Enhancing Carotenoid Bio-accessibility Through Food Matrix and Processing: A Path to Reducing Vitamin A Deficiency

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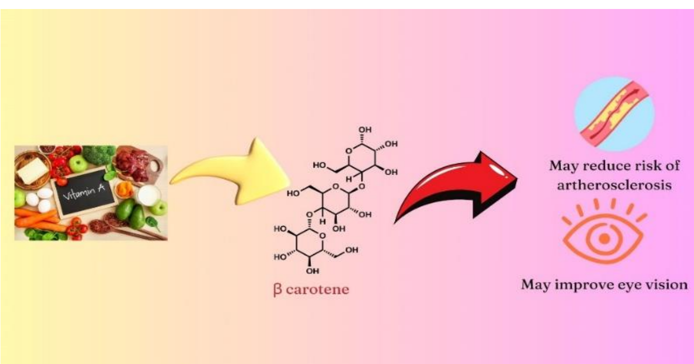
Introduction

Addressing both overt and hidden hunger is a critical aspect of global food and nutrition security. While global per capita availability of calories and protein was sufficient in 2017, there were significant deficiencies in essential nutrients like vitamin A and calcium (with intake ratios below 0.60, where 1.0 indicates adequacy). Vitamin A deficiency (VAD), in particular, has severe global health implications, contributing to over 650,000 early childhood deaths annually and causing preventable pediatric blindness. India remains notably affected by this form of "Hidden Hunger." As the global population continues to grow, providing access to fresh, nutritious, and sustainably produced food has become increasingly difficult. Nutritional deficiencies now affect more than two billion people worldwide, leading to poor health outcomes, diminished productivity, and higher rates of mortality and disease.



One promising solution to combat Vitamin A deficiency lies in carotenoids, which can be converted into vitamin A in the body. These compounds not only help address VAD but also contribute to overall health due to their antioxidant properties, which reduce the risk of chronic diseases like cancer and cardiovascular issues. Carotenoids are C40 tetraterpenoid pigments produced by plants, some bacteria, and fungi, though not by humans. Of the more than 1,100 carotenoids known, about 50 are found in human diets, with a dozen appearing in measurable concentrations in the bloodstream. Despite low daily intake (approximately 5–20 mg), carotenoids are among the most abundant liposoluble phytochemicals in the blood (~0.5–2 μM). Some carotenoids act as vitamin A precursors (provitamin A carotenoids), which are converted to vitamin A in the small intestine, playing essential roles in cell differentiation, immunity, gap junction formation, and vision adaptation. Non-provitamin A carotenoids have also attracted attention for their inverse associations with cardio-metabolic diseases and overall mortality. These health benefits are largely attributed to their antioxidant and anti-inflammatory properties, which protect against lipid peroxidation and damage caused by reactive oxygen species (ROS).

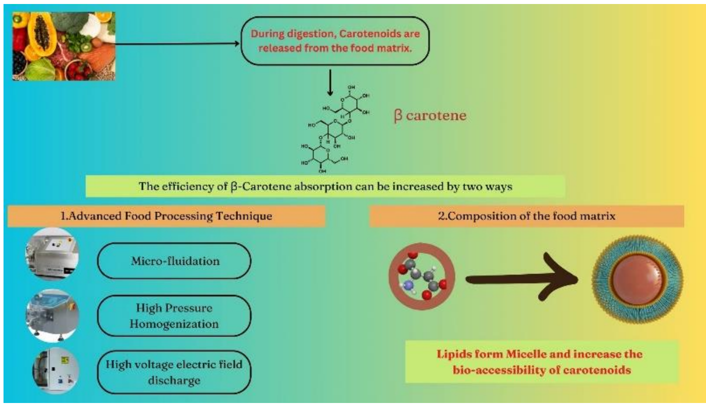
The primary sources of carotenoids in the human diet are natural fruits and vegetables. Carotenoids are found in various parts of plants, including flowers, leaves, seeds, fruits, and roots. Green and dark green leafy vegetables like kale, squash, broccoli, and parsley are rich in lutein and zeaxanthin, while tomatoes, guava, and watermelon are abundant in lycopene. β-carotene, the most potent provitamin A carotenoid, is found in high concentrations in foods like carrots, pumpkins, red peppers, and apricots.

However, the positive impact of carotenoids on health depends heavily on their bio-accessibility—the extent to which these compounds are absorbed during digestion. The type of food consumed, along with how it is processed, plays a crucial role in determining carotenoid bio-accessibility. Carotenoids are lipophilic compounds, meaning they must dissolve in lipids to be efficiently absorbed. During digestion, carotenoids are released from the food matrix, emulsified with lipids to form lipid droplets, and then incorporated into mixed micelles, which are responsible for transporting lipids and fat-soluble compounds. Only after this process can carotenoids be absorbed by intestinal cells.

The efficiency of this absorption process can vary significantly, influenced by factors such as food microstructure, processing methods, and interactions with other dietary components. These variables can either enhance or impede the body's ability to absorb carotenoids, making bio-accessibility a critical factor in maximizing the health benefits of carotenoid-rich foods.

Food microstructure and carotenoid release

Carotenoids are housed within the cellular structures of plant tissues, where components like cell



walls and chromoplasts serve as barriers that hinder their release during digestion. These barriers greatly influence how accessible carotenoids are for absorption. For instance, the carotenoids in tomatoes exist in a crystalline form, making them more difficult to release, while the liquid-crystal forms in fruits like papaya are more easily accessible. Research suggests that foods with more accessible carotenoid structures, such as the liquid-crystalline β-carotene in papaya, have up to three times higher bio-accessibility compared to those in more resistant structures like the crystalline form in carrots.

1. Enhancing Carotenoid Bioavailability through Advanced Food Processing Techniques

Advancements in food processing technology are helping to overcome these barriers, enhancing the release of carotenoids. Thermal treatments like cooking and pasteurization soften plant tissues and break down cell walls, increasing carotenoid bio-accessibility. For example, boiling carrots or tomatoes can alter their microstructure, making β-carotene and lycopene more available for absorption. However, the effectiveness of thermal processing depends on the method used and the specific food matrix, requiring a careful balance to maintain nutritional integrity while improving bio-accessibility.

In addition to thermal processing, non-thermal techniques like high-pressure homogenization (HHP), High-voltage electrical discharges (HVED), Pulsed electric fields, and Micro-fluidization are becoming more popular for enhancing carotenoid bioavailability. HHP, for instance, breaks open cell walls and membranes, facilitating carotenoid diffusion from chromoplasts. Studies have shown that carotenoid bio-accessibility in HHP-treated papaya is significantly higher than in untreated samples. HVED treatment has similarly been found to enhance carotenoid release by rupturing cell membranes in mixed juices. Likewise, Micro-fluidization increases lycopene bio-accessibility in tomato juice by breaking down tomato cell structures.

Currently, there is a growing shift towards using a combination of non-thermal processing techniques, which tend to yield better results. Combining these methods not only helps retain bioactive compounds but also enhances carotenoid bio-accessibility more effectively than single treatments

2. Influence of Food Matrix Components on Carotenoid Bio-accessibility

In addition to the plant's microstructure, the composition of the food matrix—particularly its lipids, dietary fiber, proteins, minerals, and flavonoids—plays a key role in how carotenoids are absorbed. These elements interact with carotenoids during digestion, affecting their release, solubilization, and incorporation into mixed micelles, which are essential for absorption.

Lipids: Key to Carotenoid Absorption

Since carotenoids are fat-soluble, lipids are crucial for their absorption. Lipids aid in the formation of micelles, which transport carotenoids from the intestine into the bloodstream. Research consistently shows that eating carotenoid-rich foods with dietary fats substantially improves bio-accessibility. For instance, adding oils like olive or corn oil to salads or juices can boost the bio-accessibility of β-carotene and lycopene by up to threefold.

The type of fat also matters. Long-chain triglycerides (LCTs), such as those in olive and sunflower oils, are more effective than medium-chain triglycerides (MCTs) at improving carotenoid absorption because LCTs promote better micelle formation. Additionally, using lipids in emulsified forms further increases carotenoid bio-accessibility by creating smaller lipid droplets, allowing more surface area for digestion and micelle production.

Dietary Fiber: A Mixed Impact

Dietary fiber, particularly soluble types like pectin, can both hinder and help carotenoid bio-accessibility. On one side, fiber can trap carotenoids within the food matrix, limiting their release during digestion. On the other hand, certain fibers may interfere with fat digestion, reducing micelle formation and thus carotenoid absorption.

Pectin's degree of methyl esterification (DM) and molecular weight (Mw) play key roles in its impact. Low DM pectins, which form gels in the digestive system, can obstruct fat digestion and reduce micelle formation. Conversely, Pectins with moderate DM levels support fat digestion and micelle formation, enhancing carotenoid absorption.

Proteins and Carotenoid Absorption

Proteins also influence carotenoid bio-accessibility, especially due to their ability to emulsify fats. Milk proteins like casein and whey have been found to improve carotenoid bio-accessibility by stabilizing emulsions and facilitating micelle formation. However, plant-based proteins like soy protein isolate (SPI) may reduce carotenoid absorption by forming complexes with carotenoids, preventing their incorporation into micelles.

The effect of proteins on carotenoid absorption varies by carotenoid type. Non-polar carotenoids like β-carotene benefit more from the presence of proteins, while polar carotenoids such as lutein may experience reduced bio-accessibility when digested with proteins.

Minerals and Flavonoids: Complex Interactions

Minerals such as calcium, magnesium, and zinc may inhibit carotenoid bio-accessibility by competing with carotenoids for bile salt binding, which is essential for micelle formation. Diets high in these minerals can reduce carotenoid solubilization and thus limit their absorption.

Conversely, flavonoids—a group of polyphenolic compounds found in many fruits and vegetables—can enhance carotenoid bio-accessibility. Flavonoids like hesperetin and naringenin have been shown to aid in the incorporation of carotenoids into micelles by promoting fat digestion and improving emulsification. This interaction underscores the need to consider the full composition of the food matrix when evaluating carotenoid bio-accessibility

Future Directions and Implications: Ongoing research into carotenoid bio-accessibility highlights the promising potential of optimizing food microstructure and matrix composition through innovative processing techniques to improve carotenoid absorption and amplify their health benefits. Future efforts should focus on refining non-thermal processing methods to preserve the integrity of carotenoids while maximizing their bioavailability. Additionally, developing functional foods with tailored matrix components—such as those enriched with carefully balanced lipids, fibre, and proteins—could further enhance carotenoid absorption in the human diet.

Understanding the intricate interplay between food structure, processing, and matrix components will allow for more precise dietary guidance and the creation of nutrient-rich foods that deliver optimal health outcomes. As the role of carotenoids in preventing chronic diseases and promoting long-term health continues to be explored, this knowledge becomes increasingly valuable. By harnessing cutting-edge food processing techniques and optimizing the interaction between carotenoids and other dietary elements, we can unlock their full nutritional potential, making them more accessible and beneficial for human health.

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