

Progress in the Preparation and Application of Fucoxanthin from Algae

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Abstract: This article comprehensively reviews the progress in the preparation and application of fucoxanthin derived from marine algae. Through four dimensions, including biological sources and chemical structure, production processes, structural identification methods, physiological functions, and applications, this paper delves into the advancements in fucoxanthin preparation and application, drawing on experimental data and clinical applications from relevant research. Additionally, technical issues and challenges in current fucoxanthin research are highlighted, encompassing aspects such as increased production, purity enhancement, and structural modification. Finally, the paper summarizes the research findings, outlining the future research directions and prospects for the progress in fucoxanthin preparation and application, and offers some suggestions for future fucoxanthin research.

Keywords: Fucoxanthin; Production Processes; Application Progress; Future Prospects.

1. Introduction

Fucoxanthin, a naturally occurring brown carotenoid, is widely distributed in marine algae such as brown seaweeds, green algae, and diatoms, making it one of the most abundant carotenoids in marine ecosystems [1, 2]. In recent years, fucoxanthin has garnered significant attention due to its diverse physiological functions, including antioxidant, antitumor, hypolipidemic, and weight-loss effects [3]. Many scholars consider fucoxanthin a promising bioactive substance with immense research value [4-6].

Despite the intense interest in fucoxanthin's bioactivities and potential applications, its low content in marine algae and the challenges associated with its preparation and purification have hampered its further industrial exploitation and utilization. To address these issues, scholars worldwide have conducted extensive research on fucoxanthin's preparation and applications. This research has focused on enhancing extraction efficiency, improving separation and purification techniques, and optimizing production processes to increase fucoxanthin's yield and purity, thereby expanding its application areas [7-9].

However, numerous challenges and questions remain in fucoxanthin research. For instance, there is a need to refine production processes to reduce costs while maintaining high quality. Furthermore, stability issues related to fucoxanthin require attention. Additionally, exploring the synergistic application of fucoxanthin with other natural pigments and its potential in healthcare and pharmaceutical fields offers exciting opportunities for future research.

This paper aims to comprehensively summarize the biological sources, production processes, purification methods, structural identification, physiological functions, and applications of fucoxanthin. It also discusses the technical issues, challenges, and future development directions in fucoxanthin research. By analyzing the current research findings and outstanding problems, this paper aims to provide valuable insights and guidance for further research and

development of fucoxanthin.

2. The Biological Sources and Production Processes of Fucoxanthin

2.1. Biological Sources of Fucoxanthin

Fucoxanthin, a carotenoid compound, is widely distributed in marine organisms. It has been discovered in various brown and green algae species, with the most common brown algae including rockweeds, kelp, and seaweeds, while freshwater and marine green algae are the primary sources of fucoxanthin among green algae. Additionally, some bacteria and fungi have also been found to contain fucoxanthin. Fucoxanthin derived from different sources exhibits variations in chemical structure, content, and biological activities, necessitating thorough comparisons and evaluations in its application research [10, 11]. Notably, fucoxanthin is primarily stored as fatty acid esters in the cuticle of brown algae, whereas it exists in free form within the cytoplasm of green algae. With the increasing depth of research into marine biodiversity and resources, more sources of fucoxanthin are being discovered, broadening the scope and possibilities for its application and investigation.

2.2. Production Technology of Fucoxanthin

The production of fucoxanthin primarily encompasses two methods: traditional extraction and biotechnology-based synthesis [12]. The traditional extraction method involves preliminary processing, grinding, and extraction of seaweed, followed by subsequent processes such as decolorization, desalination, filtration, and crystallization to obtain fucoxanthin products with high purity. However, this method suffers from low extraction efficiency, long production cycles, environmental impact, resource waste, and high costs.

Alternatively, the biotechnology approach utilizes genetic engineering, fermentation, and metabolic engineering techniques to synthesize fucoxanthin through microorganisms, plants, and other organisms. This method

offers advantages such as high extraction efficiency, high purity, short production cycles, and independence from seasonal and environmental variations. Common biocatalysts used for fucoxanthin production include *Escherichia coli*, yeast, and *Brassica napus*. Modifications to their genomes and metabolic engineering strategies have successfully achieved efficient fucoxanthin production.

Currently, the primary biotechnology-based method for fucoxanthin production involves engineering *Escherichia coli* to synthesize the compound. Genomic modifications enable the bacteria to produce fucoxanthin, while optimized fermentation conditions, including timing and media composition, enhance production efficiency and quality. Additionally, artificial synthesis of fucoxanthin using biotechnology involves constructing the molecular backbone from simpler molecules and completing the remaining steps through chemical reactions. Although this approach is costlier, it allows precise control over the fucoxanthin molecular structure, facilitating the development of novel fucoxanthin derivatives.

In conclusion, the choice of production method significantly impacts fucoxanthin's yield, purity, and cost, necessitating a tailored approach based on specific requirements. With the continued advancements in biotechnology, innovative techniques are being integrated into fucoxanthin production, offering promising prospects and development opportunities for its industrialization and commercialization.

3. Purification and Structure Identification of Fucoxanthin

3.1. Purification Method of Fucoxanthin

The concentration of fucoxanthin in marine algae is relatively low, necessitating purification processes to enhance its purity and yield. Currently, common purification techniques include organic solvent extraction, chromatography, and crystallization [13,14].

Organic solvent extraction is a frequently employed method, utilizing solvents such as acetone, ethanol, n-butanol, and chloroform. By mixing the algal powder with the organic solvent, followed by stirring and oscillation, an extract containing fucoxanthin is obtained. Subsequently, the extract is centrifuged, and the supernatant is collected and concentrated using a rotary evaporator, resulting in a concentrated fucoxanthin solution.

Chromatography, another widely used purification technique, encompasses gel chromatography, reverse-phase high-performance liquid chromatography (RP-HPLC), and ion-exchange chromatography. Among these, RP-HPLC stands out as an effective method for achieving high-purity fucoxanthin. In RP-HPLC, a C18 column with hydrophobic groups is employed. Through interactions between fucoxanthin and the column, and by adjusting the polarity and flow rate of the elution solvent, fucoxanthin can be effectively separated.

Apart from these two primary purification methods, crystallization is also commonly utilized, capable of purifying fucoxanthin to over 99% purity. Solvents commonly used in the crystallization process include acetone, ethanol, n-butanol, and water. By carefully controlling the crystallization temperature and rate, fucoxanthin crystals with various purities and morphologies can be obtained.

3.2. Structural Identification of Fucoxanthin

The structural identification of fucoxanthin serves as a crucial foundation for elucidating its biological activities and application prospects. The structure of fucoxanthin is characterized by several distinct structural units, including two 5,6-epoxides, two alkyl termini, and a conjugated system. Consequently, conventional analytical methods often fall short in meeting the demands of its structural elucidation. Currently, techniques such as mass spectrometry, nuclear magnetic resonance spectroscopy, and infrared spectroscopy are commonly employed for its structural identification and interpretation [15-18].

Mass spectrometry is one of the essential tools for fucoxanthin structural identification, with electrospray ionization mass spectrometry and MALDI-TOF mass spectrometry being frequently used methods [19,20]. Through mass spectrometry, the molecular weight and molecular ion peaks of fucoxanthin can be measured, enabling the inference of its structure.

Nuclear magnetic resonance spectroscopy (NMR) is another vital technique for fucoxanthin structural identification, providing information on its molecular structure and stereoconfiguration [21]. Additionally, NMR analysis can further deduce molecular structures by studying chemical shifts and dipolar coupling constants.

Infrared spectroscopy (IR) is a commonly used method for molecular structural analysis, determining the structure by detecting functional groups within the molecule [22,23]. Fucoxanthin contains multiple unique functional groups, such as epoxy groups and alkyl termini, and IR analysis can effectively determine the positions and chemical properties of these functional groups.

By comprehensively utilizing these methods, a comprehensive and accurate identification of fucoxanthin's structure can be achieved, providing crucial support for subsequent research on its biological activities and applications.

4. Physiological Function and Application of Fucoxanthin

4.1. The Physiological Functions of Fucoxanthin

Due to its unique chemical structure and biological characteristics, fucoxanthin exhibits diverse physiological functions. Firstly, fucoxanthin serves as an effective antioxidant, capable of capturing free radicals, scavenging peroxides, and counteracting oxidative stress. Research indicates that fucoxanthin possesses antioxidant capabilities that are 100 times stronger than beta-carotene and 10 times stronger than vitamin E, effectively preventing and treating various diseases such as cancer, cardiovascular disease, and diabetes [24,25]. Secondly, fucoxanthin regulates immune function. Studies have demonstrated that fucoxanthin can enhance the activity of immune cells, including T cells and natural killer cells, thereby promoting antibody production. This enhancement can effectively improve the immune system's resilience, aiding in the prevention and treatment of immune-related diseases like tumors and autoimmune disorders [26,27].

Furthermore, fucoxanthin exhibits anti-inflammatory properties. It has been shown to suppress the production of inflammatory mediators such as interleukin-1 and tumor

necrosis factor, thereby reducing inflammatory responses and effectively treating conditions like rheumatoid arthritis and inflammatory bowel disease [28,29]. Additionally, fucoxanthin is beneficial for vision. Research suggests that it can inhibit the oxidation and damage of retinal pigments, alleviating eye fatigue, improving vision, and preventing vision-related diseases such as age-related macular degeneration [30].

Therefore, fucoxanthin holds considerable potential as a natural and healthy food additive, as well as a component in health supplements, offering vast application prospects and market value.

4.2. Standalone Application of Fucoxanthin

In recent years, the research on the biological activity and medicinal value of fucoxanthin has been continuously deepened, leading to its increasingly widespread application in medicine, healthcare, food, and cosmetics.

Firstly, fucoxanthin exhibits certain biological activities in medicine, serving as an antioxidant and anti-inflammatory agent. It demonstrates preventive and therapeutic effects on various diseases, including cancer, obesity, and cardiovascular diseases.

Secondly, fucoxanthin is commonly used in the healthcare industry to regulate lipid metabolism, lower blood lipids, reduce obesity, and prevent cardiovascular diseases. Additionally, it possesses anticancer properties. Relevant studies have shown that fucoxanthin can exert its anticancer effects through inhibiting cancer cell growth, inducing cancer cell apoptosis, and blocking angiogenesis in neurofibromas [31,32].

Thirdly, fucoxanthin finds application in the food industry as a natural food coloring agent, added to various foods such as juices, beverages, candies, and pastries. Moreover, it enhances immunity and prevents gastric ulcers, serving as a natural health-promoting component in food [33,34].

Lastly, the application of fucoxanthin in the field of beauty and skincare is also gaining increasing attention. With its antioxidant, anti-inflammatory, and anti-aging properties, fucoxanthin can help improve skin texture, lighten pigmentation, and reduce skin sensitivity. In recent years, more and more cosmetic companies have begun to use fucoxanthin as an active ingredient in skincare products, developing numerous fucoxanthin-containing items such as masks, lotions, and essences. Research indicates that lotions containing 1% fucoxanthin can significantly improve facial skin elasticity and moisture content, resulting in healthier and smoother skin [35,36].

In conclusion, with the deepening research on marine organisms, fucoxanthin, a natural, safe, and highly effective bioactive substance, is expected to have increasingly broad application prospects.

4.3. Integrated Application of Fucoxanthin with Other Natural Pigments

With the increasing demand for natural food additives, research has increasingly focused on the combined application of natural pigments. As a natural pigment, fucoxanthin has attracted considerable attention in its cooperative usage with other natural pigments. Several studies have shown that the combination of fucoxanthin with other natural pigments can produce better color tones and stability while enhancing antioxidant and physiological activities [37,38].

In recent years, research has also explored the application of mixtures of marine algal pigments, including fucoxanthin, phycobiliproteins, and chlorophyll, in food products. These mixtures have been found to be suitable for the preparation of condiments, bread, cakes, and other foods, without adversely affecting the color, taste, or nutritional composition of the foods [39-41].

Furthermore, the combined application of fucoxanthin and anthocyanins has been investigated. The results indicate that the combination of fucoxanthin and anthocyanins can produce more vivid colors and exhibit stronger antioxidant activity, making them suitable for use in the preparation of beverages, juices, and other products [42,43]. Additionally, the combination of fucoxanthin and carotenoids has also been extensively studied. These compounds can be used as antioxidants in the preparation of meat products, significantly improving their color and freshness [44,45].

It is worth noting that the combined application of different natural pigments requires thorough research and testing to determine their optimal ratios and application conditions. Moreover, the stability of natural pigments is a crucial consideration as they may undergo varying degrees of degradation and discoloration in different environments [30,46,47]. Therefore, careful research and control are necessary to ensure the effectiveness and stability of natural pigments in their combined applications.

In conclusion, the integrated application of fucoxanthin with other natural pigments holds promising prospects and is significant for promoting the development and application of natural food additives.

5. Problems and Prospects in Fucoxanthin Research

5.1. Technical Issues and Challenges

Despite the vast physiological functions and promising application prospects of fucoxanthin, its research and application are confronted with several technical issues and challenges.

Firstly, the extraction and purification of fucoxanthin pose significant technical difficulties. Given its low concentration in marine algae, efficient extraction and separation techniques are required. Currently, methods such as organic solvent extraction, supercritical fluid extraction, and ultrasonic-assisted extraction are employed. However, these techniques are associated with environmental pollution and low extraction efficiency, necessitating further improvements [48,49].

Secondly, the complex structure of fucoxanthin presents difficulties in structural identification. Traditional spectroscopic methods have limitations in analyzing compounds with intricate structures, necessitating the integration of multiple spectroscopic techniques, including nuclear magnetic resonance, mass spectrometry, and infrared spectroscopy. Additionally, chemical degradation and synthesis methods are required for structural elucidation [50,51].

Furthermore, the biological effects and mechanisms of fucoxanthin require deeper exploration. Although studies have demonstrated its antioxidant, anti-inflammatory, and antitumor properties, the specific mechanisms underlying these effects remain elusive. Additionally, the safety and toxicity of fucoxanthin need further evaluation [52,53].

Lastly, fucoxanthin faces technical challenges in its

application. Issues such as stability and bioavailability during production and usage limit its current application scope, necessitating the exploration of new application avenues and performance improvements [54-56].

In summary, further exploration and research are needed in the areas of extraction and purification, structural identification, biological effects and mechanisms, safety and toxicity evaluation, and applications of fucoxanthin to facilitate its utilization in biomedicine, food, and cosmetics industries.

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6. Conclusion

This article presents a comprehensive overview of fucoxanthin, a significant carotenoid found in marine algae, focusing on its biological sources, production processes, purification methods, structural identification, physiological functions, and applications. Currently, fucoxanthin has found widespread usage across various industries, including health supplements, cosmetics, food, and pharmaceuticals. However, several technical issues and challenges persist in fucoxanthin research, such as the optimization of production processes, the development of efficient purification methods, the exploration of physiological function mechanisms, and the

investigation of dose-effect relationships. Future research should prioritize addressing these challenges and exploring the potential of fucoxanthin in broader application fields, aiming to maximize its vital physiological functions and impacts.

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