CHAPTER 11

Carotenoids: Natural Pigments with Health Benefits

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ABSTRACT: Carotenoids are a type of naturally occurring pigments which are synthesized by plants, algae and photosynthetic microorganisms. They are responsible for vibrant colors of fruits and vegetables. Carotenoids such as β-carotene, lutein, lycopene and zeaxanthin are not only significant to plant physiology but also attribute many health benefits to human beings. Humans body cannot synthesize carotenoids, so they are taken through diet. Carotenoids have drawn considerable interest from scientists due to their health promoting activities. They serve as potent antioxidants as they neutralize the free radicals and shield cells against oxidative damage. These biological abilities of carotenoids are associated with decreased chances of long-term aliments including heart problems and eye diseases. Moreover, carotenoids help to boost the immune system and maintain healthy eyes by inhibiting the damaging blue light, as well as protecting the retinal structure. Therefore, this chapter holds the intention to summarize the existing state of knowledge about carotenoids, their types, their food sources, and their effect on health.

Carotenoids are the most prevalent natural substances that are lipophilic pigments, responsible for the vibrant hues in a range of foods (Riaz et al., 2021). These are isoprenoid compounds that naturally produce characteristic yellow, red and orange coloration in flowers, fruits, vegetables and leaves along with particular fragrances in plants (Langi et al., 2018). Carotenoids are largely produced by photoautotrophs, but certain heterotrophs can also synthesize them, including fungi and prokaryotes (Rodriguez-Concepcion et al., 2018). Except a few aphid species, there are variety of other organisms, including human that cannot synthesize carotenoids, so they take them in through their diet (Eggersdorfer & Wyss, 2018). Carotenoids have two types: xanthophylls and carotenes on the basis of their structure (Latowski et al., 2014).

Carotenoids are extensively found in nature, but the widespread sources of these compounds are vibrantly colored vegetables and fruits. According to a report from 2018, there are approximately 850 natural carotenoids that have been identified (Maoka, 2020). For instance, yellow-colored pumpkins, orange-colored oranges and carrots, and red-colored tomatoes and watermelons are rich sources of them (Xavier & Pérez-Gálvez, 2016). They are found in free, esterified or complex form in plant tissues. They are also present in yellow leaves when the chlorophyll is degenerated (Rodriguez-Concepcion et al., 2018). Other sources of carotenoids are cyanobacteria, some species of fungi, algae and some other animals which can produce them *de novo* (Maoka, 2020).

Carotenoids discovery can be credited to Heinrich Wilhelm Ferdinand Wackenroder. In 1831, he coined the name "carotene" to describe the yellow pigment he extracted from carrot juice. After a few years, in 1837, Berzelius proposed the term "xanthophylls" for the yellow pigment he extracted from autumn leaves (Sankari et al., 2018). Following the identification of 'carotene', more than 600 carotenoids found in nature have been discovered. All these carotenoids are very useful in biological systems. They are essential for photosynthesis and help

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to produce phytohormones along with protecting plants from excess sunlight (Ruiz-Sola & Rodríguez-Concepción, 2012).

Carotenoids play a crucial role in promoting human health and make a major part of our daily nutrition. Their increased intake in diet has shown the ability to decrease the risk of diabetes, cancer, as well as overall mortality rates (Eroglu et al., 2023). Most frequently analyzed carotenoids in the context are lutein, zeaxanthin, lycopene and β-carotene. All these are great scavengers of reactive oxygen species (ROS) and lowers threat of diseases by protecting the body from pathogens (Khalid et al., 2019). The reason behind this is the antioxidant properties that render them a vital component for human health. Numerous investigations encompassing growing cells, animal research, and clinical trials have revealed the impact of nutritional carotenoids in minimizing hazards of enduring diseases, including heart disorders and malignancies (Rivera-Madrid et al., 2020). The current chapter discusses the synthesis and medicinal properties of carotenoids in detail.

CHEMICAL STRUCTURE, CLASSIFICATION AND BIOSYNTHESIS OF CAROTENOIDS

Chemical structure

Carotenoids are polyenes, made up of isoprenoid (C5) units. These subunits are joined to one another to form their structure. Based on the number of isoprene subunits, they are commonly categorized as C30, C40 and C50, but the most prevalent carotenoids in nature are C40 or tetraterpenoids. The molecular structure of C40 is symmetrical because the isoprene subunits are attached in head to tail sequence with exception at the center where the tail-to-tail linkage occurs (Generalić Mekinić et al., 2023). These carotenoids are synthesized by bacteria, fungi, archaea and eukaryotic organisms and a variety of terminal groups comprise their chemical structure (Yabuzaki, 2017).

Carotenoids are elongated, stick-shaped molecules, consisting of 9-11 alternative single and double bonds that form a conjugation system which allows π electrons to delocalize across the entire polyene chain. This chain may end with a cyclic group (ring) or may be terminated by a functional group containing oxygen (Namitha & Nagi 2010). The conjugation system determines the chemical reactivity of carotenoids. It also governs which light wavelengths are absorbed and thus influencing the colors we see in bacteria, fungi and vegetables containing carotenoids. For instance, β-carotene is abundantly present in pumpkin and carrot which is responsible for their orange and yellow colors. It is also found in leafy vegetables such as lettuce and spinach (Focsan et al., 2021).

Classification

Carotenoids may be categorized into two groups depending on their structural components;

- Carotenes are made up of carbon and hydrogen only. Examples include α-carotene, β-carotene, and lycopene.
- Xanthophylls are made up of hydrogen, carbon and oxygen. For example, astaxanthin, β-cryptoxanthin, lutein and zeaxanthin (Jaswir et al., 2011).

α, β carotenes and β cryptoxanthin can be transformed into provitamin A in the body. That's why they are also known as provitamin A. While others are non-provitamin A because they cannot be transformed into provitamin A, such as astaxanthin, lutein and zeaxanthin as shown in figure 1 (Kaulmann & Bohn, 2014). All these carotenoids have positive impacts on humans, including anti-obesity, anti-cancer, antioxidant along with therapeutic influence on the parts of bones (Jaswir et al., 2011).

Biosynthesis in plants and microorganisms

The biosynthesis of carotenoids occurs mainly in the plastids of plants (El-Agamey et al., 2004). There are two isoprenoid pathways from which carotenoids are produced. These are non-mevalonate (glyceraldehyde-3-phosphate) and mevalonate (MVA) pathways, responsible for the generation of isopentenyl pyrophosphate (IPP), the initial isoprene unit, in various organisms. The discovery of non-mevalonate pathways has occurred lately in plants, bacteria and fungi. Prior to this, the mevalonate pathway was considered to be the only path for the production of IPP (Paniagua-Michel et al., 2012). With the exception of plastids, plants, fungi, archaea and animals produce IPP and dimethylallyl pyrophosphate (DMAPP) via MVA pathway (Gharibzahedi et al., 2013). But synthesis of IPP occurs in plastids of higher plants via 2-C-methyl-D-erythritol-4-phosphate (MEP) pathway, as shown in Figure 2 (Giuliano et al., 2008). Then, the condensation of IPP and DMAPP forms C_{10}-geranyl pyrophosphate (GPP) that elongated to produce C_{15}-farnesyl pyrophosphate and then C_{20}-geranylgeranyl diphosphate (GGPP) (Liang et al., 2018). It occurs with the help of IPP isomerase (IPI) and GGPP synthase (GGPS).

Two molecules of GGPP then combine by the action of phytoene synthase (PSY in plants and CrtB in bacteria) to form the 15-*cis*-phytoene, the initial committed molecules in the pathway of carotenoid biosynthesis (Giuliano et al., 2008). Phytoene have conjugated molecule with three double bonds and is colorless in nature (Maoka, 2020). Phytoene then transformed into lycopene with the help of two desaturases [zeta-carotene (ZDS) and phytoene desaturases (PDS). Lycopene is a red carotenoid that is commonly present in watermelons and tomatoes. The biosynthetic route produces multiple *cis* isomers, which undergo conversion to all trans-forms through the catalytic functions of isomerases ZISO and CrtISO (Giuliano et al., 2008). Lycopene cyclase catalyzes the transformation of linear carotenoids into their cyclic terminal derivatives which include α and β carotene. Subsequently, these carotenes give rise to various xanthophylls owing to the action of their ketolases, epoxidases and hydrolases (Maoka, 2020).

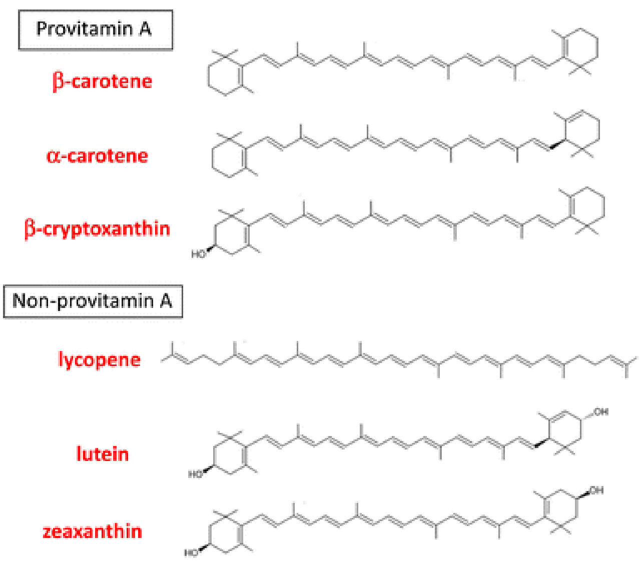

Fig 1. Figure shows the carotenoids (a) that convert into provitamin A and (b) those which do not convert into provitamin A i.e., Non-provitamin A.

Solubility, stability as well as degradation factors affecting carotenoid bioactivity

Carotenoid molecules consist of conjugated structures with multiple double bonds along their chain. Carotenoids possess their color attributes and antioxidant capabilities because of these structural characteristics (El-Agamey et al., 2004). In addition to providing useful benefits, their hydrophobic nature limits their use in food colorants and the medicinal industries. Their sensitivity to heat, oxygen and pH leads to low bioactivity, instability and least solubility (Jehlička & Oren, 2013). According to research, β-carotene has low resistance to heat. When subjected to elevated temperature, its color vanishes quickly. It is also unstable in acidic environment and is degraded to its cis-trans isomers, which impacts its absorption level in the gastrointestinal fluids. Similarly, a xanthophyll, lutein, also degrade in the presence of light and temperature (Subagio & Morita, 2001).

ANTIOXIDANT PROPERTIES AND MECHANISMS OF ACTION

In the human body, antioxidants are crucial in mitigating oxidative stress. Carotenoids are considered to be the most powerful antioxidants. Among

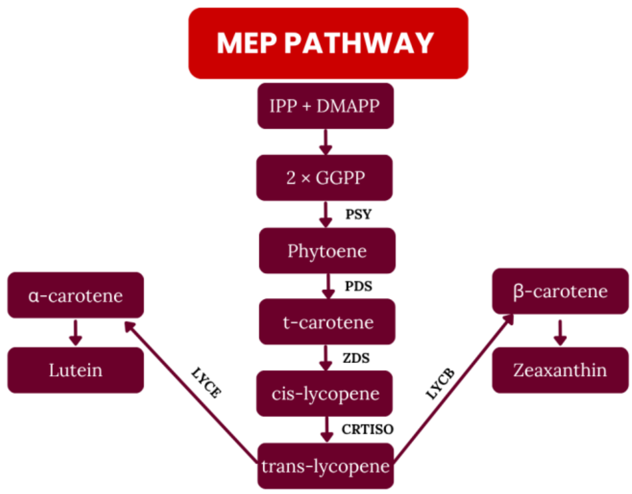

Fig 2. MEP pathway for the synthesis of carotenoids.

carotenoids, β-carotene, astaxanthin and lycopene are the most potent antioxidants and they are frequently used in pharmacological, aesthetic and medicinal fields. Moreover, carotenoids play a protective role against the emergence of various diseases including eye problems, heart diseases, hyperglycemia and various skin disorders via their antioxidant activities (Dewanjee et al., 2021). During the body's normal metabolism, reactive oxygen species (ROS) are produced and are involved in transduction of signals and in mitochondrial electron transport. These are widely conceded to function either as advantageous or harmful species (Rauf et al., 2024). The excessive ROS production, whether caused by external or internal aspects lead to a condition referred as oxidative stress that can be a major contributor to the destruction of cellular components such as lipid membrane, DNA and protein. Antioxidants of various kinds working in physiological processes counterbalance the damaging effects of these species (Jomova & Valko, 2013). Carotenoids are one of the excellent antioxidants that combat different disorders originating from oxidative stress (Bohn, 2019).

The most prominent method of carotenoids working is scavenging or quenching of two types of ROS that are peroxyl radicals and singlet molecular oxygen ($^1O_2$) and may also deactivate electronically stimulated sensitizer substances that are involved in their production (Stahl & Sies, 2003). A major reason for their antioxidative actions is the presence of electron-rich polyene structure and triplet energy levels (Rodrigues et al., 2012). Furthermore, the kind of substitution and the quantity of conjugated double bonds in carotenoids arouse their quenching abilities (Farhana et al., 2025).

Quenching of singlet oxygen

Singlet oxygen ($^1O_2$), a highly reactive form of oxygen, can induce oxidative damage in cells (Farhana et al., 2025). Carotenoids follow two distinct pathways, i.e., chemical and physical quenching, to deactivate these $^1O_2$. During physical quenching, $^1O_2$ is deactivated via transfer of energy to carotenoids, generating triplet-excited carotenoids. Then, the excited carotenoid releases its energy by vibrational exchange with solvents and returns to its ground state. Throughout the process, carotenoid stays unaltered and is capable of going through additional deactivation cycles (Stahl & Sies, 1997). While chemical quenching accounts for less than 0.5% of the overall quenching of $^1O_2$ and eventually leads to demise of molecule. Carotenoids are utmost powerful $^1O_2$ quenching agents in nature, having a quenching rate of approximately $512 \times 10^9 M^{-1} s^{-1}$ (Stahl & Sies, 2003).

Scavenging of free radicals

Carotenoids neutralize free radicals including hydroxyl radical ($HO^{\cdot}$), nitrogen-based radicals as well as superoxide anions (O_2^{-}), either by hydrogen donation or transfer of electron (Farhana et al., 2025). Carotenoids use three methods for scavenging free radicals

- Hydrogen abstraction: Carotenoids + ROO→ CAR+ ROOH
- Addition: Carotenoids + ROO→ Carotenoids +ROOH
- Electron transfer: Carotenoids + ROO → Carotenoids $^+$ + ROO^- (El-Agamey, 2004)

Comparison with other antioxidants (Flavonoids and Vitamin C)

Naturally existing antioxidants like flavonoids, carotenoids and Vitamins are currently thought to be the favorable elements found in vegetables and fruits. All these are powerful antioxidants that offer protective benefits to different ailments like hypersensitivity, cancer and heart problems (Rietjens et al., 2002; Ahmed et al., 2025).

Flavonoids are secondary metabolites and their anti-oxidative properties are confirmed by their free radical scavenging abilities along with their electron or hydrogen donating characteristics (Lespade & Bercion, 2012). Their capability to increase the activity of antioxidative enzymes and to chelate transition metal ions contribute to their antioxidative effects. Vitamin C is an antioxidant that is soluble in water and involved in minimizing oxidative stress and mitigating ROS (Verma et al., 2007).

While carotenoids have beneficial health effects due to their antioxidative potential and lipophilic nature. As they are oleophilic, they eliminate ROS from water repellent regions of plasma membrane and minimize the risk of membrane oxidation. They work through various pathways such as hydrogen abstraction, electron donation or via carotenoid-radical adduct formation based on their structural configuration and redox potential (Andarwulan et al., 2021). Carotenoids possess greater redox potential than vitamin C and E, allowing them to extract electron from ascorbic acid or α-tocopherol (Böhm et al., 1998).

ROLE OF CAROTENOIDS IN HUMAN HEALTH

Carotenoids have numerous health benefits. They mainly work antioxidant but they also serve many other functions in the body. For instance, β-carotene has a provitamin A function, and zeaxanthin is the pigment that makes up the macular pigment in the eye (Eggersdorfer & Wyss, 2018). Human bodies obtain carotenoids through their food and can accumulate them in fairly large amounts in tissues and plasma, where they perform various biological functions. Epidemiological studies have shown that daily intake of carotenoids in vegetables and fruit reduces heart problems, cancer, eye disease, blood disease and boosts immunity (Mishra et al., 2022).

Besides good effects on eye health, carotenoids have been found to promote an improvement in the cardiovascular and cognitive functions and even prevent certain types of other diseases (Eggersdorfer & Wyss, 2018). Carotenoids present in human cells help protect the skin through enhanced dermal defense against ultraviolet radiation exposure (Swapnil et al., 2021). The antioxidative properties of carotenoids stop multiple oxidants that contribute to cancer formation (Meena & Samal, 2019).

Vision Health and Eye Protection

β-carotene as a vitamin A precursor function as a vital biological element in several physiological activities such as vision. The yellow appearance of the retina serves as an indicator for carotenoid presence, also called "macular pigment" (MP) (Lima et al., 2016). The retinal distribution of particular MPs demonstrates their essential role in vision health and macular wellness, thus making them biologically important for the eye (Khachik et al., 1997). Human macula lutea and lens contain large amounts of macular xanthophylls including zeaxanthin, lutein and meso-zeaxanthin, which protect from eye diseases. Ocular carotenoids serve as protective agents for both lens and retina through their light-absorbing capabilities that target the visible spectrum (400-500nm). The presence of these natural antioxidants also aids in the prevention of free radicals formed due to complex physiological processes, thereby warding off the oxidative stress, mitochondrial disfunction and eye inflammation (Johra et al., 2020).

Immune System Modulation

Carotenoids are bioactive compounds of human diet that have diverse functions in redox metabolism. Carotenoids, especially zeaxanthin, astaxanthin, α-carotene and β-carotene and their derivatives help in redox homeostasis (Barros et al., 2018). The composition of the gut microbiota that maintains host health becomes modifiable through carotenoid intake. The human gut hosts roughly 100 trillion microbial cells which impact human metabolism, nutrition and immune functions. Host's genetics together with metabolic and immune responses as well as external factors, determine the composition of gut microbiota. Oxidants produced during normal metabolism and immunological reaction to chemicals and infectious microorganisms damage the DNA, proteins and cells of the human body. It is believed that this is the main contributor to aging and degenerative diseases such as cataracts, heart disease and impaired immune system (Mishra et al., 2022).

Fruits and vegetables contain Provitamin A (such as β-carotene) carotenoids. Studies revealed the health benefits associated with β-carotene. The body converts β-carotene into retinoic acid (RA) which serves as the recognized immune-modulatory compound. Research shows that pharmaceutical amount of lycopene and β-carotene affect immune system performance when carotenoid intake is at its lowest levels. Given the distinct ways that lycopene and RA affect transforming growth factor β-lycopene supplementation may enhance immune responses without raising the risk of cancer (Toti et al., 2018). High blood lycopene concentrations were linked to a decreased death rate in individuals with systemic lupus erythematosus in the Third National

Health and Nutrition Examination Survey (NHANES III), which included non-provitamin A carotenoids (Han & Han, 2016).

Cancer Prevention and Chemoprotective Effects

According to recent research, β-carotene can minimize calmodulin/calcium-dependent protein kinase IV, which in turn can diminish cell expansion and promote death in various cancer cell lines (Naz et al., 2017). RA receptor β enhances the anticancer stem cell activity of β-carotene, which has been shown to work on neuroblastoma (Kim et al., 2016). As key phytonutrients, several carotenoids have been served to prevent tumor growth both *in vitro* and *in vivo*. In the lung, colon, breast and prostate, they have demonstrated a variety of roles, including scavenging free radicals, inhibiting angiogenesis, preventing cell proliferation and inducing apoptosis (Bolhassani, 2015).

BIOAVAILABILITY AND FACTORS AFFECTING ABSORPTION OF CAROTENOIDS

The number of carotenoids from food that reach the intestine and become available for body use, defines carotenoid bioavailability. Bioavailability of carotenoids depends on four essential processes which start with the breakdown of food matrix, followed by conversion to bio-accessible forms before GIT absorption and metabolic transformation. The bio accessible fraction, or the quantity of bioactive and nutritional components that are available for intestinal absorption, is far more important than the food's actual contents (Wellala et al., 2022).

Digestion, absorption and metabolism of carotenoids

Carotenoid molecules go through a series of complex digestive and absorption mechanisms. The digestion process begins by releasing carotenoids from food structures during both chewing and stomach activities. Carotenoids undergo a similar process of lipid digestion in the upper unit of the human GIT. Thus, the breaking up of the fat phase of the meal is the first step of their digestion and their subsequent emulsion into lipid drops (Reboul, 2019).

During duodenal digestion, carotenoids interact with other digestive lipids (including cholesterol and phospholipids) and with lipid digestion products (e.g., monoacylglycerol, lyso-phospholipids and free fatty acids) to make mixed micelles (Reboul, 2013). Additionally, some carotenoids may bind to proteins. For instance, in contrast to mixed micelles, the milk lipocalin β-lactoglobulin can bind β-carotene (Mensi et al., 2014). Micelles carrying carotenes then interact with intestinal epithelial cells resulting in absorption. Following absorption, carotenes are subsequently integrated into chylomicrons. Moreover, after getting into the lymphatic system, the carotenoids are transferred to blood and spread all over the body.

Influence of dietary fats and other nutrients on carotenoid uptake

Dietary fats and other nutrients significantly influence the uptake of carotenoids through mechanisms affecting micelle formation, absorption and metabolism. However, the specific effect of both quantity and type of dietary fat required for optimal carotenoid absorption remained unexplored (Mashurabad et al., 2017). The overall bioavailability of the consumed carotenoids is influenced by different variables that could slow down each of these processes. The mnemonic "SLAMENGHI" explains these variables: Species of carotenoids, Linkages at molecular level, Amount of carotenoid, Matrix, Effectors, Nutrient status, Genetics, Host-related factors and Interactions among these variables (Sy et al., 2012).

Role of gut microbiota in carotenoid bioavailability

The association between carotenoids and the intestinal microbiota remains an area with insufficient information and definitive evidence. Several research studies have indicated that intestinal microbiota serves as the main factor which determines how carotenoids function effectively (Li et al., 2023). Kaulmann et al. (2016) found that intestinal microbiota creates new compounds when it ferments carotenoids, which proves that carotenoids undergo metabolic processing. Further studies have shown that supplementation of carotenoids in diet with its components including lycopene, affects the intestinal microbiota by increasing the number of Bifidobacterium and Lactobacillus. These studies give an indication of correlation between the structure and activity of carotenoids and intestinal microbiota, which means that the intestinal microbiota can be used as a potential target in employing carotenoids. The complete understanding of how carotenoids specifically interact with intestinal microbiota along with their relationship needs further investigation (Dai et al*.,* 2022). Table 1 shows the factors that increase or decrease bioavailability (Milani et al*.,* 2017).

Encapsulation and nanotechnology approaches to enhance carotenoid's stability and delivery

Encapsulation serves as an effective practical technique to enhance carotenoid solubility while protecting them from processing and digestive stress thus enabling their utilization in food and pharmaceutical products along with functional food applications. It's an efficient technique that entails walling bioactive compounds like carotenoids with micro/nano-encapsulation to entrap them within the carrier (Soukoulis & Bohn, 2018).

Nano-encapsulation has become increasingly popular because it provides various benefits, which include high loading capacity together with improved solubility, stability, encapsulation efficiency and bioavailability. Frequently utilized nanocarriers are nanoliposomes, nanostructured lipid/solid carriers, nanohydrogels and nano-emulsions (Rashwan et al.,2023).

THERAPEUTIC AND BIOMEDICAL APPLICATIONS

Carotenoids serve as essential components for eye health, normal brain function, heart health and cancer prevention. These properties extend their positive impact on human physiology (Caponio et al., 2022). The diverse functions of carotenoids throughout the human body demonstrate their involvement in essential cellular activities alongside their potential medical applications. The recent studies in this field explain the therapeutic value of carotenoids and their use in the medical field (Bas, 2024).

Use of carotenoids in pharmaceutical formulations

Carotenoids are being integrated into pharmaceutical formulations owing to their bioactive characteristics. Carotenoids such as β-carotene, lutein, and astaxanthin are utilized in systemic or topical formulations for conditions including leukemia, cardiovascular diseases, and skin disorders (Li et al., 2024). For example, pharmaceutical formulations use β-Carotene as a component to defend against oxidative damage while helping to regulate immune system activity. The anti-inflammatory properties of Astaxanthin make it useful for neuroprotection and muscle recovery formulations. The antioxidant properties of lycopene protect against lipid peroxidation and oxidative stress which contribute to carcinogenesis (Metibemu & Ogungbe, 2022). Pharmaceutical design frequently combines carotenoids with synergistic compounds to enhance bioavailability and efficacy. Encapsulation technologies, including liposomes, emulsions, and hydrogels, are utilized to improve the stability and bioavailability of carotenoids in pharmaceutical applications. These methods safeguard carotenoids from degradation and enhance their delivery to target tissues (Rehman et al., 2020).

Potential in dermatology (skin protection and anti-aging)

The human skin serves as the body's connection point to its surroundings, which is consistently exposed to free radicals (FR) from both external and internal sources. Several carotenoids exist in skin, including α, γ, and β-carotene, lutein, lycopene, and their derivatives, which provide cellular protection

Table 1. Factors affecting the bioavailability of carotenoids.

Increase Bioavailability	Decrease Bioavailability
Carotenoids that are embedded within lipid droplets	Carotenoids in microcrystalline form
Food integrating a fat source	Food integrating dietary fiber
Cooking, boiling and heating food	Raw food

against oxidative damage (Darvin et al., 2011). Recent studies indicate that carotenoids may serve as biomarkers for the antioxidants within skin. It's attributed to the formation of protective chains among antioxidants in the tissue, which act synergistically to shield one another from the damaging impacts of free radicals, especially ROS (Lademann et al., 2011). They provide intrinsic photoprotection, hence reducing the skin's vulnerability to UV-induced erythema (sunburn). Clinical studies indicate that both dietary and topical carotenoid supplementation can improve the skin's resistance to UV damage and boost overall skin health (Balic & Mokos, 2019).

Carotenoid-based nutraceuticals and dietary supplements

Nutraceuticals refer to substances that are derived from food or are components of food, offering medical or health advantages, which encompass the prevention and treatment of various diseases. An example of carotenoid containing nutraceutical is Betatene. Carotenoids are consumed through supplements to enhance their intake or to acquire particular compounds that are typically absent from the diet, such as meso-zeaxanthin. Carotenoids in supplements are used to enhance health or for cosmetic purposes (Phelan et al., 2017).

Role in cardiovascular health and metabolic disorders

Wang et al. (2023) discovered that lycopene and β-carotene play a vital role in heart health because they activate different biological pathways which decrease the risk of cardiovascular diseases. The scientific community recognizes lycopene as a vital cardioprotective substance which exists in tomatoes and their processed products because it blocks LDL oxidation that leads to atherosclerosis development and progression (Kwatra, 2020). β-carotene demonstrates vital heart protection through its ability to reduce inflammation which protects against multiple heart conditions. Carotenoids function as vital elements that combat diabetes, fatty liver disease, obesity and heart problems in the body. The benefits become evident through their antioxidant effects, anti-inflammatory actions and insulin sensitivity improvement (Kabir et al., 2022).

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

Advances in synthetic biology and metabolic engineering for carotenoid production

The enhancement of microbial cell factories through optimization methods has led to increased carotenoid production. The research results show that scientists have successfully optimized biosynthetic pathways through genetic modification of *Saccharomyces cerevisiae* and *Escherichia coli* for carotenoid production (Ambati et al., 2019). Scientists have made significant progress in carotenoid production through gene over-expression techniques and dynamic metabolic control and pathway modification methods. Scientists have developed CRISPR-Cas9 genome editing together with omics-based methods to achieve precise metabolic control for carotenoid accumulation enhancement. The interventions present a sustainable solution to replace conventional plant-based extraction methods for carotenoid production (Steven et al., 2022).

Potential of carotenoids in precision medicine and personalized nutrition

Carotenoids serve as crucial elements for precision medicine and customized nutrition because they perform various biological functions and people process them differently based on their unique metabolic and absorption characteristics. The research from Wang et al. (2022) shows that genetic differences between people determine how their bodies process these substances, so scientists need to create personalized treatment methods for each individual. The identification of personal genetic information together with biomarker analysis allows precision medicine to create individualized nutritional treatments for people who face an increased risk of developing cardiovascular disease, cancer and age-related macular degeneration. Scientists better understand carotenoid functions through new nutrigenomics and metabolomics research which enables them to develop improved preventive health measures (De Toro-Martín et al., 2017).

Emerging applications in neuroprotection and cognitive health

Carotenoids, especially xanthophylls, mostly protect brain membranes from oxidative damage, the main neurodegenerative factor. Xanthophylls like lutein, which may be orientated perpendicular or traverse the lipid bilayer, affect membrane function and structure. Their membrane association may alter the properties of brain membranes and exert an antioxidant effect (Lopresti et al., 2022). Plasma levels of carotenoids have been linked to mental and physical performance, therefore supporting their contribution to a delay of age-related cognitive deficits (Polidori et al., 2021).

Regulatory challenges and safety considerations in carotenoid supplementation

Carotenoids are now found in functional foods, dietary supplements, and nutraceuticals (Kabir et al., 2022). Their marketing is also complicated by major legal challenges concerning classification, dose restrictions, and safety assessments. Because carotenoids are controlled by different agencies based on whether they are considered food additives, supplements, or pharmaceuticals, approval procedures vary globally.

Problems concerning stability, bioavailability, and possible toxicity at extreme dose levels also require critical monitoring. Safety concerns include pro-oxidant dangers, interactions with fat-soluble vitamins, and population-specific metabolic variations. Although carotenoids such as lutein and β-carotene have established neuroprotective and health effects, one should be cautious while evaluating supplementation to avoid harm and uselessness (Verma et al., 2018).

CONCLUSION

In closing, carotenoids are essential natural pigments that have robust health benefits. Through their antioxidant and anti-inflammatory properties, carotenoids help protect against cardiovascular disorders and eye diseases as well as the development of cancer. The regular intake of fruits and vegetables high in carotenoids helps in general health and immune system fortification. Carotenoids serve various biological functions which make them valuable candidates for functional food components as well as nutraceutical products. Yet, further research is required to understand the mechanism involved and how they can be exploited to combat various diseases. Enhancing the consumption of carotenoids through balanced diets is a simple approach to improve public health outcomes and prevent diseases.

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