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Carotenoids in Plant-Based Food Systems

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ABSTRACT:

Carotenoids are plant pigments that have antioxidant and bioactive qualities; their bioavailability is dependent on mechanical and thermal processing as well as the presence of fats. Of the 40 carotenoids that are found in food, the main ones are carotenes (lycopene, β-carotene, and α-carotene) and xanthophylls (lutein, zeaxanthin, and β-cryptoxanthin). This article presents recent data on the carotenoid content of fresh vegetables, fruits, and berries; fresh vegetables have higher levels of carotenoids than fruits and berries, but their bioavailability is lower. Carotenoids are found in vegetables, fruits, and leafy greens like spinach; carrots are particularly rich in carotenoids, with 58.4% β-carotene and 40.4% α-carotene, with orange carrots having the highest levels. Among fruiting vegetables, tomatoes are a major source of lycopene (86%). Capsanthin (70%) and capsorubin (10%) are abundant in sweet and spicy chili peppers, whereas β-carotene (50–80%) is found in squash. In fact, 85% of orange chili peppers have zeaxanthin. Through genetic engineering, tomato cultivars with higher quantities of zeaxanthin (50%) and lycopene in its trans form (96%) have been created.

Carotenoids, primarily in the form of xanthophylls, are plentiful in leafy greens such as spinach, arugula, and watercress. β-carotene is the predominant carotenoid in the majority of fruits and berries, irrespective of their hue. But anthocyanins (found in hawthorn, rowan, cherries, rosehips, and blueberries) or chlorophyll (found in green apples) can cover it up. Sea buckthorn, rosehips, and cloudberries have the largest amounts of carotenoids, including β-carotene, lycopene (found in sea buckthorn and rosehips).

1. Introduction

A class of physiologically active substances known as carotenoids has long caught the interest of food industry professionals for their ability to maximize the nutritional value and color characteristics of food products, as well as nutritionists for their health benefits and role as a safe source of natural vitamin A (produced through enzymatic metabolism). Numerous characteristics of carotenoids are determined by their chemical makeup: their coloration is caused by a system of conjugated double bonds, their antioxidant activity is influenced by the number of double bonds, and their provitaminA activity is influenced by the presence of ionone rings [1–3]. There are over 750 known carotenoids in nature, the majority of which come from plants, while they can also be found in fish and shellfish (for example, fucoxanthin) and algae (for example, astaxanthin) [1, 4, 5]. Ten percent of the 40 carotenoids that are ingested by humans have vitamin A activity [1, 6–8]. It is possible to appropriately regulate technological processes to retain the bioactivity of carotenoids by having a thorough understanding of their nature, chemical characteristics, existence, and stability in complex food systems.

Carotenoids are naturally occurring pigments found in plants, fruits, and vegetables that are responsible for their vibrant red, orange, and yellow hues. These compounds play a crucial role in human nutrition and health, primarily due to their antioxidant properties and provitaminA activity. Beta-carotene, lycopene, and lutein are among the most important carotenoids, each associated with specific health benefits, such as supporting vision, reducing the risk of chronic diseases, and promoting skin health. The growing awareness of these health benefits has increased consumer demand for carotenoid-rich food products, making their analysis and quantification a significant area of study in food science and nutrition.

Concentrated vegetable products, such as tomato paste, carrot concentrate, and pumpkin puree, are widely consumed due to their extended shelf life, convenience, and high nutritional value. These products are particularly valued in the food industry as they are used in sauces, soups, baby food, and various other processed items. However, the carotenoid content in such concentrated products can vary significantly depending on the raw materials, processing techniques, and storage conditions. Thus, a thorough evaluation of carotenoid concentrations in these products is essential to ensure their nutritional quality and meet consumer expectations.

The assessment of carotenoids in food products requires precise and reliable analytical techniques. Chromatographic methodsand IR spectroscopy, particularly high-performance liquid chromatography (HPLC), have emerged as the gold standard for carotenoid analysis. These methods provide accurate identification and quantification of individual carotenoids, allowing researchers and food manufacturers to monitor the quality of vegetable-based products effectively. In addition to HPLC, advanced spectrophotometric techniques are also utilized to complement the analysis and ensure robust data.

This study aims to perform a comparative analysis of carotenoid content in different concentrated vegetable products. The selected products include tomato paste, carrot concentrate, and pumpkin puree, which are commonly consumed and represent a diverse spectrum of carotenoid profiles. The primary objective is to quantify the concentrations of beta-carotene, lycopene, and lutein in these products and identify significant variations in their carotenoid content. Such variations can arise due to differences in the raw vegetable's composition, processing methods, or the degree of concentration during production.

Understanding the carotenoid content in concentrated vegetable products is crucial for several reasons. First, it provides insights into the nutritional quality of these products, helping consumers make informed dietary choices. Second, it allows food manufacturers to optimize their production processes and develop products that meet specific nutritional standards. Finally, this knowledge contributes to the broader field of nutritional science by shedding light on the factors that influence carotenoid stability and bioavailability in processed foods.

By conducting a comprehensive analysis of carotenoid profiles, this research aims to bridge the gap between consumer demand for healthy products and the food industry’s ability to deliver such products. The findings of this study will serve as a valuable resource for food scientists, nutritionists, and policymakers seeking to promote carotenoid-rich diets and enhance the nutritional quality of processed vegetable products. Moreover, it underscores the importance of carotenoids in dietary planning and the development of functional foods tailored to the needs of modern consumers.

The comparative analysis of concentrated vegetable products for their carotenoid content is a timely and relevant endeavor. It addresses the growing demand for nutritionally rich food products while contributing to the advancement of analytical methods in food science. This study not only highlights the significance of carotenoids in human health but also provides practical applications for improving the quality and nutritional value of concentrated vegetable products.

The aim of this study was to provide an analytical review of data published by the international scientific community over the past decades in the field of carotenoid research as biologically active compounds within food systems. The primary informational modules, deemed most significant for the development of new-format food systems, included health benefits (biological activity, provitamin A, and antioxidant properties), natural sources, and factors influencing carotenoid content in plant-based food products.

2. Carotenoids' Chemical Characteristics

Eight isoprene units combine to form a polyprenoid chain with a conjugated system of double bonds to generate carotenoids, which are molecules with 40 carbon atoms. The endpoints of this chain have the ability to cyclize, creating a variety of ionone rings [1, 2, 5]. While the existence of ionone rings dictates the vitamin A activity of carotenoids, the length of the chain affects their hue, which can range from yellow and orange to deep red. Maximum protection against singlet oxygen (O_2) is shown by carotenoids with nine or more conjugated links. They are separated into two classes: xanthophylls, which have extra oxygen atoms in the form of hydroxy-, methoxy-, epoxy-, or keto groups, and carotenes, which are made up solely of carbon and hydrogen atoms. While lycopene is bright red, carotenes, such as α- and β-carotenes, are usually orange in hue. The hues of xanthophylls are more varied: lutein, zeaxanthin, and violaxanthin are yellow, while astaxanthin is vivid crimson and capsanthin is deep red.

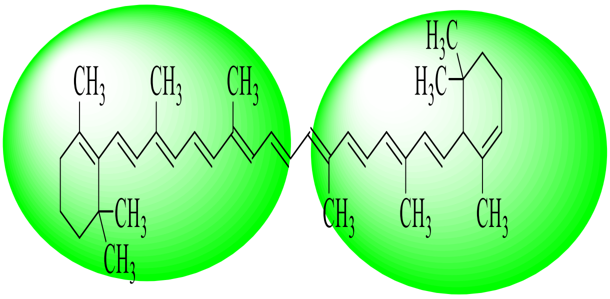
The color of peppers (Capsicum annuum) changes from orange to red when keto groups are added to the conjugated chain, as occurs when zeaxanthin is oxidized to capsanthin and capsorubin [7, 9]. As observed in leafy vegetables, green fruits, and blue-colored berries, other pigments like chlorophyll or anthocyanins frequently cover up the orange hue of carotenoids [10–13].

Three carotenes (α-carotene, β-carotene, and lycopene) and three xanthophylls (β-cryptoxanthin, zeaxanthin, and lutein) are the main types of the 40 carotenoids that are consumed by diet [1, 2, 5].

Carotenoids' Chemical Structure: Frequently Found in Fresh Fruits, Vegetables, and Food Items

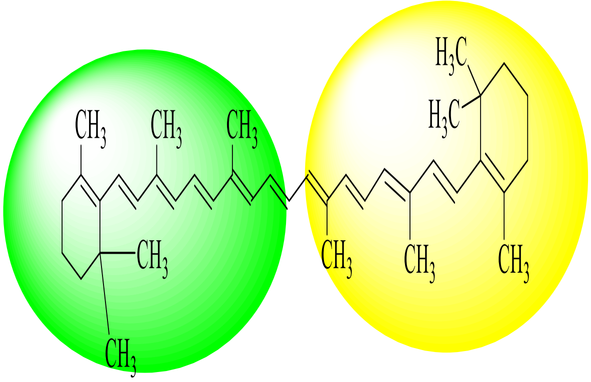
Numerous fruits, vegetables, and dietary items include carotenoids, which have a distinctive chemical structure that adds to their color and biological activity. The conjugated double bonds that give these compounds their color and antioxidant qualities are usually found in their polyisoprene backbone. The structures of some of the most prevalent carotenoids are shown below:

Both α- and β-carotene Orange and yellow fruits and vegetables include both of these carotenes. Their structure, which consists of a 40-carbon chain with conjugated double bonds, is identical. Carrots, pumpkins, and sweet potatoes are popular sources of β-carotene, a precursor of vitamin A. The structure of α-carotene is identical, but it has an extra cyclization at one end. Long conjugated double bonds are present in both; β-carotene has a symmetrical structure, whereas α-carotene has a slightly different bond arrangement.



α-carotene.

1,3,3-trimethyl-2-((1*E*,3*E*,5*E*,7*E*,9*E*,11*E*,13*E*,15*E*,17*E*)-3,7,12,16-tetramethyl-18-(2,6,6-trimethylcyclohex-2-en-1-yl)octadeca-1,3,5,7,9,11,13,15,17-nonaen-1-yl)cyclohex-1-ene



β-carotene.

2,2'-((1*E*,3*E*,5*E*,7*E*,9*E*,11*E*,13*E*,15*E*,17*E*)-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaene-1,18-diyl)bis(1,3,3-trimethylcyclohex-1-ene)

Lycopene

Watermelon, tomatoes, and red peppers are typical sources of the red pigment lycopene. It is bright red because it lacks the β-ring at one end, but otherwise has a structure identical to that of β-carotene. Structure: Lycopene's strong red hue and antioxidant properties are attributed to its eleven conjugated double bonds.

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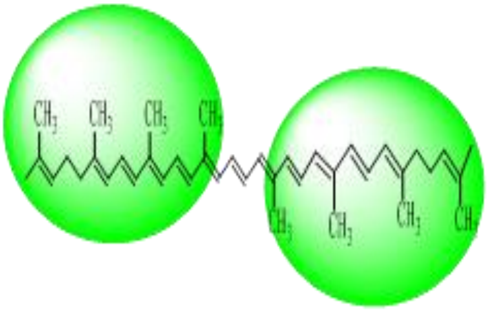


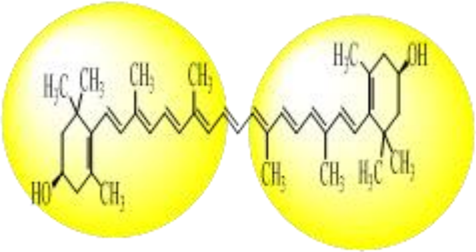
(6E,8E,10E,12E,14E,16E,18E,20E,22E,24E,26E)-2,6,10,14,19,23,27,31-octamethyldotriaconta-2,6,8,10,12,14,16,18,20,22,24,26,30-tridecaene. **Lycopene**

Zeaxanthin and Lutein

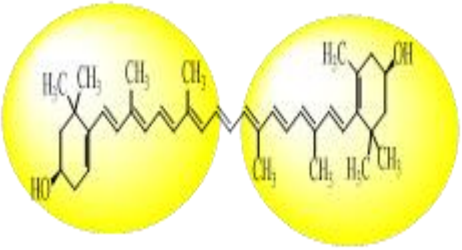
Leafy greens including spinach, kale, and maize contain these yellow xanthophylls. They are frequently found in supplements and are essential for eye health. Zeaxanthin has one extra hydroxyl group, although its structure is identical to that of lutein.

Structure: The yellow coloring and antioxidant qualities of lutein and zeaxanthin are attributed to their polyene chains, which contain hydroxyl groups at certain locations.

Zeaxanthin is a common pigment in the carotenoid group (a xanthophyll), derived from the Latin **Zea** corn and the Greek xanthos yellow; it is the pigment that colors the seeds of this plant. Plants and certain microbes contain it. The pigment called zeaxanthin gives paprika, maize, saffron, and a variety of other fruits and berries their distinctive yellow hue. Zeaxanthin and lutein, two carotenoids, are found in the retina of the eye, mostly in the macula, the center part. They are essential for shielding the retina from blue and ultraviolet radiation. Although they are not stereoisomers, lutein and zeaxanthin are isomers.



(1R,1'R)-4,4'-((1E,3E,5E,7E,9E,11E,13E,15E,17E)-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaene-1,18-diyl)bis(3,5,5-trimethylcyclohex-3-en-1-ol). **Zeaxanthin**

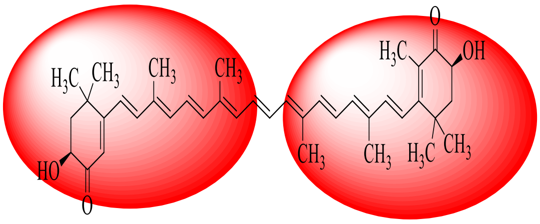


(R)-4-((1E,3E,5E,7E,9E,11E,13E,15E,17E)-18-((R)-4-hydroxy-6,6-dimethylcyclohex-1-en-1-yl)-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaen-1-yl)-3,5,5-trimethylcyclohex-3-en-1-ol. **Lutein**

Astaxanthin

Known for its vivid red hue, astaxanthin is present in algae and seafood like salmon and shrimp. This carotenoid has more functional groups that include oxygen, giving it a more complicated structure.

Structure: Astaxanthin's red color and potent antioxidant qualities are derived from a polyene chain with conjugated double bonds and oxygenated functional groups.



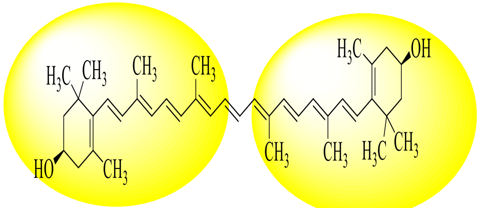
(S)-6-hydroxy-3-((1E,3E,5E,7E,9E,11E,13E,15E,17E)-18-((S)-4-hydroxy-6,6-dimethyl-3-oxocyclohex-1-en-1-yl)-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaen-1-yl)-2,4,4-trimethylcyclohex-2-en-1-one. **Astaxanthin**

Most red-colored aquatic species include astaxanthin, which has been discovered in the tissues of a variety of fish, shrimp, birds, and plants. Astaxanthin is the main ingredient that gives salmonids their red skin color. Due of its great reliance on nutrition and living environment, its content differs between species and individuals. Several kinds of lichens in the Arctic zone have also been shown to contain astaxanthin and other chemically similar astaxanthinoids.

Beta-Cryptoxanthin

Beta-cryptoxanthin is another xanthophyll found in fruits such as oranges and tangerines. It has a similar structure

to β-carotene but with a hydroxyl group attached to the molecule. One carotenoid that belongs to the oxygen-containing subgroup of carotenoids called xanthophyll is beta-cryptoxanthin. It is frequently present in various vegetables, such pumpkins, and fruits, including papayas, tangerines, and oranges. Like beta-carotene, beta-cryptoxanthin is a yellow-orange precursor to vitamin A, however its provitamin A activity is thought to be lower. Chemical Structure: What sets beta-cryptoxanthin apart from other carotenoids like beta-carotene is its polyene chain with conjugated double bonds and a hydroxyl group (-OH) linked to one of the rings.



(1*R*,1'*R*)-4,4'-((1*E*,3*E*,5*E*,7*E*,9*E*,11*E*,13*E*,15*E*,17*E*)-3,7,12,16-tetramethyloctadeca-1,3,5,7,9,11,13,15,17-nonaene-1,18-diyl)bis(3,5,5-trimethylcyclohex-3-en-1-ol)

Carotenoids' Provitamin a Properties

The enzymatic metabolism of carotenoids in the human and animal body produces vitamin A, which is the only safe and natural source of the vitamin. However, provitaminA activity is not present in all carotenoids. Only a small percentage (about 10%) of the 40 carotenoids that people commonly eat have vitamin A activity. These are those that have a polyene chain of at least 11 carbon atoms and a β-ring devoid of oxygen-containing functional groups. These consist of β-cryptoxanthin and the trans- and trans-cis isomers of α-, β-, and γ-carotene.

The most powerful provitaminA carotenoid among them is β-carotene, which splits into two retinol (vitamin A) molecules per molecule. Under the action of the enzyme β-carotene-15,15'-dioxygenase, β-carotene undergoes oxidative metabolism along the central 15–15 π-bond, converting it to vitamin A. Vitamin A is not found in plant-based diets because plants lack this enzyme. Whereas α- and γ-carotenes only produce one molecule of vitamin A, one molecule of β-carotene produces two.Equivalence: 1 µg of vitamin A is equal to 6 µg of β-carotene. Is no vitamin A action in lycopene or δ-carotene.

Table 1: Carotenoids with Provitamin a Activity [3, 14]

№	**Carotenoid**	**Conversion Efficiency (%)**	**№**	**Carotenoid**	**Conversion Efficiency (%)**
1	Trans-β-Carotene	100	7	Trans-β-cryptoxanthin	57
2	9-cis-β-Carotene	38	8	9-cis-β-Cryptoxanthin	27
3	13-cis-β-Carotene	53	9	15-cis-β-Cryptoxanthin	42
4	Trans-α-Carotene	53	10	β-Carotene-5,6-epoxide	21
5	9-cis-α-Carotene	13	11	γ-Carotene	43-50
6	13-cis-α-Carotene	16	12	-	-

The effectiveness of different carotenoids' conversion to vitamin A is shown in this table-1 as a percentage of their provitaminA activity. While different isomers and carotenoids exhibit varied degrees of effectiveness, trans-β-carotene has the highest conversion efficiency at 100%.

Carotenoids themselves are non-toxic, and the formation of vitamin A from them is enzymatically limited. Therefore, when consuming foods containing carotenoids, vitamin A overdose does not occur, and the upper tolerable intake level has not been established. The average intake of β-carotene in different countries ranges from 1.8 to 5.0 mg per day. For the population of Uzbekistan, the physiological requirement for β-carotene in adults is set at 5 mg per day.

Properties of Antioxidants

Their function as lipophilic antioxidants is determined by the quantity of conjugated double bonds in the polyene chain of carotenoid structure, which results from the delocalization of π-electrons. In order to interact with free radicals, a carotenoid can either donate a hydrogen

atom to create relatively stable carotenoid radicals or transfer electrons to form an adduct. Carotenoids' antioxidant activity rises in tandem with their oxidative potential. The best way to "trap" singlet oxygen (O_2) is via carotenoids, which dissipate excess excitation energy and transform it into its usual triplet state. Carotenoids either directly react with O_2 or receive excitation energy from "triplet" chlorophyll. Up to 300 singlet oxygen molecules can be destroyed by each β-carotene molecule. Carotenoids—lycopene 100 times, astaxanthin 500 times, and β-carotene 25 times—trap O_2 more aggressively than vitamin E. The strongest UV protection is provided by astaxanthin, which contains keto groups at both ends of the conjugated double bond structure. It is required 1000 times less than lutein and 100 times less than β-carotene. With lycopene exhibiting the strongest action, lutein, β-carotene, and lycopene together can prevent 40–50% of UV-induced lipid peroxidation. Carotenoids have been shown to have the following antioxidant activity in in vitro models: **lycopene >α-tocopherol>α-carotene >β-cryptoxanthin>zeaxanthin>β-carotene > lutein.** Compared to their trans-isomers, carotenoids' cis-isomers have higher antioxidant activity.

It has been found that the antioxidant properties of carotenoids work in concert with those of other fat-soluble antioxidants, including coenzyme Q10 and α-tocopherol. While tocopherols absorb peroxyl radicals from carotenoids that can start free radical chain reactions, carotenoids shield tocopherols against oxidation, mostly from singlet oxygen. Only at a ratio of 1:4 can β-carotene and α-tocopherol be found to work in concert, but a 1:12 ratio is needed for the more unsaturated astaxanthin and α-tocopherol. Antagonism results from an increase in carotenoids' content. Even at high carotenoid concentrations, the antioxidant activity is enhanced when phospholipids are added to the system.

Bioavailability

Among their numerous biological characteristics, carotenoids' escape from the food matrix is crucial for human absorption. Carotenoids' bioavailability is influenced by their dietary sources. The bioavailability of fresh (unprocessed) plant components is three times greater in fruits and berries than in vegetables. In particular, spinach has just 5–10% bioavailability of β-carotene due to its binding to chloroplasts, but fresh carrots have 17–25% bioavailability. The following is a ranking of carotenoids' bioavailability:

Broccoli florets > sweet potatoes > carrots > yellow pepper. Carotenoid bioavailability is increased by an average of two times when lipids are present in the plant material or food, and by three times when it is processed mechanically and thermally. The cell walls of plants are broken down by grinding. thus the rate of carotenoid release rises when the particle size falls (as in carrots, for example). Carotenoids from fresh and dried veggies have far higher bioavailability when fats are added. For instance, using spinach paste and corn oil to create nanoemulsions enhanced the bioavailability of spinach carotenoids from 3.1% to 19.2%. The higher oil content in the nanoemulsions explains why carotenoid transfer from spinach to fat droplets and mixed micelles is more efficient because of the increased lipid content. In comparison to an emulsion without thermal processing of tomatoes, the bioavailability of carotenoids was improved by 10% in an emulsion formed from cooked tomatoes and olive oil, and by 23.4% in an emulsion created from thermally processed tomatoes with olive oil. This action is explained by the fact that heated olive oil may dissolve carotenoids in the small intestine by forming mixed micelles, and that olive oil's inherent antioxidants, or phenols, can shield carotenoids from oxidation.

The bioavailability of lycopene in tomato juice was enhanced in the following sequence by using fermentation to break down tomato cell structure and encourage the creation of mixed micelles: Fermented (11.4%) < unfermented-emulsified (13.6%) < fermented-emulsified (22.7%) < unfermented (8.5%).

However, the bioavailability of β-carotene and lycopene in tomatoes was unaffected by heating or pulsed electric fields. Nevertheless, the bioavailability of β-carotene and lycopene in chromoplasts declined when heating and pulsed electric fields were combined.

The decrease in bioavailability linked to chromoplast membrane and carotenoid-protein complex alteration suggests that cellular structures that promote carotenoid absorption can be disrupted by treatments like heating and pulsed electric fields (PEF). Carotenoids are stored in chromoplasts, which are made of proteins and membranes that contribute to the stability and bioavailability of these substances. The human digestive

system may find it more difficult to absorb carotenoids if these structures are changed, for instance by heating or pulsed electric fields. Moreover, the structural complexity of tomatoes is associated with variations in the effects of pulsed electric fields on the bioavailability of various tomato components. This implies that various tomato sections (such as the skin, meat, and seeds) may react differently to treatments depending on their physical and chemical characteristics. Depending on the treatment approach, certain regions may be more vulnerable to structural alterations, which might result in either a rise or fall in the bioavailability of carotenoids. How well carotenoids are released and absorbed depends in large part on the overall complexity of the tomato's structure.

Carotenes and xanthophylls are examples of natural carotenoids. Fresh vegetables are a source of plants.

The vibrant yellow, orange, and red hues of plants are caused by a varied set of naturally occurring pigments called carotenoids. These substances, which are essential to human health, fall into two major groups: xanthophylls and carotenes. Whereas xanthophylls, like lutein and zeaxanthin, have oxygen atoms in their chemical structure, carotenes are just hydrocarbon carotenoids, like β-carotene. Both classes of carotenoids are essential to plants because they shield them from oxidative damage and absorb light for photosynthesis. Furthermore, carotenoids are vital for human nutrition, particularly as provitamins for vitamin A, which is necessary for healthy skin, eyesight, and the immune system.

Fresh vegetables are the main dietary sources of natural carotenoids for humans. A wide range of carotenoids are found in vegetables, and the amount of each can differ greatly according on the kind of plant, the cultivar, and the growing environment. Carrots, tomatoes, pumpkins, and spinach are among the most common plant sources of carotenoids; each one contributes a different kind of carotene, including lutein, lycopene, and β-carotene.

A Significant Source of β-Carotene: Carrots

One of the most popular and extensively consumed vegetables that contains carotenoids, especially β-carotene, a kind of provitamin A, is the carrot (Daucuscarota). The carotenoid that gives carrots their distinctive orange hue is called β-Carotene. While other carotenoids, including α-carotene, are also found in carrots, β-carotene is the most prevalent.

Fresh carrots can contain up to 268.64 mg of carotenoids per 100 g of fresh weight (FW). Of these, β-carotene accounts for a large percentage (156.91 mg/100 g FW), followed by α-carotene (108.53 mg/100 g FW).

Depending on the color of the root, carrots might have different amounts of carotenoids. Dark orange carrots may have up to 160 mg/100 g FW, but yellow carrots may have as little as 2–6 mg/100 g FW. Furthermore, certain carrot varieties—like red carrots—are high in lycopene, while others—like yellow carrots—have higher lutein content. These carotenoids benefit human health in a number of ways and are significant antioxidants.

Lycopene-Rich Tomatoes

Another important source of carotenoids, especially lycopene, is tomatoes (Solanumlycopersicum. Tomatoes are one of the main dietary sources of the red carotenoid pigment lycopene, which is a powerful antioxidant. Because of its potent antioxidant qualities, lycopene helps shield cells from oxidative damage and may lower the risk of cardiovascular disease and some types of cancer. Although the quantity of lycopene varies among tomato species, mature red tomatoes contain about 85% lycopene as a carotenoid. Depending on the cultivar, tomatoes can have anywhere between 24.07 and 261.86 µg of total carotenoid content per g of fresh weight (FW). β-carotene and lutein are substantially less abundant than lycopene, which may range from 9.61 to 227.11 µg/g FW. Generally speaking, the tomato's skin contains a higher concentration of lycopene than other portions of the fruit. When fully mature, the skin's lycopene concentration can range from 2644 to 7020 µg/100 g FW, the flesh's from 1843 to 3302 µg/100 g FW, and the seeds' from 597 to 1695 µg/100 g FW.

Pumpkin: A Good Source of Lutein and β-Carotene

Another excellent source of carotenoids, especially lutein and β-carotene, is pumpkins (Cucurbita spp.). The orange hue of pumpkin flesh is a result of these carotenoids. A strong antioxidant, β-carotene is a precursor to vitamin A, which is necessary for good skin and eyesight. Another pigment included in pumpkins is lutein, which is particularly crucial for eye health.The carotenoid concentration of pumpkins varies according

on the type and growing conditions, but they are a great source of provitamin A. With a comparable composition to carrots, pumpkins often contribute a substantial quantity of carotenoids to the diet.

Other Carotenoids-Packed Vegetables

Carotenoids are also found in other plants including broccoli, spinach, kale, and sweet potatoes. For instance, when cooked, sweet potatoes may be a great source of provitamin A and are high in β-carotene. Significant concentrations of the carotenoids lutein and zeaxanthin, which are good for eye health and may lower the incidence of cataracts and age-related macular degeneration, are found in spinach and kale. Carotenoids are also present in broccoli, but they are less abundant than in other vegetables. The food matrix, cooking techniques, and the amount of fat in the meal are some of the variables that affect the bioavailability of carotenoids from vegetables. Because they are fat-soluble, carotenoids are better absorbed when dietary fats are present. Cooking vegetables, such as tomatoes and carrots, can increase the bioavailability of carotenoids by breaking down the plant cell walls and making the carotenoids more accessible for absorption.

For example, cooking tomatoes enhances the release of lycopene, making it more bioavailable to the body. Similarly, adding olive oil or other healthy fats to dishes that contain carotenoid-rich vegetables can increase the absorption of these nutrients. The presence of other nutrients, such as vitamin E, can also help enhance carotenoid absorption.

Table 2: with carotenoid content in some vegetables (mg/100 g)

Vegetables	**Carotenes**	**Xanthophylls**	**β-carotene**	**α-carotene**	**Lycopene**	**Lutein**
RootVegetables						
Carrot	5.36–19.20	0.39–12.8	n/d–10.0	0.15–0.51	n/d	n/d
FruitVegetables						
Tomato	0.40–7.03	n/d–1.1	0.9–76.7	0.1–0.62	n/d	n/d
Pumpkin	0.05–29.4	0.05–8.2	n/d	0.03–12.9	0.06–2.24	n/d–1.8
Pepper	0.9–2.38	0.06–0.60	2.2 n/d–2.8	8.5–15.1	0.003–0.8	
Watermelon	2.29–2.37	n/d	3.55–4.86	n/d	n/d	n/d–1.03
Melon	1.59	0.03	–	0.04	–	
CabbageVegetables						
BrusselsSprouts	0.45	0.06	–	1.59	–	
CurlyBrazilianKale	4.12	n/d	n/d	5.25	n/d	–
Broccoli	0.78–1.89	0.01	–	1.1–3.51	–	0.015
Cauliflower	0.005	–	–	0.005	0.016	0.080
ChineseCabbage	0.008	–	–	0.024	0.003	0.0079
LeafyGreens&Spinach						

Vegetables	Carotenes	Xanthophylls	β-carotene	α-carotene	Lycopene	Lutein
Spinach	1.89–5.59	n/d	n/d	3.35–7.76	n/d–0.33	n/d
Lettuce (Saladacrua)	1.76	0.18	0.89	2.22	–	
Arugula	0.19–2.84	n/d	n/d	0.52–5.0	n/d–0.0015	n/d–0.0013
Watercress	0.008–2.72	–	–	0.52–5.61	0.019	0.011
SwissChard	2.7	0.035	n/d	2.7	n/d	n/d

Notes:n/d means "not detected" or "not determined.

New tomato varietals are continuously being created using genetic engineering techniques. The lycopene concentration of some tomato hybrids and cultivars cultivated in Canada has been raised to 227.11 µg/g dry weight (DW), with trans-lycopene predominating at 218.64 µg/g DW. Simultaneously, the overall concentration of β-carotenes in all cis and trans forms decreased by [25]. The "Xantomato" tomato cultivar has 39 µg/g (or 577 µg/g DW) of zeaxanthin, which makes up as much as 50% of the fruit's total carotenoid concentration [34, 35]. β-carotene is the primary pigment found in pumpkin. β-carotene takes about 50–80% of the overall carotenoid content, which ranges from 2.5 to 8.6 mg/100 g, whereas α-carotene makes up roughly 10%. The carotenoid concentration of pumpkins cultivated in tropical regions can reach 9.3 mg/100 g, whereas the carotenoid content of CucurbitamoschataDuch pumpkins grown in Brazil canreach 40 mg/100 g [37,38–40]. The species and botanical variation of pumpkin affect its overall carotenoid content, however the botanical variety has a greater impact on the amount of β-carotene than the species does. For instance, the total carotenoid concentration of Cucurbita maxima varies by variety from 0.47 to 7.09 mg/100 g, although the variations are less pronounced in Cucurbitapepo and C. Carotenoids may be found in a variety of peppers, including sweet and spicy types. Compared to other popular vegetables, peppers have a very different carotenoids content, which also affects the fruits' color. Orange types accumulate the highest amounts of carotenoid content, which varies from 23.21 to 34.94 mg/100 g. White peppers have ten times as much carotenoids as red peppers, which have four to five times as many. Capsanthin (70%) and capsorubin (10%) make up the majority of the carotenoids found in red peppers, whereas β-carotene and β-cryptoxanthin comprise no more than 20%. Some types have been reported to contain zeaxanthin, but not lutein, antheraxanthin, or violaxanthin. Orange peppers are mostly composed of zeaxanthin (up to 85%), lutein (up to 16%), and trace levels of β-carotene. Capsanthin and capsorubin are absent, but β-cryptoxanthin and antheroxanthin (less than 1%–2% each) are present. Although the overall carotenoid content of white peppers ranges from 11.38 to 29.7 mg/100 g dry weight (DW), lutein makes up as much as 70% of the peppers. There are more pepper-specific carotenoids than capsanthin and capsorubin. Lutein predominates in white bell peppers,however it is present in lesser numbers (44.6%), whereas it is 48.3% in the white Habanero variety [9, 17, 35].

With a comparatively low total carotenoid concentration (varying from 41 µg/g DW in cauliflower to 215 µg/g DW in broccoli), cabbage and leafy vegetables are mostly composed of xanthophylls, which include lutein, zeaxanthin, β-cryptoxanthin, and others including violaxanthin, neoxanthin, and antheraxanthin [31]. Broccoli is especially high in lutein, making up 25–50% of the total. But compared to cabbage, spinach, arugula, and watercress have higher levels of carotenoids, with lutein making up as much as 50% and total xanthophylls up to 75% [12, 31, 38, 41, 43]. Watercress has 1.77 and 2.61 mg/100 g-12- of neoxanthin and violaxanthin, respectively, whereas arugula has 1.81 and 1.47 mg/100 g. Xanthophylls make nearly 75% of spinach's total carotenoid concentration, which can range from 7.6 to 12.5 mg/100 g. Among the known xanthophylls are lutein, violaxanthin, and neoxanthin [29]. With a total carotenoid concentration of 25.94 mg/100 g DW [17], only sweet potato types with orange flesh may be regarded as a source of carotenoids among root vegetables. The amount of β-carotene in orange-fleshed sweet potatoes can range from 0.37 to 6.7 mg/100 g, and 22 to 78% of it is still present after boiling. Potatoes contain very few carotenoids, mostly xanthophylls, with β-carotene either absent or present in amounts up to 0.65 µg/g of dry weight (DW). During thermal processing (boiling or baking), carotenoids are almost completely destroyed. Lutein is the most thermally stable carotenoid [43]. Fruits and berries have a much lower total carotenoid content compared to vegetables, ranging from 0.02 to 6.2 mg/100 g, but they have better bioavailability and can be important dietary sources of β-carotene and lutein (Table 3). Often, the orange color of fruits indicates a high content of β-carotene, as seen in apricots, mangoes, and mandarins. For example, in apricots, β-carotene content ranges from 1.44 to 39.07 µg/g, with lutein and zeaxanthin not exceeding 0.5 µg/100 g, and no α-carotene or antheraxanthin detected. However, the fruit color with high β-carotene content can be masked by anthocyanins, as in cherries, hawthorn, and rowan berries, or by chlorophyll, as in green apples and mangoes. In apples, the total carotenoid content ranges from 29.48 to 49.17 µg/g, primarily concentrated in the skin, and is nearly independent of the fruit color. In green apples, the content of β-carotene and lutein can be as high as or even higher than in red apples, up to ten times more. The carotenoid composition includes lutein, violaxanthin, neoxanthin, β-carotene, and esterified carotenoids (mainly violaxanthin and neoxanthin). In yellow and red apples, the most abundant carotenoids are trans-neoxanthin and trans-violaxanthin, while in green apples, cis-neoxanthin predominates, and in the Granny Smith variety, the amount of cis-violaxanthin exceeds its trans-form. Among subtropical fruits, the carotenoid composition has been most studied in oranges. The carotenoid content in orange pulp ranges from 0.8 to 2.4 mg/100 g, while in red oranges, it is 2.8 mg/100 g. The carotenoid profile of most varieties is characterized by the predominance of 5,6-epoxycarotenoids (violaxanthin and antheraxanthin geometric isomers), followed by 5,8-epoxycarotenoids (luteoxanthin and mutatoxanthin), β-cryptoxanthin, zeinoxanthin (monohydroxycarotenoids), zeaxanthin, lutein (dihydroxycarotenoids), and α- and β-carotenes. Overall, the pulp of orange oranges is dominated by xanthophylls (82.7–93.0%), except for red oranges, which have a higher proportion of carotenes (around 70%). β-Cryptoxanthin is the predominant carotenoid in Late and Ambersweet oranges. Among tropical fruits, mangoes contain a significant amount of carotenoids, with 3.8 mg/100 g, predominantly β-carotene, while papayas contain mostly lycopene. Among berries with high total carotenoid content, sea buckthorn (up to 15 mg/100 g), rose hips (up to 30 mg/100 g), and cloudberries (up to 3 mg/100 g) can be highlighted, with carotenoids predominating (Table 4) [47, 48, 50, 51]. The total carotenoid content in sea buckthorn varies significantly depending on the botanical variety and growing location, ranging from 53 to 97 mg/100 g dry weight. Most of the carotenoids are in bound form as diesters (about 50%) and monoesters (about 17%). Free carotenoids include trans-β-carotene >cis-β-carotene [46, 47]. Variations in carotenoid content in rose hips depend on the ecotype and growing conditions. The highest total carotenoid content (1590.4 µg/g dry weight) was found at the end of the harvest season in the hybrid R. dumalis, while the lowest amounts were found in R. spinosissima species (684.5 µg/g dry weight) [49]. The carotenoid composition is dominated by carotenes, with the highest proportions of β-carotene and lycopene, but γ- and ζ-forms of carotene are also present. The content of xanthophylls is about 10 times lower than that of carotenes. Xanthophylls include neoxanthin, zeaxanthin, lutein, violaxanthin, and rubixanthin, with the latter predominating (about 70%) [48, 49]. In wild northern berries, the carotenoid content is insignificant. Among them, cloudberries stand out with a total carotenoid content of 2.84 mg/100 g dry weight, predominantly β-carotene (83%), which reaches 2.32 mg/100 g dry weight. Zeaxanthin content is five times lower, and the amounts of other identified carotenoids (lutein, neoxanthin, violaxanthin, antheraxanthin) do not exceed 0.05 mg/100 g. In blueberries, the total carotenoid content is 2.14 mg/100 g dry weight, with lutein predominating at around 70%. Bog cranberry and lingonberry contain only 0.2 and 0.14 mg/100 g of carotenoids, but in lingonberries, lutein predominates (38%), and in cranberries, β-carotene (40%) [50, 51]. Among other berries, the highest carotenoid level was

found in blackberries, while strawberries had the lowest carotenoid content. According to [13-35], blackberries had the highest β-carotene content (101.4 µg/100 g), followed by black currants (61.6 µg/100 g). Table-3

Table 3: outlines the carotenoid content and highlights the dominant carotenoids in each fruit or berry.

Fruit/Berry	TotalCarotenoidContent	DominantCarotenoid(s)	AdditionalNotes
SeaBuckthorn	Upto 15 mg/100 g	β-Carotene, Zeaxanthin, Lutein	Content varies from 53 to 97 mg/100 g dry weight; diesters and monoesters predominate.
RoseHips	Upto 30 mg/100 g	β-Carotene, Lycopene	Total carotenoids vary based on ecotype and growing conditions.
Cloudberries	Upto 3 mg/100 g	β-Carotene	Predominantly β-carotene (83%), other carotenoids present in trace amounts.
Blueberries	2.14 mg/100 g	Lutein	Luteincontentisabout 70%.
Lingonberries	0.14 mg/100 g	Lutein	Luteincontentis 38%.
Cranberries	0.2 mg/100 g	β-Carotene	β-Carotenecontentis 40%.
Blackberries	Highestamongberries	β-Carotene	Highest β-carotene content (101.4 µg/100 g) among berries.
BlackCurrants	61.6 µg/100 g	β-Carotene	

The highest amount of α-carotene was found in raspberries (23.7 µg/100 g). Lutein was present in higher amounts in raspberries (317.0 µg/100 g), followed by blackberries (270.1 µg/100 g). The highest level of zeaxanthin was found in blackberries (29.0 µg/100 g), followed by blueberries (14.0 µg/100 g). Blackberries had the highest value of β-cryptoxanthin (30.1 µg/100 g).

3. Excremental part

Carotenoids are important plant pigments found in many fruits and vegetables, playing a key role in nutrition due to their antioxidant properties and provitaminA activity. To accurately analyze the carotenoids present in plant-based foods, chromatographic methods, particularly High-Performance Liquid Chromatography (HPLC), and Intelligent Quantification (IQ) analysis are used.

Chromatographic analysis is essential for the separation, identification, and quantification of carotenoids. HPLC is the most commonly used technique due to its high sensitivity and ability to separate complex mixtures of carotenoids. The process begins with the extraction of carotenoids from plant tissues using solvents such as acetone or methanol. After the sample is prepared, the carotenoids are separated on a reverse-phase C18 column. The mobile phase typically consists of a mixture of organic solvents, and the carotenoids are detected using UV-Vis spectroscopy, which measures absorbance at specific wavelengths, typically around 450 nm for β-carotene. The areas under the chromatographic peaks are used for quantification, with calibration curves based on known standards.

Gas Chromatography (GC) can also be applied, though it requires derivatization of carotenoids to make them volatile enough for analysis. This method is less commonly used for carotenoids but can be valuable in certain cases, especially when coupled with mass spectrometry (MS) for more detailed molecular analysis.

IQ (Intelligent Quantification) analysis involves advanced software and algorithms to process and quantify the chromatographic data. The raw data from HPLC or GC is processed to enhance the signal and eliminate noise. The software identifies peaks using spectral libraries or known retention times.

Quantification is performed by analyzing the peak areas and heights, with calibration curves ensuring accurate measurements. IQ analysis allows for faster, more precise quantification and can automatically detect minor carotenoids, providing detailed insights into the carotenoid profile of the sample.

In conclusion, chromatographic techniques, particularly HPLC, are indispensable for the accurate analysis of carotenoids in plant-based food systems. Coupled with IQ analysis, these methods provide a comprehensive and efficient way to assess the carotenoid content in various foods, contributing to our understanding of their nutritional value and health benefits.

4. Conclusion

In recent years, the international scientific community has published a number of studies on the total carotenoid content and composition in fresh vegetables, fruits, and berries, their biological activity, antioxidant properties, and factors that enhance bioavailability. Genetic engineering methods are being used to create new varieties of tomatoes with increased levels of trans-lycopene and zeaxanthin.

The primary sources of carotenoids in human nutrition are fresh vegetables: carrots, fruits (tomatoes, pumpkins, peppers), and leafy greens (spinach, arugula, watercress), despite their low bioavailability. Fruits and berries, though lower in total carotenoid content compared to vegetables, have higher bioavailability and are mainly sources of carotenoids with provitaminA activity.

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