases, cancer and neurodegenerative conditions. Additionally, β-carotene contributes to skin health and photoprotection, highlighting its therapeutic relevance. In the pharmaceutical sector, β-carotene is widely incorporated into nutraceuticals, dietary supplements and formulations designed to prevent vitamin A deficiency. However, its clinical and industrial utilization is challenged by poor aqueous solubility, chemical instability and limited bioavailability. Recent advances in nanotechnology-based delivery systems and encapsulation strategies have significantly improved its stability, bioavailability and therapeutic efficacy. Industrially, β-carotene is extensively employed as a natural colorant, functional food ingredient, cosmetic additive and animal feed supplement, with increasing demand driven by consumer preference for natural and sustainable products. Emerging developments in biotechnological production, precision nutrition and advanced delivery platforms are further expanding its applications. Despite its broad therapeutic potential, concerns related to high-dose supplementation and variable bioavailability warrant further investigation. Overall, β-carotene represents a promising functional bioactive compound with diverse applications, and continued interdisciplinary research is essential to fully harness its potential for improving human health and promoting sustainable industrial development.

1. Introduction

Carotenoids are a diverse class of naturally occurring pigments synthesized by plants, algae, fungi, and certain microorganisms, where they play essential roles in light harvesting and photoprotection during photosynthesis. Chemically, carotenoids are lipophilic tetraterpenoids composed of eight isoprene units, forming a characteristic polyene chain with conjugated double bonds responsible for their coloration and antioxidant activity. More than 700 carotenoids have been identified to date and are broadly classified into carotenes, which are hydrocarbons (*e.g.,* β-carotene, α-carotene, lycopene), and xanthophylls, which are oxygenated derivatives (*e.g.*, lutein, zeaxanthin) (Rodriguez-Amaya, 2016). Functionally, carotenoids are further categorized as provitamin A and non-provitamin A carotenoids based on their capacity to be converted into retinol (vitamin A) in humans. Among them, β-carotene is the most efficient provitamin A carotenoid and plays a critical role in human nutrition (Eggersdorfer and Wyss, 2018). β-carotene is widely distributed in nature, particularly in orange- and yellow-colored fruits and vegetables such as carrots, pumpkins, sweet potatoes, and

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mangoes, as well as in green leafy vegetables including spinach and kale, where its pigment is masked by chlorophyll (Khoo *et al.,* 2011). As a dietary precursor of vitamin A, β-carotene undergoes enzymatic cleavage in the intestinal mucosa by β-carotene-15,152 -mono-oxygenase, producing retinal, which is subsequently converted to retinol or retinoic acid according to physiological requirements (Harrison, 2012). These metabolites are essential for numerous biological processes, including vision, immune regulation, cellular differentiation, and maintenance of epithelial tissues. The nutritional significance of β-carotene is particularly evident in developing countries, where plant-based diets serve as the primary source of vitamin A, making it a key component in strategies to combat vitamin A deficiency (WHO, 2020).

Beyond its provitamin A activity, β-carotene has gained considerable attention as a functional bioactive compound due to its diverse biological effects. One of its most notable properties is its strong antioxidant activity. The extensive conjugated double-bond system enables β-carotene to effectively quench singlet oxygen and neutralize free radicals, thereby protecting cellular components from oxidative damage (Krinsky and Johnson, 2005). Since oxidative stress is implicated in the pathogenesis of several chronic diseases including cardiovascular disorders, cancer, diabetes, and neurodegenerative diseases. β-carotene may contribute to disease prevention through its antioxidative mechanisms (Fiedor and Burda, 2014). Moreover, β-carotene has been reported to modulate cell signaling pathways, influence gene expression, and enhance intercellular communication, further supporting its role as a multifunctional bioactive compound (Tanumihardjo *et al.,* 2016). In recent years, β-carotene has gained significant attention as a functional bioactive compound due to its diverse biological activities beyond its role as a provitamin A. One of its most prominent properties is its antioxidant capacity. The extensive conjugated double-bond system of β-carotene enables it to effectively quench singlet oxygen and neutralize free radicals, thereby protecting cells from oxidative damage (Krinsky and Johnson, 2005). Oxidative stress is a major contributing factor in the development of chronic diseases such as cardiovascular disorders, cancer, diabetes and neurodegenerative conditions. By mitigating oxidative stress, β-carotene contributes to the prevention and management of these diseases (Fiedor and Burda, 2014). Additionally, β-carotene has been shown to influence cell signaling pathways, regulate gene expression and enhance intercellular communication, further supporting its classification as a multifunctional bioactive compound (Tanumihardjo *et al*., 2016).

The health-promoting effects of β-carotene extend across multiple physiological systems. Vitamin A derived from β-carotene is essential for the formation of rhodopsin, a light-sensitive pigment in the retina required for vision under low-light conditions (Sommer and Vyas, 2012). Additionally, β-carotene supports immune function by maintaining epithelial integrity and enhancing immune cell activity, thereby improving resistance to infections (Stephensen, 2001). Its antioxidant properties also provide photoprotective effects on the skin by reducing damage induced by ultraviolet radiation and environmental stressors, highlighting its relevance in dermatological applications (Stahl and Sies, 2012). Epidemiological studies further suggest an inverse association between dietary β-carotene intake and the risk of several chronic diseases, although results from supplementation trials have been inconsistent (Bjelakovic *et al.,* 2013).

The significance of β-carotene extends beyond its nutritional role into important pharmaceutical and industrial applications. In the pharmaceutical sector, β-carotene is widely incorporated into dietary supplements and therapeutic formulations aimed at preventing or managing vitamin A deficiency (Kabilan *et al*., 2025). Compared with preformed vitamin A, β-carotene is considered relatively safer because its conversion to retinol is physiologically regulated, thereby minimizing the risk of hypervitaminosis A (Harrison, 2012). Nevertheless, evidence from clinical studies indicates that high-dose β-carotene supplementation, particularly among smokers, may be associated with adverse outcomes, underscoring the need for careful and context-specific use (Bjelakovic *et al.,* 2013). To overcome challenges related to its low solubility and instability, advanced drug delivery strategies such as nanoencapsulation, nanoemulsions, and lipid-based carrier systems are increasingly being explored to enhance the stability, bioavailability, and therapeutic potential of β–carotene (Yuan *et al.,* 2015).

Industrially, β-carotene is extensively utilized as a natural colorant (E160a) in food products, providing both visual appeal and nutritional value. The growing consumer preference for clean-label and naturally derived ingredients has significantly increased its application in the food and beverage industry (Rodriguez-Amaya, 2019). In the cosmetic sector, β-carotene is incorporated into topical formulations due to its antioxidant and photoprotective properties, which help mitigate skin aging and oxidative damage induced by environmental stressors (Stahl and Sies, 2012). Additionally, β-carotene is widely used in animal feed and aquaculture to enhance pigmentation and improve the nutritional quality of animal-derived products. Advances in sustainable production technologies, particularly microbial and algal biosynthesis, have further strengthened the industrial relevance of β-carotene (Del Campo *et al.,* 2007).

From a global health perspective, β-carotene plays a vital role in addressing micronutrient deficiencies, especially vitamin A deficiency, which remains a major public health challenge in many low- and middle-income countries. Vitamin A deficiency can result in severe health consequences, including night blindness, impaired immune function, and increased mortality risk among children and pregnant women (WHO, 2020). To mitigate this problem, several strategies have been implemented, including dietary diversification, food fortification, and biofortification programs. Notable examples include the development of β-carotene-rich crops such as golden rice and orange-fleshed sweet potato, which aim to enhance dietary vitamin A intake in vulnerable populations (Bouis and Saltzman, 2017). Furthermore, the rising global burden of non-communicable diseases has highlighted the importance of dietary antioxidants like β-carotene in promoting long-term health and reducing disease risk.

Recent advances in food science and nanotechnology have further expanded the application potential of β-carotene. Owing to its hydrophobic nature and susceptibility to oxidation and degradation, improving its stability and bioavailability remains a key research focus. Novel delivery systems such as nanoemulsions, liposomes, and biopolymer-based encapsulation technologies have demonstrated promising results in enhancing the stability, absorption, and functional efficacy of β-carotene in both functional foods and pharmaceutical formulations (Yuan *et al.,* 2015).In view of its diverse biological, nutritional, and technological roles, β-carotene represents a prominent functional bioactive compound with broad implications for human health, pharmaceutical development, and industrial applications.

Despite extensive research, gaps remain in understanding its bioavailability, metabolic pathways, and the long-term effects of supplementation. Therefore, this review aims to provide a comprehensive overview of β-carotene, focusing on its chemical characteristics, biological functions, nutritional sources, health benefits, and pharmaceutical and industrial applications. By integrating current knowledge and highlighting emerging research trends, this review seeks to contribute to the advancement of scientific understanding and practical utilization of β-carotene for improving human health and well-being.

2. Chemistry and chemical characteristics of β-carotene

2.1 Chemical structure and molecular formula

β-carotene is a naturally occurring tetraterpenoid hydrocarbon belonging to the carotenoid family, characterized by its distinctive orange pigment and biological significance. Chemically, it is composed of 40 carbon atoms ($C_{40}H_{56}$), formed through the condensation of eight isoprene units, giving rise to a long polyene chain with conjugated double bonds. This conjugated system, consisting of alternating single and double bonds, is responsible for its intense coloration and unique photophysical properties. The molecule is symmetrical, consisting of two identical β-ionone rings at each end connected by a central polyene chain, which plays a critical role in its biological activity and provitamin A function.

The extensive conjugated double-bond system in β-carotene enables it to absorb light in the visible spectrum, typically within the 400-500 nm range, which imparts its characteristic yellow to orange coloration. This structural feature also contributes to its potent antioxidant activity, as the delocalized π-electron system facilitates interaction with reactive oxygen species (ROS), allowing efficient quenching of singlet oxygen and neutralization of free radicals. Structurally, β-carotene contains two terminal β-ionone rings, which are crucial for its provitamin A activity. These rings enable enzymatic cleavage by β-carotene-15, 152 -monooxygenase to generate retinal, a direct precursor of vitamin A. Importantly; only carotenoids possessing at least one unsubstituted β-ionone ring can function as vitamin A precursors, making β-carotene one of the most efficient provitamin A carotenoids. The hydrophobic nature of β-carotene arises from its purely hydrocarbon structure, which lacks polar functional groups. This pronounced lipophilicity influences its biological behavior, including its incorporation into lipid membranes and its transport in the bloodstream *via* lipoproteins. However, the same structural characteristics also render β-carotene susceptible to oxidative degradation, particularly under conditions of light exposure, oxygen, and elevated temperature. Consequently, understanding the molecular architecture of β-carotene is essential for elucidating its physicochemical properties and optimizing its stability and functionality in food, pharmaceutical, and industrial applications.

2.2 Stereochemistry and isomerism

β-carotene exhibits geometric isomerism due to the presence of multiple double bonds in its polyene chain. The most stable and predominant form in nature is the all-trans (all-E) isomer, in which all double bonds are in the trans configuration. This linear structure allows for maximum conjugation and stability, making it the most biologically active and commonly occurring form in fresh plant materials. In addition to the all-trans form, β-carotene can exist in several cis (Z) isomeric forms, including 9-cis, 13-cis and 15-cis configurations. These cis isomers are typically formed during processing, storage, or exposure to heat and light. Isomerization leads to changes in the molecular geometry, resulting in a bent structure that affects both the physical and biological properties of the molecule. For instance, cis isomers generally exhibit lower color intensity and altered absorption spectra compared to the all-trans form.

The biological significance of β-carotene isomers has been extensively studied. The all-trans form is considered to have higher provitamin A activity and better absorption efficiency, whereas cis isomers may differ in their bioavailability and antioxidant capacity. Studies have shown that cis and trans isomers exhibit distinct biological behaviors, including differences in cellular uptake, metabolism and physiological effects (Telegina *et al*., 2023). Furthermore, during digestion and metabolism, cis isomers may be partially converted into the all-trans form before absorption, indicating a dynamic interconversion process. Processing techniques such as cooking and storage can significantly influence the isomeric composition of β-carotene in foods. Thermal treatment, for example, can promote isomerization, increasing the proportion of cis isomers. Interestingly, certain processing methods may enhance bioaccessibility by breaking down the food matrix and facilitating the release of β-carotene, despite partial isomerization (Imsic *et al*., 2010). Therefore, the stereochemical configuration of β-carotene plays a crucial role in determining its stability, bioavailability and functional properties.

2.3 Physicochemical properties

β-carotene exhibits distinct physicochemical properties primarily determined by its nonpolar hydrocarbon structure. It is highly lipophilic and hydrophobic, showing negligible solubility in water but high solubility in organic solvents such as hexane, chloroform and lipid-based systems. Consequently, in biological systems and food matrices, β-carotene associates predominantly with lipid components and is absorbed through mechanisms similar to dietary fats. During digestion, it is incorporated into mixed micelles formed by bile salts and dietary lipids, facilitating its transport across the intestinal epithelium. The compound's highly conjugated polyene structure also makes it susceptible to environmental degradation. Exposure to oxygen, light and heat can induce oxidative reactions and structural breakdown, resulting in reduced stability and biological activity. Additionally, its crystalline nature in certain forms can limit its solubilization and absorption. Studies have shown that the physical form of β-carotene (*e.g.,* crystalline vs. emulsified) significantly affects its bioavailability, with emulsified forms demonstrating enhanced absorption (Kotake-Nara *et al*., 2020). These physicochemical characteristics strongly influence its industrial and pharmaceutical applications. While its lipophilicity favors incorporation into oil-based food and cosmetic formulations, its instability necessitates protective strategies such as encapsulation. Modern approaches, including nanoemulsions and microencapsulation, have been developed to improve the stability, solubility and delivery of β-carotene in functional foods and pharmaceutical products (Molteni *et al*., 2022).

2.4 Stability and degradation mechanisms

β-carotene is inherently unstable due to its highly unsaturated polyene structure, making it susceptible to degradation under environmental conditions such as light, heat, and oxygen. These factors promote oxidative reactions, isomerization, and molecular cleavage, leading to the formation of degradation products and a reduction in biological activity. Exposure to light, particularly ultraviolet radiation, induces photooxidation, which disrupts the conjugated double-bond system. Thermal processing can further accelerate degradation and cause isomerization from the all-trans to cis forms. Although, limited isomerization may improve bioaccessibility, excessive degradation significantly diminishes the nutritional and functional value of β-carotene. Oxidative degradation occurs through interactions with reactive oxygen species, resulting in the formation of epoxides, aldehydes, and other cleavage products that decrease the concentration of intact β-carotene and may alter its biological activity.

Storage conditions play a crucial role in preserving β-carotene stability, with factors such as temperature, light exposure, and oxygen availability significantly influencing degradation kinetics (Imsic *et al.,* 2010). To enhance stability, various strategies have been developed, including the use of antioxidants, improved packaging systems, and encapsulation technologies. Encapsulation within protective matrices such as liposomes, polymeric nanoparticles, or emulsions effectively shields β-carotene from environmental stress, improving its stability and shelf-life. These approaches are increasingly applied in food and pharmaceutical formulations to maintain the quality and efficacy of β-carotene-containing products.

2.5 Biosynthetic pathway of β-carotene in plants and microorganisms

β-carotene is biosynthesized through the isoprenoid pathway, primarily *via* the methylerythritol phosphate (MEP) pathway in the plastids of plants and many microorganisms. The pathway begins with the condensation of isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP) to form geranylgeranyl pyrophosphate (GGPP), a key precursor in carotenoid biosynthesis. Two molecules of GGPP are subsequently condensed by phytoene synthase to produce phytoene, the first colorless carotenoid intermediate. Phytoene then undergoes a sequence of desaturation and isomerization reactions, catalyzed by enzymes such as phytoene desaturase and β-carotene desaturase, leading to the formation of lycopene. Lycopene is further cyclized by lycopene β-cyclase, resulting in the formation of β-carotene, characterized by two terminal β-ionone rings (Figure 1).

In plants, β-carotene biosynthesis occurs within chloroplasts and chromoplasts, where it contributes to light harvesting and photoprotection during photosynthesis. Several microorganisms, particularly microalgae such as *Dunaliella salina*, are also capable of accumulating substantial amounts of β-carotene. These organisms are increasingly exploited for commercial β-carotene production due to their high productivity and sustainable cultivation. The biosynthesis of β-carotene is regulated by environmental factors including light intensity, temperature, and nutrient availability. Recent advances in genetic and metabolic engineering have facilitated the development of biofortified crops and engineered microbial strains with enhanced β-carotene production, thereby improving both nutritional quality and industrial supply.

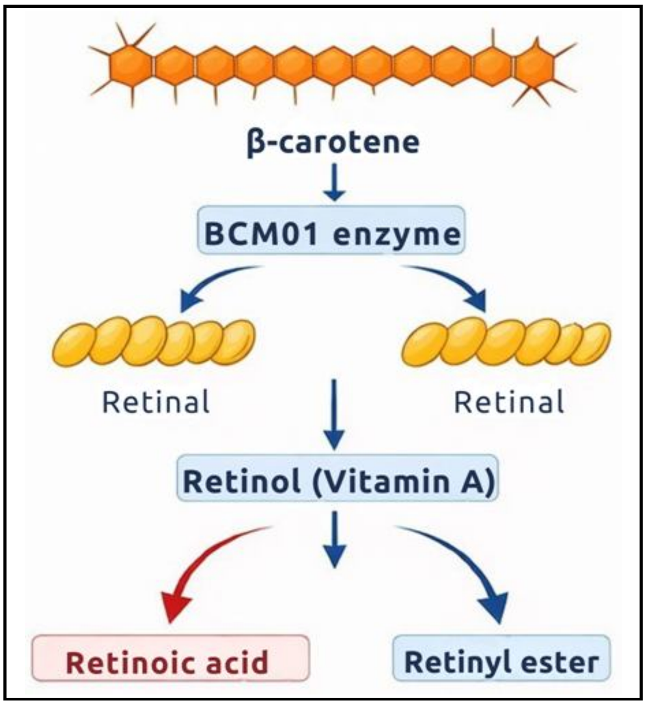

Figure 1: Enzymatic conversion of β-carotene into vitamin A derivatives (retinal, retinol and retinoic acid) *via* BCMO1.

2.6 Absorption, metabolism, and bioavailability of β-carotene

The absorption and metabolism of β-carotene in the human body are complex processes influenced by multiple dietary and physiological factors. As a lipophilic compound, β-carotene requires the presence of dietary fats for efficient absorption. During digestion, it is released from the food matrix, solubilized into mixed micelles with the aid of bile salts and transported to the intestinal epithelium. The primary site of absorption is the small intestine, particularly the duodenum, where β-carotene is taken up by enterocytes through passive diffusion and facilitated transport mechanisms (Honda, 2018). Once inside the enterocytes, β-carotene may undergo enzymatic cleavage by β-carotene-15,152 -monooxygenase to produce retinal, which is then converted into retinol or retinoic acid. Alternatively, intact β-carotene can be incorporated into chylomicrons and transported *via* the lymphatic system to the liver and other tissues.

Bioavailability of β-carotene is influenced by several factors, including its chemical form, food matrix, processing and individual physiological conditions. For instance, the presence of dietary lipids enhances its absorption, while fiber and other components may inhibit it. Additionally, the physical form of β-carotene plays a significant role, with emulsified and nanoencapsulated forms showing improved bioavailability compared to crystalline forms (Kotake-Nara *et al*., 2020). Isomerism also affects bioavailability, with the all-trans form generally being more efficiently absorbed than cis isomers. However, processing methods such as cooking can increase the bioaccessibility of β-carotene by breaking down cell walls and facilitating its release from the food matrix (Aherne *et al*., 2010). Furthermore, advanced delivery systems, including nanoemulsions and lipid-based carriers, have been shown to significantly enhance the bioavailability of β-carotene by improving its solubility and stability (Molteni *et al*., 2022). Overall, the absorption and bioavailability of β-carotene are determined by a complex interplay of chemical, dietary and physiological factors. Understanding these mechanisms is essential for optimizing its nutritional and therapeutic applications.

3. Dietary sources and nutritional aspects of β-carotene

3.1 Major dietary plant sources

β-carotene is predominantly obtained from plant-based foods, particularly fruits and vegetables that exhibit yellow, orange and dark green pigmentation. These colors arise from the accumulation of carotenoids in chromoplasts and chloroplasts, with β-carotene being one of the most abundant and nutritionally significant compounds. Common dietary sources include carrots (*Daucus carota* L.), sweet potatoes (*Ipomoea batatas* L.), pumpkins (*Cucurbita* spp.), mangoes (*Mangifera indica* L.), papaya (*Carica papaya* L.) and apricots (*Prunus armeniaca* L.), as well as leafy vegetables such as spinach (*Spinacia oleracea* L.), kale (*Brassica oleracea* L.) and amaranth greens. These foods are widely recognized for their high provitamin content and antioxidant potential (Khoo *et al*., 2011).

Quantitatively, β-carotene content varies significantly among plant sources. For instance, sweet potatoes and carrots are among the richest sources, containing up to 23,000 µg and 10,000 µg per cup, respectively, whereas leafy vegetables such as spinach and lettuce also provide substantial amounts despite their green coloration. The presence of chlorophyll in green vegetables often masks the orange hue of carotenoids, but these vegetables remain important contributors to dietary β-carotene intake. Regular consumption of a variety of fruits and vegetables is therefore recommended to ensure adequate intake, with five servings per day providing approximately 6-8 mg of β-carotene. In addition to their nutritional value, plant sources of β-carotene are associated with improved health outcomes due to their synergistic composition of vitamins, minerals, fiber and phytochemicals (Table 1). Epidemiological studies have consistently shown that diets rich in carotenoid-containing fruits and vegetables are linked to reduced risks of chronic diseases, including cardiovascular disorders and certain cancers. Importantly, β-carotene from natural food sources is considered safe and beneficial, as its conversion to vitamin A is regulated according to physiological needs (Grune *et al*., 2010).

Table 1: β-carotene content in major fruits and vegetables

Food source	β-carotene (µg/100 g fresh weight)	Vitamin A equivalent (µg RAE)	References
Carrot	8285	690	Khoo *et al*., 2011
Sweet potato (orange flesh)	8500-11500	708-958	Bouis and Saltzman, 2017
Pumpkin	3100	258	Rodriguez, 2016
Spinach	5600	467	Khoo *et al*., 2011
Kale	9200	767	Rodriguez, 2016
Mango	640	53	Khoo *et al*., 2011
Papaya	950	79	Khoo *et al*., 2011
Amaranthus leaves	2900	242	Grune *et al.,* 2010
Moringa leaves	6780	565	Grune *et al*., 2010

3.2 Underutilized and indigenous crops as alternative sources of β-carotene

Beyond commonly consumed fruits and vegetables, numerous underutilized and indigenous crops serve as valuable sources of β-carotene, particularly in developing regions. These crops often possess high nutritional potential but remain underexploited due to limited awareness, commercialization, or agronomic development. Examples include orange-fleshed sweet potato, drumstick leaves (*M. oleifera*), amaranthus species, colocasia leaves and indigenous pumpkin varieties. Orange-fleshed sweet potato has gained global attention as a biofortified crop rich in β-carotene, contributing significantly to vitamin A intake in regions affected by micronutrient deficiencies. Similarly, leafy vegetables such as *M. oleifera* and amaranthus are recognized for their exceptionally high carotenoid content and are often referred to as "nutrient-dense superfoods." These crops are particularly important in rural and tribal communities, where they provide affordable and accessible sources of essential nutrients. Indigenous fruits such as jackfruit (*A. heterophyllus*), bael (*A. marmelos*) and certain wild berries also contain appreciable levels of β-carotene. The promotion and utilization of these crops can play a critical role in improving nutritional security and dietary diversity. Furthermore, these species are often well adapted to local agro-climatic conditions, making them suitable for sustainable agricultural practices. The inclusion of underutilized crops in dietary systems has been emphasized as a strategy to combat hidden hunger and micronutrient deficiencies. Their integration into mainstream agriculture and food systems, along with awareness programs and value addition, can enhance their contribution to β-carotene intake and overall human health.

3.3 Microbial and microalgal sources of β-carotene

β-carotene is not only derived from plant sources but is also synthesized by several microorganisms, including microalgae, fungi, and certain bacteria, which are increasingly recognized as sustainable and efficient sources for industrial and nutritional applications. Among these, the microalga *Dunaliella salina* is one of the most prominent natural producers, capable of accumulating high levels of β-carotene when exposed to environmental stress conditions such as high salinity and intense light. Microalgal β-carotene is particularly valued for its high purity, natural origin, and favorable isomeric composition, consisting of both all-trans and cis forms. This composition contributes to improved bioavailability and enhanced antioxidant activity. Consequently, large-scale commercial production of β-carotene from microalgae has expanded considerably due to its scalability and greater environmental sustainability compared with synthetic production methods. Fungal species, particularly *Blakeslea trispora*, are also widely employed for industrial β-carotene production through fermentation-based processes. Recent advances in biotechnology and metabolic engineering have significantly improved microbial production systems by generating high-yield strains and optimizing fermentation conditions, thereby enhancing production efficiency and reducing manufacturing costs. Microalgal and microbial production platforms offer several advantages, including controlled cultivation conditions, independence from seasonal and geographical constraints, and reduced land and water requirements. These features make them promising alternative sources for the sustainable production of natural β-carotene for applications in the food, pharmaceutical, and cosmetic industries.

3.4 Genetic, processing, and storage factors influencing β-carotene levels

The β-carotene content of foods is influenced by several genetic, environmental, and post-harvest factors. Genotypic variation is one of the primary determinants, as different cultivars of the same plant species may contain markedly different carotenoid concentrations. For example, orange-fleshed varieties of sweet potato possess substantially higher β-carotene levels compared with white- or yellow-fleshed varieties. Maturity stage at harvest also plays an important role in determining β-carotene concentration. In many fruits and vegetables, carotenoid levels increase during ripening due to the transformation of chloroplasts into chromoplasts and the subsequent accumulation of carotenoid pigments. Consequently, ripe fruits such as mango and tomato typically exhibit higher β-carotene content than their unripe counterparts. Processing methods, including cooking, drying, and storage, can significantly influence β-carotene levels. Thermal processing may cause partial degradation and isomerization of β-carotene; however, it can also enhance its bioaccessibility by disrupting plant cell walls and facilitating the release of bound carotenoids. Cooking techniques such as boiling and steaming have been reported to improve the availability of β-carotene despite moderate losses due to heat exposure (Imsic *et al.,* 2010). Storage conditions further affect β-carotene stability. Exposure to light, oxygen, and elevated temperatures can accelerate oxidative degradation, leading to a decline in carotenoid content and nutritional quality. Appropriate handling, processing, and storage practices are therefore essential to preserve β-carotene levels and maintain its nutritional and functional value.

3.5 Dietary intake, recommended levels and safety limits

Unlike many micronutrients, there is no specific Recommended Dietary Allowance (RDA) established exclusively for β-carotene. Instead, dietary recommendations are expressed in terms of vitamin A requirements, measured as retinol activity equivalents (RAE). The RDA for vitamin A is approximately 900 µg RAE/day for adult men and 700 µg RAE/day for adult women, which can be met through a combination of preformed vitamin A and provitamin A carotenoids such as β-carotene (NIH, 2023). Dietary intake of β-carotene varies widely across populations. In many regions, average intake levels range from 1.5 to 3 mg/day, which may be insufficient to meet optimal vitamin A requirements, particularly in populations with limited access to animal-derived foods (Böhm *et al*., 2021). Some studies suggest that an intake of 4-7 mg/day of β-carotene may be beneficial for maintaining adequate antioxidant status and supporting health (Ziegler *et al*., 1996). β-Carotene obtained from natural food sources is generally considered safe, as its conversion to vitamin A is regulated by the body, preventing toxicity (Grune *et al*., 2010). However, excessive intake from supplements has been associated with adverse effects, particularly in high-risk groups such as smokers. Clinical studies have reported an increased risk of lung cancer in smokers consuming high doses (20-30 mg/day) of β-carotene supplements (Molteni *et al*., 2022)

Despite these findings, β-carotene is characterized by low toxicity and high intakes from food sources do not typically result in harmful effects. The most common side effect of excessive intake is hypercarotenemia, a harmless condition characterized by yellow-orange discoloration of the skin (Nutrition and Cancer, 1988). Regulatory bodies have not established a definitive upper intake level for β-carotene from dietary sources, although caution is advised when using supplements (EFSA, 2024). Overall, obtaining β-carotene from a balanced diet rich in fruits and vegetables is considered the safest and most effective approach. Public health recommendations emphasize dietary diversification and increased consumption of carotenoid-rich foods to meet nutritional requirements and promote overall health.

4. Biological functions and mechanisms of action of β-carotene

4.1 Provitamin A activity and retinoid conversion

β-carotene is the most important provitamin A carotenoid, functioning as a major dietary precursor of vitamin A in humans. After ingestion, it is enzymatically cleaved by β-carotene-15,152 -monooxygenase (BCMO1) to yield two molecules of retinal, which can be further converted into retinol or retinoic acid depending on physiological requirements (Harrison, 2012; Tanumihardjo *et al*., 2016). This conversion is tightly regulated, preventing excessive accumulation of vitamin A and ensuring metabolic balance. Recent studies highlight that β-carotene-derived retinoids are essential regulators of cellular differentiation, immune modulation and embryonic development through activation of nuclear receptors such as retinoic acid receptors (RARs) and retinoid X receptors (RXRs) (Shanaida *et al*., 2025). These findings reinforce the critical role of β-carotene in maintaining physiological homeostasis beyond its nutritional function.

4.2 Role in vision and epithelial health

β-carotene contributes significantly to visual function through its conversion into retinal, a key component of rhodopsin in the retina. Rhodopsin is essential for phototransduction, particularly under low-light conditions and deficiency of vitamin A leads to night blindness and other visual impairments (Sommer and Vyas, 2012). In addition to vision, β-carotene plays a crucial role in maintaining epithelial integrity. Retinoids derived from β-carotene regulate epithelial cell differentiation and mucosal barrier function, which are essential for protecting against pathogens and maintaining immune defense (Stephensen, 2001). Emerging evidence also indicates that carotenoids, including β-carotene, accumulate in ocular tissues such as the macula, where they exert photoprotective effects by reducing oxidative stress and helping to prevent degenerative eye disorders, including age-related macular degeneration (Shanaida *et al*., 2025).

4.3 Antioxidant activity and singlet oxygen quenching

One of the principal biological functions of β-carotene is its antioxidant activity, primarily mediated through singlet oxygen quenching and neutralization of reactive oxygen species (Figure 2). Its polyene chain of conjugated double bonds enables efficient absorption of excess energy from singlet oxygen and dissipation as heat, thereby protecting lipids, proteins, and DNA from oxidative damage (Krinsky and Johnson, 2005). Recent studies indicate that β-carotene contributes to the prevention of oxidative stress-related disorders, including cardiovascular diseases, cancer, metabolic disorders, and neurodegenerative conditions (Bufka *et al.,* 2024). It also exhibits neuroprotective effects by scavenging free radicals and reducing oxidative damage in neuronal tissues (Lubis *et al.,* 2025). However, its antioxidant activity is context-dependent; under conditions of high oxygen tension or excessive intake, β-carotene may exert pro-oxidant effects, highlighting the importance of balanced dietary consumption (Fiedor and Burda, 2014).

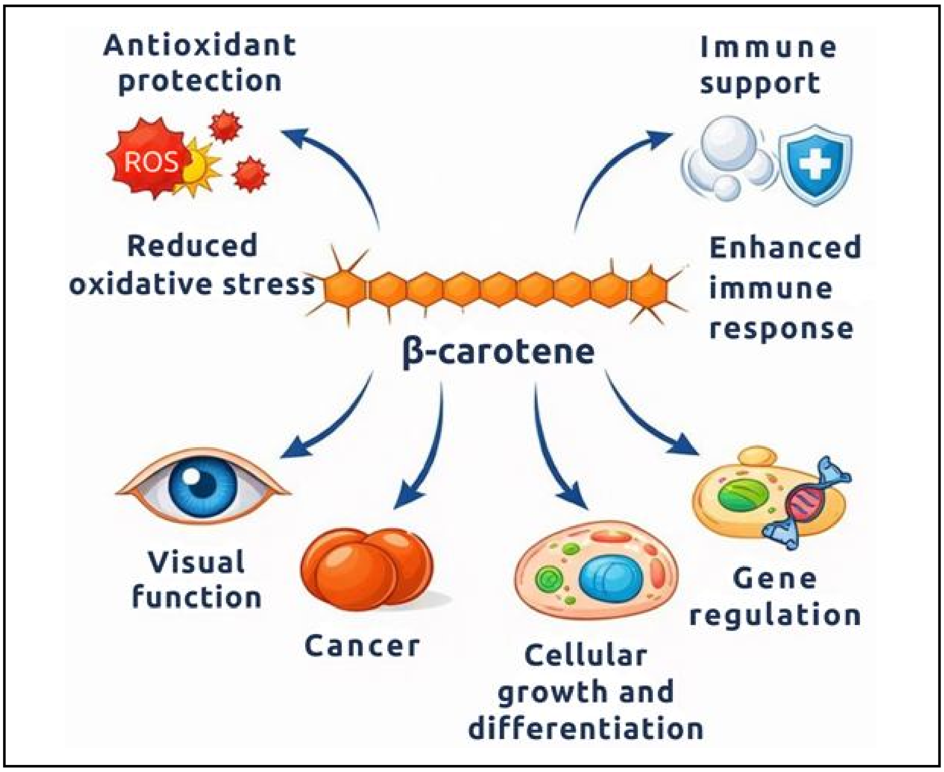

Figure 2: Major biological functions of β-carotene, including antioxidant activity, immune enhancement, visual function and regulation of cellular growth and differentiation.

4.4 Interaction with other antioxidants and micronutrients

β-carotene functions within a complex antioxidant network, interacting synergistically with micronutrients such as vitamin C, vitamin E, and polyphenols to enhance cellular antioxidant defense and maintain redox balance. In biological membranes, β-carotene cooperates with vitamin E to inhibit lipid peroxidation, while vitamin C regenerates oxidized vitamin E, thereby sustaining antioxidant activity (Stahl and Sies, 2012). Emerging evidence further indicates that carotenoids collectively contribute to immune regulation and lymphocyte differentiation, emphasizing their complementary biological roles (Roy *et al*., 2023). These synergistic interactions highlight the importance of obtaining β-carotene from a balanced diet rich in diverse nutrients rather than from isolated supplementation.

4.5 Cellular uptake, transport, and intracellular distribution

The absorption and cellular uptake of β-carotene involve both passive diffusion and protein-mediated transport. After digestion, β-carotene is incorporated into mixed micelles and absorbed by intestinal enterocytes via transporters such as scavenger receptor class B type I (SR-BI) and CD36 (Reboul, 2013). Once absorbed, β-carotene is either cleaved into retinoids or transported intact via chylomicrons into circulation and subsequently distributed to tissues such as the liver, adipose tissue and skin. Within cells, β-carotene is predominantly localized in lipid-rich compartments, including cell membranes and lipid droplets, where it contributes to antioxidant defense. Recent research suggests that the intracellular distribution of carotenoids is closely linked to their functional roles, including photoprotection, membrane stabilization and regulation of oxidative stress pathways (Bufka *et al*., 2024).

4.6 Gene regulation and cellular signaling pathways

β-carotene and its metabolites play a significant role in gene regulation and cellular signaling pathways. Retinoic acid, derived from β-carotene, regulates gene expression by binding to nuclear receptors (RARs and RXRs), which control genes involved in cell proliferation, differentiation and apoptosis (Clagett-Dame and DeLuca, 2002). Recent studies indicate that β-carotene also exerts regulatory effects independent of its conversion to vitamin A. It can modulate oxidative stress-responsive signaling pathways, influence inflammatory responses and regulate intercellular communication (Tanumihardjo *et al*., 2016). Additionally, carotenoid-derived metabolites have been shown to participate in gene regulation through interactions with nuclear receptors and transcription factors, contributing to disease prevention and cellular homeostasis (Ahmed *et al*., 2024). Emerging evidence further suggests that β-carotene may play a role in epigenetic modulation and immune signaling, highlighting its potential in precision nutrition and therapeutic applications. These multifaceted regulatory functions reinforce its classification as a multifunctional bioactive compound.

5. Pharmacological and health-promoting effects of β-carotene

β-carotene is a potent bioactive compound with diverse pharmacological and health-promoting effects. As a provitamin A carotenoid, it supports vision, immune function, and epithelial integrity. Its strong antioxidant activity enables scavenging of reactive oxygen species, thereby reducing oxidative stress and inflammation. β-carotene contributes to cardiovascular protection by preventing lipid peroxidation and improving endothelial function. It also exhibits anticancer potential by modulating cell proliferation and inducing apoptosis. Additionally, it enhances skin health and photoprotection against UV damage and supports cognitive and metabolic functions. Overall, β-carotene plays a crucial role in disease prevention and maintenance of overall physiological health (Figure 3).

5.1 Antioxidant and anti-inflammatory effects

β-carotene is widely recognized for its potent antioxidant and anti-inflammatory properties, which contribute significantly to its health-promoting effects. Its polyene structure, characterized by conjugated double bonds, enables efficient scavenging of reactive oxygen species and quenching of singlet oxygen, thereby protecting cellular components such as lipids, proteins, and DNA from oxidative damage. Oxidative stress is a major contributing factor in the pathogenesis of several chronic diseases, including cardiovascular disorders, diabetes, and cancer. Recent studies have demonstrated that β-carotene alleviates oxidative stress by enhancing endogenous antioxidant defense mechanisms and modulating inflammatory mediators such as tumor necrosis factor-α (TNF-α) and various interleukins (Anand *et al.,* 2022; Tufail *et al.,* 2024). Furthermore, β-carotene has been shown to suppress pro-inflammatory signaling pathways and reduce lipid peroxidation, thereby contributing to the prevention of chronic inflammatory conditions (Islam *et al.,* 2024). Collectively, these antioxidant and anti-inflammatory effects help maintain cellular homeostasis and reduce the risk of oxidative stress-associated diseases.

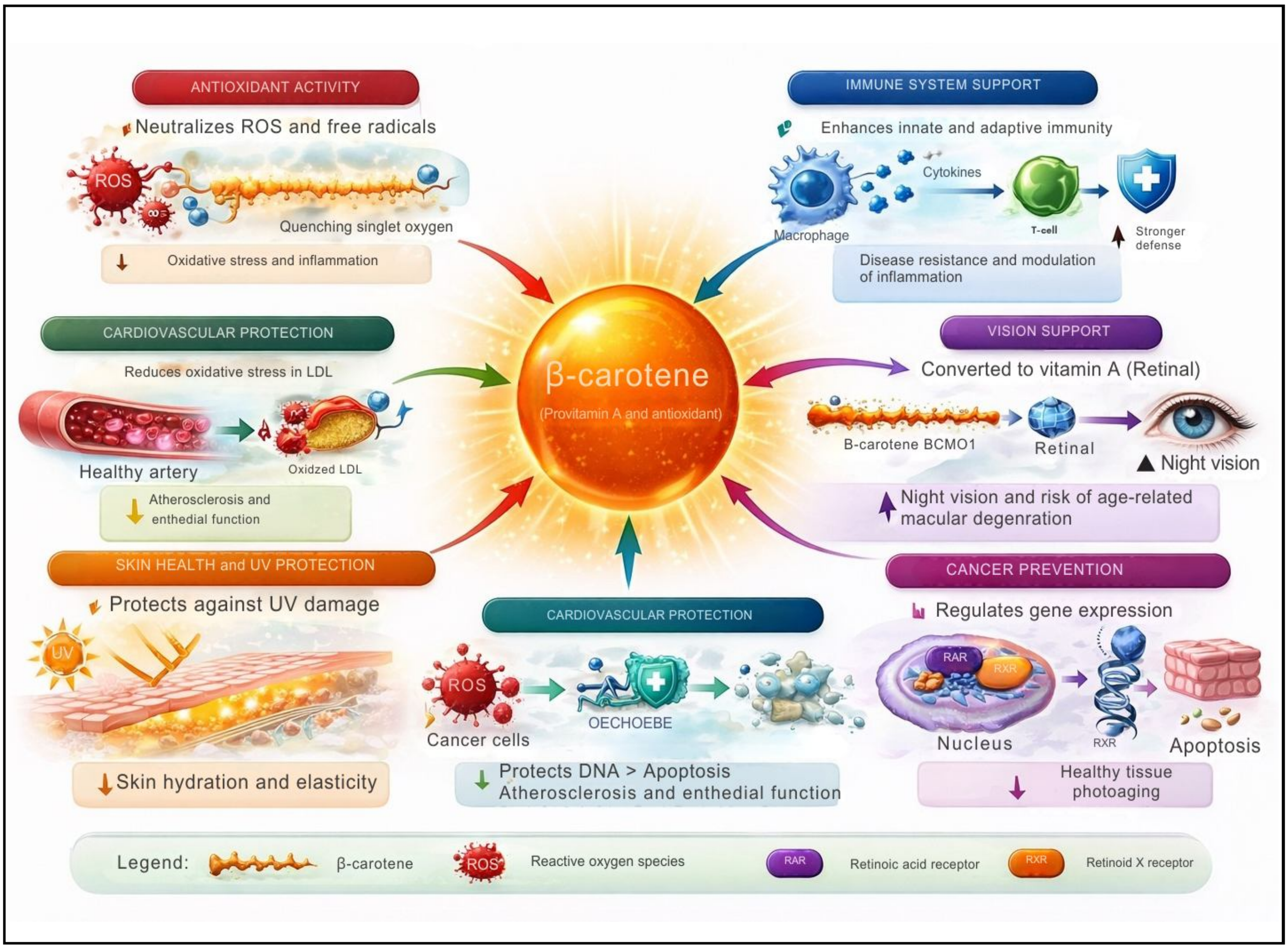

Figure 3: Schematic representation of the pharmacological and health-promoting effects of β-carotene.

5.2 Cardioprotective effects

β-carotene plays a significant role in cardiovascular health owing to its antioxidant and antiatherogenic properties. By mitigating oxidative stress, it inhibits the oxidation of low-density lipoproteins (LDL), a key initiating event in the pathogenesis of atherosclerosis. In addition, β-carotene contributes to the maintenance of endothelial function and attenuates vascular inflammation, thereby reducing the risk of cardiovascular diseases. Recent studies suggest that β-carotene, together with other carotenoids, exerts synergistic cardioprotective effects by improving lipid profiles, reducing inflammatory mediators, and inhibiting atherosclerotic plaque formation (Bas *et al.,* 2024). Epidemiological evidence further indicates that diets rich in β-carotene-containing fruits and vegetables are associated with a decreased incidence of coronary heart disease and improved overall cardiovascular outcomes (Tufail *et al.,* 2024). Moreover, β-carotene interacts with other antioxidant micronutrients, enhancing the overall antioxidant defense system and protecting vascular tissues from oxidative damage. Collectively, these findings underscore the importance of β-carotene as a cardioprotective component of a balanced diet.

5.3 Antidiabetic and metabolic health benefits

β-carotene has been increasingly studied for its role in metabolic health and diabetes management. Its antioxidant activity helps reduce oxidative stress, which is a major contributor to insulin resistance and pancreatic β-cell dysfunction. By mitigating oxidative damage, β-carotene supports insulin sensitivity and glucose metabolism. Recent research suggests that carotenoids, including β-carotene, are associated with improved metabolic profiles, including reduced blood glucose levels, improved lipid metabolism and decreased inflammation in individuals with metabolic disorders (Tufail *et al*., 2024). Additionally, β-carotene has been shown to modulate adipocyte function and reduce markers of metabolic syndrome such as obesity, dyslipidemia and hypertension (Wal *et al*., 2023). Furthermore, β-carotene may influence gene expression related to glucose metabolism and insulin signaling pathways, contributing to its antidiabetic effects. These findings suggest that regular consumption of β-carotene-rich foods can play a supportive role in preventing and managing metabolic disorders.

5.4 Anticancer and chemopreventive effects of β-carotene

β-carotene exhibits significant anticancer and chemopreventive properties, primarily through its antioxidant, anti-inflammatory and immune-modulating effects. It helps prevent DNA damage caused by oxidative stress, thereby reducing the risk of mutations and cancer development.Recent studies indicate that β-carotene can inhibit tumor progression by modulating cell proliferation, inducing apoptosis and enhancing immune responses (Anand *et al*., 2022). Additionally, β-carotene has been shown to regulate signaling pathways involved in cancer development, including pathways related to oxidative stress and inflammation (He *et al*., 2024). Epidemiological evidence suggests that diets rich in β-carotene-containing fruits and vegetables are associated with a reduced risk of various cancers, including lung, breast and colorectal cancers. However, it is important to note that while dietary β-carotene is beneficial, high-dose supplementation has shown inconsistent results and may increase cancer risk in certain populations, such as smokers. Overall, β-carotene contributes to cancer prevention through multiple mechanisms, including antioxidant protection, immune enhancement and regulation of cell signaling pathways.

5.5 Neuroprotective effects

β-carotene also plays a crucial role in neuroprotection and brain health, primarily through its antioxidant and anti-inflammatory actions. The brain is highly susceptible to oxidative stress due to its high oxygen consumption and lipid content, making antioxidants like β-carotene essential for neuronal protection. Recent studies have highlighted the role of β-carotene in preventing neurodegenerative diseases such as Alzheimer's and Parkinson's disease by reducing oxidative damage, inhibiting neuroinflammation and protecting neuronal cells (Lubis *et al*., 2025). Additionally, carotenoids have been shown to improve cognitive function and memory by enhancing neuronal signaling and reducing oxidative stress in brain tissues (Islam *et al*., 2024). β-carotene may also influence neurogenesis and synaptic plasticity through its role in gene regulation and signaling pathways. Its ability to cross the blood-brain barrier and accumulate in neural tissues further supports its neuroprotective potential. These findings suggest that β-carotene could play a significant role in maintaining cognitive health and preventing age-related neurological disorders.

5.6 Role of β-carotene in ocular health and visual function

β-carotene plays a crucial role in maintaining ocular health and preventing visual disorders, primarily through its function as a precursor of vitamin A and its antioxidant properties. Vitamin A derived from β-carotene is essential for the synthesis of rhodopsin, a visual pigment necessary for phototransduction in the retina. Deficiency of this pathway leads to night blindness and, in severe cases, xerophthalmia and irreversible blindness. Beyond its provitamin A role, β-carotene contributes to ocular protection by mitigating oxidative stress, a key factor in the pathogenesis of eye diseases such as cataracts, age-related macular degeneration (AMD) and diabetic retinopathy. Oxidative damage to retinal cells and lens proteins can lead to structural and functional deterioration, which is counteracted by carotenoids through free radical scavenging and light-filtering effects (Johra *et al*., 2020; Kumar *et al*., 2024).

Recent studies also suggest that carotenoids, including β-carotene, contribute to macular health by reducing phototoxic damage and improving visual performance. Although, lutein and zeaxanthin are more concentrated in the macula, β-carotene complements their action by supporting systemic vitamin A levels and enhancing overall antioxidant defense in ocular tissues. Regular intake of β-carotene-rich foods is therefore associated with reduced risk of degenerative eye diseases and improved visual function.

5.7 Immunomodulatory effects

β-carotene exerts significant immunomodulatory effects, enhancing both innate and adaptive immune responses. Its role is closely linked to its conversion into retinoic acid, which regulates immune cell differentiation and function. Retinoic acid influences the development of T cells, B cells and antigen-presenting cells, thereby playing a central role in immune homeostasis. Recent evidence indicates that β-carotene supplementation improves immune function by enhancing lymphocyte proliferation, increasing natural killer (NK) cell activity and modulating cytokine production (Medina-García *et al*., 2025). Additionally, β-carotene has been shown to stimulate immunoglobulin synthesis and improve macrophage function, thereby strengthening the body's defense against infections (Zhuang *et al*., 2022; Shanaida *et al*., 2025).

Furthermore, β-carotene supports the integrity of epithelial barriers, which act as the first line of defense against pathogens. By maintaining mucosal health and reducing oxidative stress, it enhances resistance to infections and contributes to overall immune resilience. These findings highlight the importance of β-carotene in preventing infectious diseases and supporting immune function, particularly in populations with compromised nutritional status.

5.8 Skin health and photoprotective effects

β-carotene plays an important role in skin health and photoprotection, primarily through its antioxidant and anti-inflammatory properties. The skin is continuously exposed to environmental stressors such as ultraviolet (UV) radiation, pollution and oxidative stress, which contribute to premature aging, inflammation and carcinogenesis. Carotenoids, including β-carotene, accumulate in the skin and act as endogenous photoprotective agents by neutralizing reactive oxygen species generated by UV exposure. Clinical and experimental studies have demonstrated that β-carotene reduces UV-induced erythema (sunburn) and protects against photooxidative damage (Singh *et al*., 2024).

Recent systematic reviews further indicate that carotenoids improve skin hydration, elasticity and collagen synthesis while reducing inflammation and oxidative damage (Stanescu *et al*., 2025). They also modulate matrix metalloproteinases and support dermal matrix integrity, thereby slowing the process of skin aging.In addition, β-carotene contributes to skin pigmentation and provides a natural protective coloration that may enhance resistance to UV radiation. However, it is important to note that dietary β-carotene offers moderate photoprotection and should complement, rather than replace, conventional sun protection measures such as sunscreen.

6. Pharmaceutical applications of β-carotene

6.1 Role in nutraceuticals and dietary supplements

β-carotene is widely utilized in nutraceutical and dietary supplement formulations due to its dual function as a provitamin A precursor and a potent antioxidant. It is frequently incorporated into multivitamin preparations, functional foods and dietary supplements aimed at improving nutritional status, preventing micronutrient deficiencies and supporting immune and metabolic health. As a naturally occurring bioactive compound, β-carotene contributes to enhanced antioxidant defense by scavenging reactive oxygen species and mitigating oxidative stress. Recent studies indicate that carotenoids, including β-carotene, are increasingly employed as functional ingredients in nutraceutical formulations owing to their antioxidant, anti-inflammatory and immunomodulatory properties (Shanaida *et al.,* 2025). In addition, β-carotene is considered an important component of preventive healthcare strategies, where it supports cardiovascular health, metabolic balance and immune function (Tufail *et al.,* 2024).

6.2 Role in the prevention and management of vitamin A deficiency

β-carotene plays a critical role in preventing and managing vitamin A deficiency (VAD), particularly in developing regions where access to animal-derived vitamin A sources is limited. As a provitamin A carotenoid, β-carotene is enzymatically converted into retinol in the body, thereby supporting essential physiological functions including vision, immune competence and epithelial tissue integrity. Vitamin A deficiency remains a major global public health concern, especially among children and pregnant women in low- and middle-income countries. Strategies such as dietary diversification, supplementation and food fortification with β-carotene–rich sources have been widely implemented to address this issue (Reboul, 2013). Supplementation with β-carotene has been shown to improve vitamin A status and reduce the incidence of deficiency-related conditions such as night blindness and increased susceptibility to infections. Recent research highlights the importance of biofortification and food fortification strategies as sustainable approaches for combating VAD (Kumar *et al.,* 2024). Biofortified crops such as orange-fleshed sweet potato and golden rice have been developed to enhance dietary β-carotene intake in vulnerable populations. Importantly, β-carotene is considered safer than preformed vitamin A in supplementation programs because its conversion to retinol is physiologically regulated, thereby minimizing the risk of hypervitaminosis A.

6.3 Antioxidant role in pharmaceutical formulations

β-carotene is widely used in pharmaceutical formulations due to its strong antioxidant properties, which help protect active pharmaceutical ingredients (APIs) and biological systems from oxidative degradation. Its ability to scavenge free radicals and quench singlet oxygen makes it an effective stabilizing agent in formulations prone to oxidative stress. Recent studies indicate that carotenoids, including β-carotene, are increasingly incorporated into pharmaceutical and cosmeceutical formulations to enhance product stability and therapeutic efficacy (Shanaida *et al*., 2025). In addition to acting as an antioxidant excipient, β-carotene contributes to the therapeutic value of formulations by providing additional health benefits, such as anti-inflammatory and photoprotective effects. In advanced pharmaceutical systems, β-carotene is being delivered using novel drug delivery technologies, including liposomes, nanoemulsions and polymeric nanoparticles. These systems improve its solubility, stability and bioavailability, overcoming limitations associated with its hydrophobic nature. Encapsulation techniques also protect β-carotene from degradation caused by light, heat and oxygen, thereby enhancing its shelf-life and efficacy.

Moreover, β-carotene is used in dermatological and ophthalmic formulations for its protective effects against oxidative stress and environmental damage. Its incorporation into topical and oral formulations supports skin health, reduces inflammation and protects against UV-induced damage. Overall, the incorporation of β-carotene into pharmaceutical formulations reflects its multifunctional role as both a bioactive compound and a stabilizing agent, making it highly valuable in modern drug development and formulation science.

6.4 Drug delivery and formulation challenges

Despite its significant therapeutic potential, the application of β-carotene in pharmaceutical formulations is limited by several drug delivery and formulation challenges. One of the primary limitations is its poor aqueous solubility, resulting from its highly lipophilic hydrocarbon structure. This characteristic restricts its dispersion in aqueous biological environments and consequently reduces its absorption and bioavailability (McClements and Xiao, 2023). β-carotene also exhibits chemical instability, as its extensive conjugated double-bond system is highly susceptible to degradation in the presence of light, oxygen, heat and acidic conditions. Oxidative degradation may lead to the formation of epoxides and cleavage products, thereby diminishing its biological activity (Saini *et al.,* 2022). Furthermore, β-carotene demonstrates low and variable oral bioavailability, primarily due to inefficient release from the formulation matrix, limited incorporation into mixed micelles during digestion and variability in intestinal absorption. Factors such as dietary fat intake, gastrointestinal conditions and inter-individual metabolic differences further influence its absorption. From a formulation perspective, maintaining uniform dispersion and preventing crystallization or aggregation remain major challenges. These issues can reduce bioaccessibility and complicate formulation design. Consequently, innovative delivery systems are required to improve solubility, enhance stability and enable controlled or targeted delivery (Singh *et al.,* 2024; Liu *et al.,* 2023).

6.5 Nano- and micro-encapsulation strategies for β-carotene delivery

Nano- and micro-encapsulation technologies have emerged as effective strategies to overcome the physicochemical limitations of β-carotene. Encapsulation involves incorporating β-carotene within protective matrices or carrier systems that shield it from environmental degradation while enhancing its stability and bioavailability. Nanoencapsulation systems such as nanoemulsions, liposomes, solid lipid nanoparticles (SLNs) and polymeric nanoparticles have attracted considerable interest. These systems increase surface area, improve solubility, protect against oxidative degradation and enable controlled release. For instance, nanoemulsion-based delivery systems facilitate the dispersion of β-carotene in aqueous environments and improve gastrointestinal absorption (Gul *et al.,* 2023). Liposomes and other lipid-based carriers mimic biological membranes, allowing efficient encapsulation and targeted delivery. Similarly, solid lipid nanoparticles and nanostructured lipid carriers enhance molecular stability and protect β-carotene from oxidation (Saini *et al.,* 2022).

Microencapsulation techniques such as spray drying, coacervation and inclusion complex formation are widely used for stabilizing β-carotene in food and nutraceutical systems. These approaches utilize biopolymers such as proteins, polysaccharides and gums to form protective microcapsules that improve shelf-life and enable controlled release. Recent advances focus on biodegradable and biocompatible materials such as chitosan, alginate and whey proteins to develop safe and sustainable delivery systems (Zhang *et al.,* 2024).

6.6 Strategies for enhancing the bioavailability of β-carotene

Enhancing the bioavailability of β-carotene is essential for maximizing its nutritional and therapeutic efficacy. Due to its hydrophobic nature and susceptibility to degradation, multiple strategies have been developed to improve its absorption and utilization in the body. Lipid-based delivery systems represent one of the most effective approaches for enhancing β-carotene absorption. These systems promote solubilization and facilitate incorporation into mixed micelles during digestion, which enhances intestinal uptake. The presence of dietary fats significantly improves β-carotene absorption, highlighting the importance of co-ingestion with lipid-containing foods (Reboul, 2023). Nanoformulations such as nanoemulsions and lipid nanoparticles further improve bioavailability by enhancing solubility, protecting β-carotene from degradation and promoting efficient intestinal transport (Gul *et al.,* 2023). Emulsion-based systems and carriers derived from proteins or polysaccharides also improve dispersion in aqueous environments and enable controlled release.

Food processing techniques, including thermal treatment and mechanical homogenization, can increase bioaccessibility by disrupting plant cell matrices and releasing bound β-carotene. However, these processes must be carefully optimized to prevent oxidative degradation. In addition, biofortification and metabolic engineering approaches are being explored to enhance the intrinsic content and bioaccessible forms of β-carotene in food crops, thereby providing sustainable strategies to improve dietary intake and nutritional outcomes (Zhang *et al.,* 2024). Collectively, advanced delivery technologies, optimized processing methods and dietary strategies play a crucial role in improving the bioavailability and therapeutic potential of β-carotene.

7. Industrial applications of β-carotene

7.1 β-carotene as a natural colorant in the food industry

β-carotene is extensively used as a natural food colorant (E160a) owing to its intense yellow to orange-red pigmentation and well-established safety profile. It is widely incorporated into a variety of food products, including dairy products (milk, cheese and butter), beverages, confectionery, bakery products, margarine and other processed foods, primarily to enhance visual appeal and consumer acceptability. Its application is particularly prominent in clean-label formulations, where natural additives are increasingly preferred over synthetic colorants. Recent studies suggest that, in addition to improving the sensory attributes of food products, β-carotene can contribute nutritional value due to its antioxidant properties (Rifqi *et al.,* 2023). Furthermore, β-carotene has been approved as a safe color additive by major regulatory authorities, including the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), supporting its extensive utilization in the food industry.

7.2 β-carotene in functional food and nutraceutical formulations

β-carotene is a key ingredient in the development of functional foods and beverages, where it serves both nutritional and functional roles. It is commonly added to juices, fortified drinks, cereals and dairy products to enhance their provitamin A content and antioxidant capacity. The incorporation of β-carotene into functional foods aligns with the growing consumer demand for health-promoting products. It contributes to immune support, vision health and overall well-being, making it a valuable component in nutraceutical-based food formulations. Additionally, β-carotene enhances the aesthetic appeal of functional foods by imparting natural coloration. Recent advancements include the use of carotenoid-enriched packaging systems and delivery matrices, which improve stability and extend shelf life of functional foods (Roy *et al*., 2023). Furthermore, nanoemulsion-based delivery systems are being explored to enhance the dispersion and bioavailability of β-carotene in beverage formulations.

7.3 Cosmetic and personal care applications

β-carotene has significant applications in the cosmetic and personal care industry, where it is used for its antioxidant, anti-aging and photoprotective properties. It is incorporated into skincare products such as creams, lotions, serums and sunscreens to protect the skin from oxidative stress and ultraviolet (UV) radiation. Due to its strong antioxidant activity, β-carotene helps reduce lipid peroxidation and prevents premature skin aging. It also contributes to skin hydration, elasticity and overall appearance. Additionally, β-carotene is used as a natural pigment in cosmetic formulations, providing a desirable color to products such as lipsticks, blushes and creams. Recent studies highlight that β-carotene is widely utilized in cosmetic formulations to prevent oxidative damage and UV-induced skin disorders, including skin cancer (Tufail *et al*., 2024). The increasing consumer preference for natural and plant-based cosmetic ingredients has further driven the demand for β-carotene in this sector.

7.4 Animal feed and aquaculture applications of β-carotene

β-carotene is extensively used in animal feed and aquaculture as a natural pigment and nutritional supplement. It enhances the coloration of animal products such as egg yolks, poultry skin and fish flesh, thereby improving their market value and consumer appeal.In aquaculture, carotenoids are particularly important for imparting characteristic coloration to species such as salmon and shrimp. Additionally, β-carotene improves reproductive performance, immune function and growth rates in animals.It also serves as a provitamin A source in animal nutrition, supporting physiological functions such as vision, immunity and reproduction. The use of β-carotene in feed formulations has increased significantly due to its dual role as a pigment and a nutritional supplement (Singh *et al*., 2024)

7.5 Agricultural and biotechnological applications

β-carotene plays an important role in agricultural and biotechnological applications, particularly in the development of biofortified crops and sustainable production systems. Biofortification strategies aim to enhance the β-carotene content of staple crops such as rice, maize and sweet potato to address vitamin A deficiency. Genetic engineering and metabolic engineering approaches have been employed to develop crops with enhanced carotenoid biosynthesis, such as “golden rice,” which is enriched with β-carotene. These innovations have significant implications for improving nutritional security in developing regions.In addition, microbial and algal production systems are being explored for large-scale, sustainable production of β-carotene. Microalgae such as *Dunaliella salina* are widely used for commercial production due to their high yield and ability to accumulate β-carotene under stress conditions (Singh *et al*., 2022). Biotechnological advancements are also enabling the development of eco-friendly extraction and production methods, reducing reliance on synthetic processes and enhancing sustainability.

7.6 Natural versus synthetic β-carotene

β-carotene used in industrial applications is available in both natural and synthetic forms, each with distinct advantages and limitations. Natural β-carotene is derived from plant sources, algae, or microorganisms, while synthetic β-carotene is produced through chemical synthesis.Natural β-carotene is generally preferred due to its higher bioactivity, presence of mixed isomers and consumer perception as a safer and more sustainable option. It is widely used in clean-label and organic products. However, its production is often more expensive and subject to variability in yield and quality.In contrast, synthetic β-carotene offers advantages such as cost-effectiveness, high purity and consistent quality, making it suitable for large-scale industrial applications. It is widely used in processed foods, dietary supplements and pharmaceuticals. Despite these advantages, there is increasing consumer preference for natural ingredients, which is driving the demand for naturally sourced β-carotene. Regulatory and labeling requirements also influence the choice between natural and synthetic forms.

8. Future perspectives and emerging trends in β-carotene research

8.1 Sustainable and biotechnological production of β-carotene

The increasing demand for β-carotene across food, pharmaceutical and cosmetic industries has intensified the need for sustainable and scalable production methods. Traditional extraction from plant sources is often limited by seasonal variability, low yields and high production costs. Consequently, biotechnological approaches, particularly microbial and algal production systems, have gained significant attention as sustainable alternatives. Microalgae such as *Dunaliella salina* are among the most efficient natural producers of β-carotene, capable of accumulating high concentrations under stress conditions such as high salinity and intense light. These systems offer advantages including rapid growth rates, minimal land requirements and reduced environmental impact (Karthikeyan *et al*., 2023). Similarly, fungal systems such as *Blakeslea trispora* are widely used in industrial fermentation for β-carotene production due to their high yield and scalability.

Recent advances in metabolic engineering and synthetic biology have further enhanced β-carotene production in microorganisms such as *Escherichia coli* and yeast. By optimizing biosynthetic pathways and regulating gene expression, researchers have achieved significantly increased production efficiencies (Liu *et al*., 2024). Additionally, CRISPR-based genome editing technologies are being employed to develop high-yield strains with improved stability and productivity. Sustainable production is also being supported by the use of renewable substrates and waste valorization strategies, where agro-industrial by-products are utilized as feedstocks for microbial cultivation. These approaches contribute to circular bioeconomy models and reduce production costs and environmental footprint. Overall, biotechnological innovations are expected to play a pivotal role in meeting the growing global demand for β-carotene.

8.2 β-carotene in functional foods and precision nutrition

β-carotene is increasingly recognized as a key component in the development of functional foods and precision nutrition strategies. Functional foods enriched with β-carotene provide health benefits beyond basic nutrition, including antioxidant protection, immune support and prevention of chronic diseases. Recent research emphasizes the integration of β-carotene into personalized nutrition approaches, where dietary interventions are tailored based on individual genetic, metabolic and lifestyle factors. Variations in genes involved in carotenoid metabolism, such as BCMO1, influence the efficiency of β-carotene conversion to vitamin A, highlighting the importance of individualized dietary recommendations (Borel *et al*., 2023). The incorporation of β-carotene into fortified foods, biofortified crops and nutraceutical products is a promising strategy for addressing micronutrient deficiencies and improving public health outcomes. Biofortified crops such as orange-fleshed sweet potato and golden rice have demonstrated significant potential in enhancing β-carotene intake in vulnerable populations. Moreover, the use of smart food systems, including functional beverages and fortified staples, is expanding the application of β-carotene in modern diets. These innovations are aligned with global trends toward preventive healthcare and nutrition-based disease management.

8.3 Nanotechnology-based delivery systems for β-carotene

The integration of β-carotene with nanotechnology and advanced delivery systems represents a major advancement in enhancing its stability, bioavailability and therapeutic efficacy. Due to its hydrophobic nature and susceptibility to degradation, conventional formulations often fail to deliver optimal results. Nanotechnology offers innovative solutions to overcome these limitations. Recent developments include the use of nanoemulsions, liposomes, solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) for β-carotene delivery. These systems improve solubility, protect β-carotene from environmental degradation and facilitate controlled release (McClements, 2023). Nanoencapsulation also enhances intestinal absorption and bioavailability, making β-carotene more effective in functional foods and pharmaceutical applications. Advanced delivery systems are also being explored for targeted delivery, where β-carotene can be directed to specific tissues or cells to enhance therapeutic outcomes. For example, nanocarriers can be designed to deliver β-carotene to the skin for photoprotection or to the brain for neuroprotection.

8.4 Research gaps and future directions in β-carotene studies

Despite extensive research on β-carotene, several knowledge gaps and challenges remain, offering significant opportunities for future investigation. One of the major limitations is the variability in its bioavailability and metabolic conversion to vitamin A, which is influenced by genetic, dietary and physiological factors. A deeper understanding of these variations is necessary to develop strategies that optimize β-carotene absorption, metabolism and utilization. Another critical area of research involves evaluating the long-term safety and efficacy of β-carotene supplementation, particularly in high-risk populations such as smokers and individuals with chronic diseases. Although dietary intake of β-carotene from natural food sources is generally considered safe, high-dose supplementation has shown inconsistent and, in some cases, adverse outcomes, highlighting the need for well-designed clinical studies.

The interactions between β-carotene and other nutrients or bioactive compounds also require further investigation. Elucidating these interactions may improve dietary recommendations and enhance the effectiveness of functional foods and nutraceutical formulations. Moreover, additional research is needed to clarify the molecular mechanisms underlying the biological actions of β-carotene, including its involvement in gene regulation, epigenetic modulation and cellular signaling pathways. Advances in omics technologies, such as genomics, proteomics and metabolomics, are expected to provide deeper insights into these mechanisms.

Future studies should also emphasize the development of sustainable and cost-effective production methods, including biotechnological approaches and green extraction technologies. In parallel, strengthening regulatory frameworks and standardization of β-carotene products will be essential to ensure their quality, safety and efficacy. Overall, interdisciplinary research integrating nutrition, biotechnology, nanotechnology and clinical sciences will be crucial for fully realizing the potential of β-carotene as a multifunctional bioactive compound with applications in health, food and pharmaceutical industries.

9. Conclusion

β-carotene is a highly valuable and multifunctional bioactive compound with diverse applications in nutrition, health, pharmaceuticals and industrial sectors. As the most efficient provitamin A carotenoid, it plays a critical role in maintaining vision, immune function, epithelial integrity and overall physiological homeostasis. In addition to its role as a precursor of vitamin A, β-carotene exhibits significant antioxidant and anti-inflammatory activities, which contribute to the prevention and management of chronic diseases, including cardiovascular disorders, diabetes, cancer and neurodegenerative conditions. The widespread occurrence of β-carotene in plant-based foods makes it an important dietary component for addressing global micronutrient deficiencies, particularly vitamin A deficiency in populations that rely heavily on plant-derived diets. Nevertheless, several limitations, including poor aqueous solubility, susceptibility to degradation and variable bioavailability, restrict its optimal utilization in pharmaceutical and functional food applications.

Recent technological advancements, such as nanoencapsulation, advanced delivery systems and biotechnological production approaches, have significantly improved the stability, bioavailability and delivery efficiency of β-carotene. Furthermore, the increasing demand for natural, sustainable and clean-label ingredients has enhanced its relevance in the food, nutraceutical and pharmaceutical industries. Future research should focus on improving bioavailability, elucidating individual metabolic variability and conducting well-designed long-term clinical studies to validate its therapeutic potential. Overall, β-carotene represents a promising functional bioactive compound with substantial potential for promoting human health and supporting sustainable industrial innovations.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article

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