https://doi.org/10.48048/tis.2024.7984

Current Progress in Exploring Structural Changes in Brown Algae Fucoxanthin and Its Potential Bioactivity for Human Health

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Received: 22 January 2024, Revised: 11 March 2024, Accepted: 2 April 2024, Published: 5 June 2024

Abstract

Fucoxanthin is a carotenoid found in brown seaweed. Its potential anti-cancer, anti-obesity, anti-inflammatory and antioxidant properties have recently attracted interest. This interest is driven by the growing awareness of natural compounds promoting well-being, ongoing research into their health impacts and their appeal to the food and supplement industries. Brown seaweed is a major source of fucoxanthin and its global cultivation is on the rise. Fucoxanthin's structural characteristics contribute to its bioactivity. Isomerization, influenced by factors like light and heat, can alter its biological activity. Recent studies highlight the importance of the *cis*/*trans* isomer ratio in determining fucoxanthin's biological effects. This review uses narrative approaches to explore fucoxanthin's potential applications in the food and pharmaceutical industries, emphasizing its source from brown seaweed and considerations for maximizing bioavailability and stability. The dynamic landscape of fucoxanthin research underscores its promising role in human health, encapsulating its multifaceted benefits within a concise framework.

Keywords: Bioactivity, Brown seaweed, *Cis-trans* isomers, Fucoxanthin, Stereomutation, Structure changes

Introduction

Fucoxanthin also referred to as xanthophyll, is a naturally occurring compound classified as a carotenoid. Originating from brown seaweed and diatoms, it gives these organisms a brown to a yellow hue. Fucoxanthin is situated within the membrane-bound thylakoids of the chloroplast, where it forms complexes with chlorophyll *a*, *c* and apoproteins. Fucoxanthin is a key pigment in photosynthesis, particularly in capturing solar photon energy in areas devoid of chlorophyll *a* and *c*. Fucoxanthin alone can enhance the efficiency of photosynthesis, particularly in the absorption range of a broader light spectrum (449 - 540 nm) [1], in contrast, chlorophyll *a* and *c* exhibit strong light absorption in the spectrums of 400 - 450 nm and 650 - 700 nm. Moreover, it is crucial to safeguard the host from molecular damage caused by sunlight through photooxidative protection.

Fucoxanthin has garnered substantial attention in recent years, particularly within the domains of nutrition, health and wellness [2,3]. There are at least 5 factors contributing to this heightened interest. Firstly, the increasing awareness of the significance of natural compounds in promoting well-being has spurred a greater focus on bioactive compounds such as fucoxanthin. Secondly, ongoing research has delved into its impact on oxidative stress, inflammation, obesity and potential anti-cancer properties. The third factor involves the exploration of fucoxanthin for integration into functional foods and nutraceuticals, aligning with consumer preferences for natural and functional ingredients that provide health benefits beyond basic nutrition. Fourthly, consumers expressing a preference for natural ingredients in their food and supplements find fucoxanthin appealing as a naturally occurring compound in brown seaweed, aligning with this trend. Lastly, the fifth factor pertains to companies in the food and supplement industries recognizing the market potential of fucoxanthin and actively seeking ways to incorporate it into various products.

The distinctive properties and bioactivity of fucoxanthin for human health can be attributed to its structural characteristics. Fucoxanthin's structure comprises a polyene backbone featuring an allenic bond,

along with various oxygenic functional groups such as epoxy, hydroxyl and carbonyl. These structural elements significantly contribute to its potent hydroxyl radical scavenging activity [2] and its ability to chelate ferrous metal ions [3]. Fucoxanthin demonstrates various biological effects, encompassing anticancer, anti-obesity, antidiabetic, anti-inflammatory, antioxidant, anti-dermatitis and neuroprotective activities. However, the practical applications of fucoxanthin face constraints arising from challenges related to water solubility, instability and restricted bioaccessibility. This review aims to discuss the potential applications of fucoxanthin in the food and pharmaceutical industries, with a focus on its source from brown seaweed and concerns regarding its consumption. The review will also examine the influence of the chemical structure of fucoxanthin, its geometric changes and how these factors impact its bioavailability and biological activity.

Methods

In this study, we employed narrative approaches to conduct a comprehensive review analysis that followed 3 crucial steps: literature screening and data extraction and analysis. We collected relevant literatures by using the keyword "Fucoxanthin; Isomer" and refined the extracted data into 3 distinct categories: (1) fucoxanthin in brown seaweeds, (2) fucoxanthin isomers and (3) bioactivity of fucoxanthin. In order to analyze the data, we address the following research questions: what is the spatial and quantitative distribution of fucoxanthin in various species of brown seaweed and what are the pertinent consideration for its suitability and safety in consumable application, accounting factors such as extraction methodologies, stabilities and potential implications? We also addressed questions on how do the structural characteristics of fucoxanthin contribute to its bioactivity and how is the biological activity modulated through isomerization processes influenced by factors such as light and heat? Additionally, what recent insights do studies provide regarding the significance of the cis/trans isomer ratio in determining fucoxanthin's biological effects?

Brown seaweed and its fucoxanthin content

Table 1 showcases the edible brown seaweed, which is frequently used as both human food and feedstock. The most widely consumed algae species are brown algae, constituting 66.5 % of consumption, followed by red algae at 33 % and green algae at 5 % [4]. Presently, Japan, China and South Korea are the nations exhibiting the highest levels of seaweed consumption. There exist approximately 1,500 species of brown seaweed in the natural environment. However, only 9 species are recognized as safe for human consumption, namely *Fucus vesiculosus, Fucus serratus, Himanthalia elongata*, *Undaria pinnatifida*, *Ascophyllum nodosum*, *Laminaria digitata, Laminaria saccharina, Laminaria japonica* and *Alaria esculenta* [5]. The pigment content displays notable variability across distinct species and is subject to extrinsic influences (**Table 1**). Within a given species, considerable ranges are evident, indicating intraspecific diversity. The morphology such as the laminae and stipe of each species even the closely related species will affect the fucoxanthin content.

Table 1 Edible brown seaweed species commonly used for food and feed, the quantification value of fucoxanthin concentration and type of extraction used.

Example of species	Fucoxanthin concentration (mg kg^{-1}) *d.w.*	Extraction method; Solution	Ref.
Alaria crassifolia	1,100	Solvent extraction; MeOH	[6]
Alaria esculenta	870	Solvent extraction; AcO	[7]
Ascophyllum nodosum	200	Ultrasound-assisted extraction; EtOH	[8]
Analipus japonicas	1,400	Solvent extraction; MeOH	[6]
Cladosiphon okamuranus	270	Solvent extraction; MeOH	[9]
Dictyopteris australis	230	Solvent extraction; AcO	[10]
Dictyota dichotoma	6,420	Solvent extraction; MeOH	[11]
Dictyota dentata	4,110	Solvent extraction; AcO-MeOH	[12]
Ecklonia kurome	1,680	Solvent extraction; Ch-MeOH	[13]
Fucus serratus	2,180	Solvent extraction; EtOH	[14]

Example of species	Fucoxanthin concentration (mg kg^{-1}) *d.w.*	Extraction method; Solution	Ref.
Fucus vesiculosus	700	Solvent extraction; MeOH	[7]
Himanthalia elongata	1,860	Solvent extraction; n-Hx, DE, Ch	[15]
Hizikia fusiformis	20	Solvent extraction;	
Kjellmaniella crassifolia	150	Solvent extraction; MeOH	[16]
Laminaria japonica	190	Solvent extraction; MeOH	[17]
Laminaria digitata	650	Solvent extraction; AcO 62.2%	[7]
Laminaria religiosa	240	Solvent extraction; MeOH	[18]
Laminaria saccharina	240	Solvent extraction; AcO	[19]
Padina tetrastromatica	750	Ultrasound-assisted extraction; EtOH 80 %	[20]
Padina australis	1,640	Solvent extraction; AcO-MeOH	[12]
	1,290	Solvent extraction; Ch-MeOH	[13]
Padina minor	500	Solvent extraction; EtOH	[21]
Padina pavonica	430	Solvent extraction; EtOH	[21]
Petalonia binghamiae	580	Solvent extraction; MeOH	[18]
Saccharina japonica	30	Solvent extraction; MeOH	[16]
Saccharina sculpera	700	Solvent extraction; MeOH	[6]
Sargassum binderi	730	Solvent extraction; MeOH	[22]
Sargassum confusum	1,600	Solvent extraction; MeOH	[6]
Sargassum crassifolium	1,640	Solvent extraction; Ch-MeOH	[13]
	750	Solvent extraction; AcO-MeOH	[12]
Sargassum fusiforme	2,620	Solvent extraction; AcO-EtOH	[23]
Sargassum polycystum	410	Solvent extraction; EtOH	[21]
Sargassum siliquastrum	1,990	Solvent extraction; Ch-MeOH	[13]
Sargassum thunbergii	1,800	Solvent extraction; MeOH	[6]
Sphaerotrichia divaricata	200	Solvent extraction; MeOH	[6]
Undaria pinnatifida	2,670	Solvent extraction; MeOH	[18]
	990	CO_2 extraction; EtOH	[24]

Note: Ethanol (EtOH); Methanol (MeOH); Acetone (AcO); Chloroform (Ch); n-Hexane (n-Hex); Diethyl ether (DE); Ethyl Acetate (EA); Carbon dioxide (CO_2); dry weight (*d.w.*).

According to data from the Food and Agriculture Organization (FAO) in 2021, the global cultivation of brown seaweeds exhibited a notable escalation, rising from 13,000 tonnes in 1950 to 16.4 million tonnes in 2019 [25,26]. The average annual growth rate over the period from 1950 to 2019, at 10.9 %, surpassed the 7.9 % growth observed in the overall world aquaculture of all species. In the year 2019, brown seaweeds constituted 47.3 % of global seaweed cultivation by weight and 52 % by value. The cultivation of brown seaweeds has been predominantly focused on 2 cold-water genera: *Laminaria*/*Saccharina*, commonly referred to as kelp and *Undaria*, also known as wakame.

In the year 2019, the cultivation of *Laminaria*/*Saccharina*, predominantly *Laminaria japonica*, accounted for 12.3 million tonnes, representing 35.4 % of global seaweed cultivation [26]. This production was sourced from 7 countries: China, the Republic of Korea, the Democratic Peoples of the Republic of Korea, Japan, the Faroe Islands, Norway and Spain. Additionally, the cultivation of *Undaria*, primarily *U.*

pinnatifida, amounted to 2.6 million tonnes, constituting 7.4 % of global seaweed cultivation. This production originated from 4 countries: China, the Republic of Korea, Japan and France. Additional minor brown seaweed species in cultivation include 304,000 tonnes of *Sargassum*, primarily *S. fusiforme*, cultivated in 2 Eastern Asian countries: China (270,000 tonnes) and the Republic of Korea (34,000 tonnes). Furthermore, 105 tonnes of *Alaria esculenta*, also known as bladderlocks, dabberlocks, or winged kelp, are cultivated in 3 Northern European countries: Norway (44 tonnes), Ireland (42 tonnes) and the Faroe Islands (19 tonnes). Additionally, 90 tonnes of *Cladosiphon okamuranus*, also known as mozuku, are cultivated in Tonga, with additional cultivation of *C. okamuranus* in Okinawa, Japan. Finally, 2 tonnes of *Macrocystis pyrifera*, also referred to as giant kelp, are cultivated in Chile.

Arsenic contamination and consequences for downstream uses

One concern in utilizing brown seaweed as a source of functional food ingredients is the necessity to identify and quantify the levels of arsenic present in seaweed products [27]. Brown seaweed has the highest total arsenic concentration compared to red or green seaweed taken up via phosphate transporters, especially during phosphate-limited environments. Arsenic species can be classified into toxic (inorganic arsenic, classified as class I carcinogens), non-toxic (arsenobetaine), or potentially toxic (fat-soluble arsenic, arsenosugars and other organoarsenicals) [28]. Predominantly found in seaweeds, arsenosugars are typically bound to glycerol, sulfonate, or phosphonate [29-31]. Arsenosugars, being polar, readily dissolve in aqueous and methanolic solutions [32,33], despite the common use of such solvent systems for the extraction of fucoxanthin from brown seaweed (**Table 1**). These arsenosugars exhibit resistance to degradation in the stomach and undergo metabolism in the lower gastrointestinal tract, yielding at least 12 different metabolites, including dimethylarsinate, methylarsinate and dimethylarsinoylethanol [34,35]. However, the toxicity of these metabolites remains unknown.

In brown seaweeds, such as *Ascophyllum nodosum*, *Laminaria digitata*, *Fucus vesiculosus*, *Fucus spiralis*, *Alaria esculenta* and *Saccharina latissima*, revealed that total arsenic content ranged from 4.1 to 111.0 μg/g, with the majority of arsenic present as arsenosugars (inorganic arsenic content was <1.0 μg/g) [36]. *Laminaria digitata*, sources from the USA and Ireland, were found to contain inorganic arsenic at concentrations ranging from 2.8 to 20.0 μg/g [36] and 2.2 to 87.0 μg/g [29], respectively. In contrast, *Laminaria japonica* obtained from China exhibited inorganic arsenic levels ranging from 0.16 to 0.58 mg/kg, falling below the established maximum limits in China (1.0 mg/kg of dry weight) [37], France (3.0 mg/kg of dry weight) [38] and Australia/New Zealand (1.0 mg/kg of dry weight) [39]. The observed disparity in inorganic arsenic concentrations underscores the importance of routine testing for inorganic arsenic content in food products derived from *Laminaria* spp. Although heavy metal concentrations in edible seaweeds typically remain below toxic thresholds, the potential bioaccumulation of arsenic poses a risk, necessitating further investigations into the toxicokinetics of heavy metals.

Several methods have been developed to eliminate arsenic. A significant reduction in total arsenic content was observed in *H. fusiforme* (syn. *Sargassum fusiforme*), commonly known as “Hijiki”, when both heating and salt treatment were concurrently applied, compared to using either method individually. Boiling *H. fusiforme* several times in seawater led to a reduction of 86 - 92 % in total arsenic content [40]. This reduction is ascribed to the water-solubility of arsenic, with decreasing water content due to an elevated NaCl concentration during soaking. The stability of arsenobetaine prevents its extraction during boiling. In a recently developed method involving heating in water at 90 °C, a notable decrease in arsenic content in *H. fusiforme* by approximately 33 - 80 % was observed [41]. Further immersion in a 2 % NaCl solution resulted in an additional reduction in arsenic content by more than 5 - 20 %. Notably, the arsenic concentration of *S. fusiforme* was reduced to 32 % using citric acid and 40 % using hot water. The combined application of both methods further decreased the content to 11.9 %, while employing the fermentation method reduced the arsenic content to 2 % [42].

Basic structures and its isomers

Fucoxanthin is a xanthophyll carotenoid because it contains oxygen. **Figure 1** depicts the chemical structure of fucoxanthin (3′-acetoxy-5,6-epoxy-3,5′-dihydroxy-6′,7′-didehyro-5,6,7,8,5′,6′-hexahydro-β,β-carotene-8-one; $C_{42}H_{58}O_6$; CAS no. 3351-86-8; Mw = 658.92 g mol^{-1}; ε_{443nm} = 109×10^3 mol^{-1} cm^{-1} in acetone) has 2 6-membered ring derivatives at the terminal position joined by a polyene chain. The polyene chain has 7 conjugated double bonds, at 1 end is an allenic bond and the second has a β,γ-epoxy ketone group. Fucoxanthin functional groups attached to the rings are 2 hydroxyl groups at C-3 and 5′ and a keto group at position C-8.

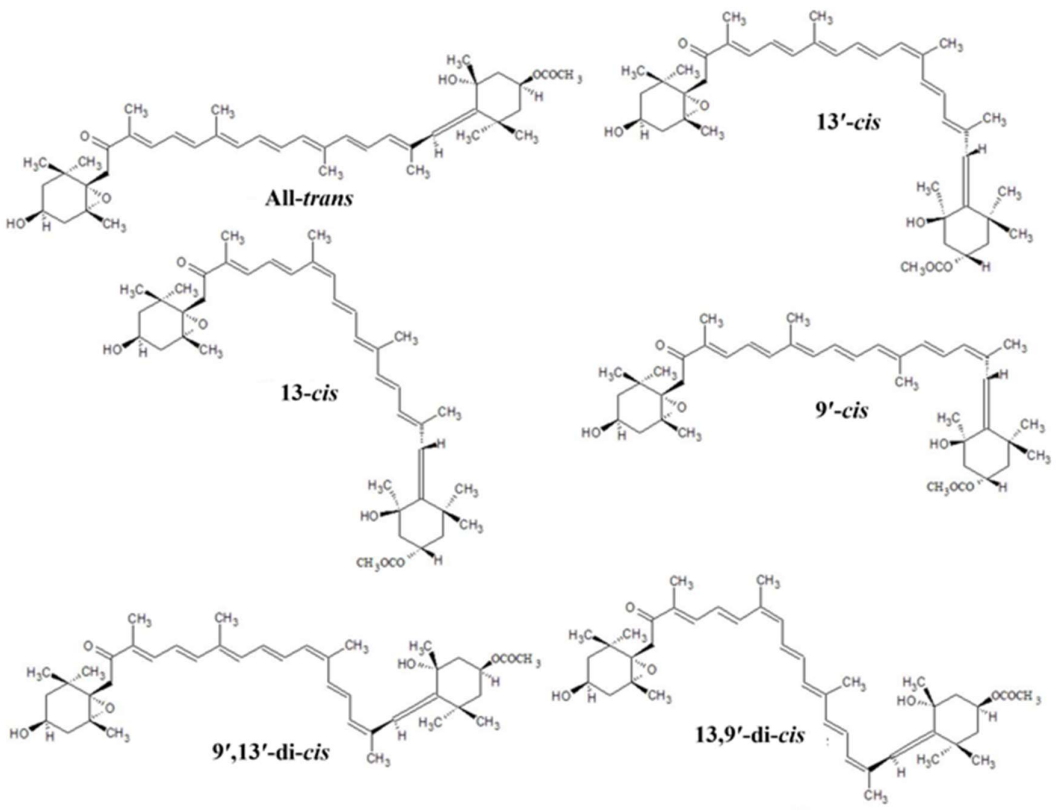

Figure 1 Molecular structure of the mono- and di-cis isomer of fucoxanthin.

Fucoxanthin has a molar refractivity of 195.4 ± 0.4 cm^3 and polarizability of 77.5 ± 0.5 10^{-24} cm^3. Fucoxanthin is susceptible to degradation when exposed to heat, light, oxygen, enzymes, unsaturated lipids and other prooxidant molecules [43]. Its structure and chirality can be easily affected, making it unstable. Fucoxanthin breakdown can occur at temperatures ranging from 25 - 60 °C in the absence of light and air at pH 4.6; however, a pH of 7.4 can help reduce fucoxanthin degradation [44]. Carotenoids, including fucoxanthin, exist in 2 isomeric configurations, *trans* or *cis*, due to the presence of conjugated double bonds in their polyene chains.

Based on the HPLC chromatogram reported by Hougan and Liaaen-Jensen (1992), through an efficient and gentle extraction of crude carotenoids from *Fucus serratus*, *Fucus vesiculosus*, *Ascophyllum nodosum*, *Pelvetia canaliculata*, *Laminaria digitata* and *Laminaria saccharine*, types of naturally occurring fucoxanthin isomers is the all-*trans* fucoxanthin [45]. The 3 mono *cis* isomers (**Figure 2(A)**), i.e. 13-*cis*, 9′-*cis* and 13′-*cis*, appeared to be artifacts formed during the isolation process (**Figure 2(B)**). A UV-Vis spectrophotometer can be used to record the absorption spectrum of fucoxanthin by scanning from 300 to 800 nm (**Figures 2(C)** and **2(D)**). The fucoxanthin has a broad peak with the main center at 445 ± 5 nm. The *cis* isomer of fucoxanthin can be detected by a band that appeared at a wavelength of 330 ± 5 nm [46], which is called a *cis* peak.

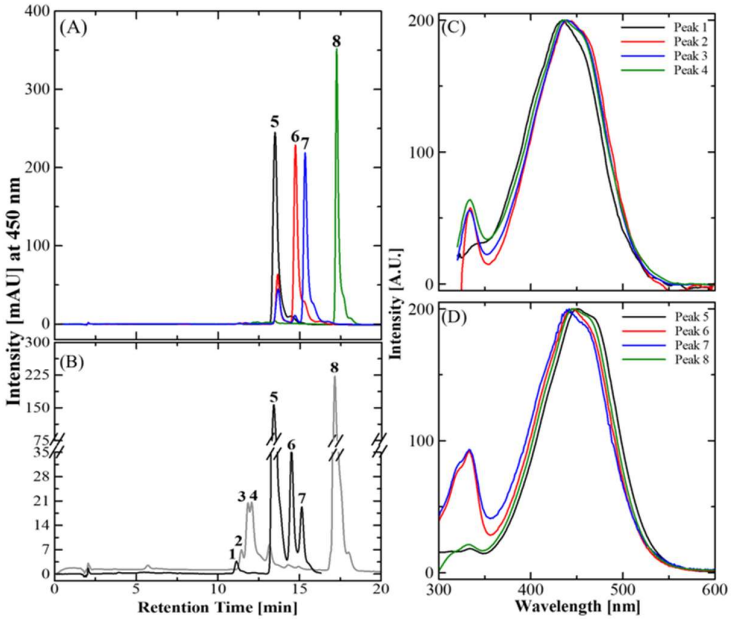

Figure 2 Chromatograms of the thermal induced products of all-*trans* (black line), 13'-*cis* (red line), 13-cis (blue line) and 9'-*cis* (green line) fucoxanthin before (A, control at 30 C); all-*trans* (black line) and 9'-*cis* (grey line) after exposure at 90 °C (B) for 180 min; In situ UV-Vis spectra of peaks 1 - 2 (unknown di-*cis* fucoxanthin) and peak 3 - 4 (9′,13′-di-*cis* and 13,9′-di-*cis* fucoxanthin) (C) and peaks 5 - 8 (mono-*cis* fucoxanthin) (D).

To identify the types of *cis*-isomers, an empirical absorption ratio, Q-ratio, can be used by calculating the ratio between the absorbance value of the absorption maximum band at the *cis* peak and the main peak [47]. A plot between the Q-ratio and the number of carbon double bonds in the shorter arm of fucoxanthin isomers was then used to verify the procedures. The all-*trans* has the lowest Q-ratio and 0 number of C sp2 bond in the shorter arm, then the ratio increases as follows, 9′-cis, 13-*cis* and 13′-*cis*, respectively [48].

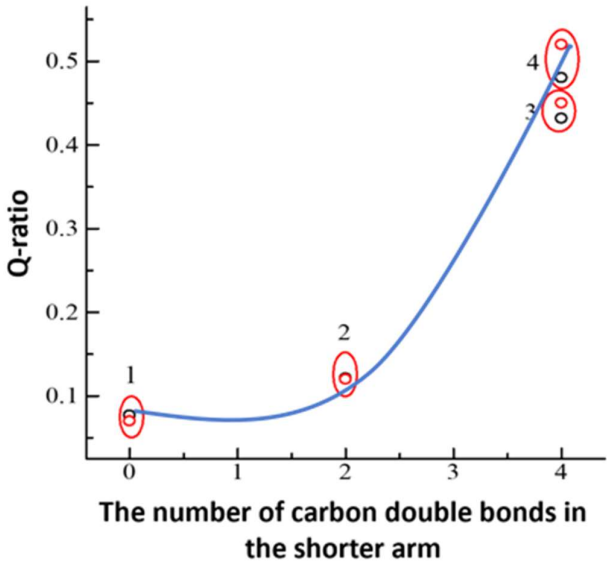

Figure 3 Plot the relationship between Q-ratio and the number of carbon double bonds in the shorter arm of fucoxanthin isomers. The values for the black hole circle and the red hole circle were cited from the reports by Wibowo *et al.* (2022) [48] and Haugan and Liaaen-Jensen (1994) [45], respectively.

Various methods have been developed to separate the geometric isomers of fucoxanthin, such as all-*trans*, 13-*cis*, 13′-*cis* and 9′-*cis*. These isomers can be effectively separated using a C30 column with varying elution gradient mixtures, such as methanol (MeOH), isopropanol and n-hexane mixture [49], MeOH, water (H_2O) and methyl tert-butyl ether (MTBE) mixture and MeOH and acetonitrile (ACN) mixture [50]. To achieve higher purity of all-trans fucoxanthin, centrifugal partition chromatography has been developed [51]. In addition, a combination with flash chromatography or reversed phase (RP)-high-performance liquid chromatography (HPLC) using a C18 column has successfully enhanced the purity of all-*trans* fucoxanthin up to 99 % [52]. C18 and C30 columns are widely used for the separation and purification of carotenoids. However, the use of a C18 column is more suitable for hydrophilic carotenoids only and is not very effective in separating geometric isomers, particularly within the xanthophyll group [53]. On the other hand, the C30 column is more efficient in resolving geometric isomers of carotenoids, including mono-*cis* or di-*cis* isomers [54-56]. A new method for purifying different isomers of fucoxanthin from brown seaweeds has been developed. The purification process involves 2 steps: Open-column chromatography (OCC) and reversed-phase (RP)-high-performance liquid chromatography (HPLC) [48]. Initially, a highly pure fucoxanthin fraction is obtained through silica-gel OCC. Then, 4 major fucoxanthin isomers - all-*trans*, 13′-*cis*, 13-*cis* and 9′-*cis* - are simultaneously separated and purified using RP-HPLC with an analytical C30 column and gradient elution in a mixture of water, methanol and methyl tert-butyl ether. Finally, a large-scale purification via RP-HPLC utilizing a preparative C18 column proves effective for the purification of all-trans and 9′-cis, yielding a 95 % recovery.

Effect of changes in geometric structure on functions and biological activities

Isomerization is a process that occurs frequently in carotenoids due to the presence of conjugated double bonds in their structures. Generally, the *trans* isomers of carotenoids are more commonly found in food and are more stable compared to their *cis* counterparts. Factors such as exposure to light, thermal energy, chemical reactions and interaction with biological molecules like proteins contribute to the *cis*–*trans* isomerization process. In this review, we will focus on light and thermal energy as the most common factors that contribute to the isomerization of fucoxanthin.

The exposure to light could promote the isomerization of fucoxanthin at an early storage stage and photodegradation in long-term storage. Light-induced stereomutation of fucoxanthin is usually catalyzed by iodine to transform all-*trans* fucoxanthin into 9′-*cis*, 13′-*cis*, 13-*cis*, 9′,13′-di-*cis*, 13,9′-di-*cis*, 13,13′-di-*cis* and 15-*cis* [57]. The recent report, stereomutation of fucoxanthin using illumination and catalyzed by iodine has been studied with HPLC method using YMC C30 column showed the isomer products of di-*cis*, di-*cis*$_1$, 9′,13′-di-*cis*, 13,9′-di-*cis*, all-*trans*, 13′-*cis*, 13-*cis*, 9′-*cis* and 9-*cis*, as function of retention time subsequently [48].

Figure 4 depicts the conversion diagram of fucoxanthin isomers as induced by light illumination and thermal treatment. The illumination of fucoxanthin in canola oil at 300 or 2,000 lux resulted in the degradation of total, all-*trans*, 13-*cis* and 13′-*cis* and the formation of 9′-*cis* [43]. Interestingly, the initial formation of all-*trans* occurred and the concurrent initial sudden degradation of 13-*cis* and 13′-*cis* was observed at both light intensities. The formation of 9′-*cis* was significantly promoted by the illumination implying that 9′-*cis* is more light-stable than the other *cis* isomers. Heating is the most extensively studied factor influencing fucoxanthin extractability and stability. Increasing of heat results in the spontaneous degradation of all-trans fucoxanthin and promote some amounts of it to be transformed into *cis* counterparts with activation energies of 13′-*cis*, 13-*cis* and 9′-*cis* were calculated to be 6.44 kJ/mol (40 - 80 °C) and −6.8 kJ/mol (80 - 100 °C), 4.12 kJ/ mol (40 - 80 °C) and −12.4 kJ/mol (80 - 100 °C) and 4.84 kJ/mol (40 - 80 °C) and −7.54 kJ/mol (80 - 100 °C), respectively [47].

The structural change of carotenoids plays a crucial role in the alteration of their biological activity. For example, it is proposed that the *cis*-isomers of carotenoids can enhance their cellular incorporation by augmenting their solubility [58,59]. A study was carried out to evaluate the effect of geometrical isomers of fucoxanthin, a carotenoid found in brown seaweeds, on the growth of HL-60, Caco-2, PC-3 and LNCap cancer cells [50]. The results indicated that the cellular uptake and incorporation of the all-*trans* form of fucoxanthin was higher compared to its *cis* counterparts. On the other hand, *cis* forms of fucoxanthin showed a higher inhibitory effect compared to their trans counterparts.

According to a recent study by Kurinjery and Kulanthaiyesu [60], fucoxanthin has been found to possess anti-hyaluronidase properties in vitro, which was confirmed through molecular docking. The results of the molecular docking show that the 13′-*cis* form of fucoxanthin exhibited the highest docking score of –8.2 kcal/mol, followed by the 9′-cis and all-*trans* forms. Interestingly, while the all-*trans* form of fucoxanthin has been found to exhibit higher biological activity compared to its cis counterparts, its docking affinity towards anti-hyaluronidase was lower. This suggests that the ratio of *cis*/*trans* isomers plays a

crucial role in determining the biological activity of fucoxanthin, with the all-*trans* form exhibiting more antioxidant action [60-62].

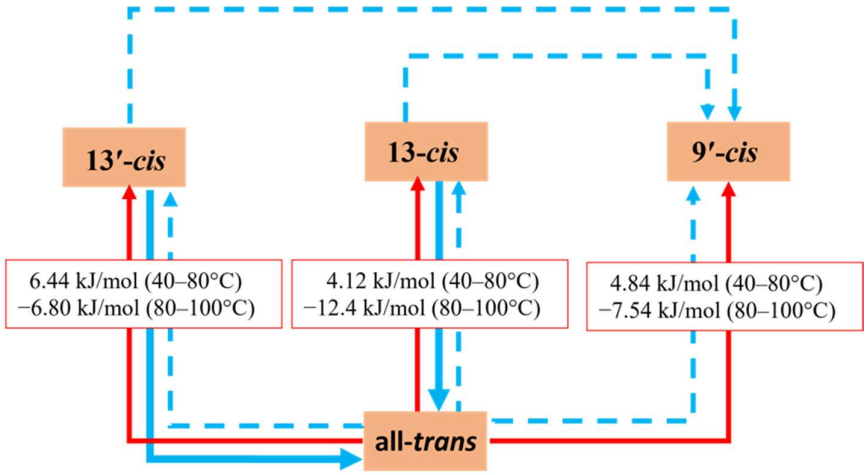

Figure 4 Stereomutation conversion of fucoxanthin by illumination as reported by Zhao *et al.* (2014) [43] and by thermal induction as reported by Wibowo *et al.* (2022) [47] shown in blue and red arrows, respectively. For light-induced isomerization (blue line), the solid arrows show direct rapid conversion occurred at the initial process.

Conclusions

In conclusion, fucoxanthin, a carotenoid inherent in brown seaweed, emerges as a multifaceted compound with pivotal roles in photosynthesis and photoprotection. As a rich source of fucoxanthin, brown seaweed cultivation has witnessed a global uptick, though concerns surrounding arsenic levels necessitate vigilant monitoring. The structural intricacies of fucoxanthin contribute substantively to its bioactivity, with recent studies highlighting the nuanced impact of isomer ratios on its biological responses. This comprehensive review underscores the dynamic landscape of fucoxanthin research, portraying it as a promising agent for advancing human health within the realms of nutrition and pharmaceuticals. Optimizing its bioavailability and stability remains a key focus, paving the way for future explorations and applications in harnessing the potential of fucoxanthin for enhanced well-being.

Acknowledgments

We thank the Central Laboratory for Research and Services at Diponegoro University, Indonesia for their support of the research facilities.

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