Asia Pacific Science Press

Journal of Advances in Engineering and Technology
ISSN(O): 3005-7507
ISSN(P): 3005-7493
https://doi.org/10.62177/jaet.v1i1.2

Progress in Preparation and Application of Fucoxanthin from Marine Algae

Bo Zhang [1], Feng Wan [1]

[1] Beijing University of Science and Technology, Beijing 100083, China

Abstract: This paper reviews the preparation and application of fucoxanthin from marine algae. It details the progress in various aspects, including biological origin, chemical structure, production process, structure identification, physiological functions, and applications, based on experimental data and clinical applications. The paper also highlights technical challenges and issues in fucoxanthin research, such as improving yield, purity, and structure modification. Finally, it summarizes the research findings and discusses future research directions and prospects for fucoxanthin from marine algae, offering suggestions for further studies.

Keywords: Fucoxanthin, Production Process, Application Progress, Prospect

---

Published: July 16, 2024

1. Introduction

Fucoxanthin is a natural coffee-colored carotenoid widely found in marine algae, such as brown algae, green algae, and diatoms. It is one of the most abundant carotenoids in marine ecosystems [1,2]. In recent years, fucoxanthin has attracted significant attention due to its physiological functions, including antioxidant, anti-tumor, hypolipidemic, and weight loss effects [3]. Many scholars consider fucoxanthin a bioactive substance with wide application prospects and great research value [4-6]. However, despite its promising biological activity and application potential, the industrial development and utilization of fucoxanthin are limited by its low content in marine algae and the challenges associated with its preparation and purification.

Recent studies have focused on improving the yield and purity of fucoxanthin by enhancing extraction rates, refining separation and purification processes, and optimizing production methods, which have further expanded its application fields [7-9]. Nevertheless, numerous problems and challenges remain in fucoxanthin research. These include improving the production process while effectively reducing production costs and addressing the stability of fucoxanthin. Additionally, exploring the combined application of fucoxanthin with other natural pigments and investigating its prospects in health products, medicine, and other fields are essential.

This paper systematically summarizes the biological sources, production processes, purification methods, structure identification, physiological functions, and applications of fucoxanthin. It also discusses the existing technical problems and challenges in fucoxanthin research, along with future development directions and prospects. By analyzing existing research results and identifying current issues, this paper provides valuable references and guidance for further research and development of fucoxanthin.

2. Biological Source and Production Process of Fucoxanthin

2.1 Biological Sources of Fucoxanthin

Fucoxanthin is a carotenoid compound widely distributed in marine organisms. It has been identified in various brown algae and green algae. The most common brown algae containing fucoxanthin include fucoidin, kelp, and Undaria pinnatifida, while the primary fucoxanthin-producing algae in green algae are freshwater green algae and marine green algae. Additionally, some fungi have also been found to contain fucoxanthin. Fucoxanthin from different sources exhibits variations in chemical structure, content, and biological activity, necessitating thorough comparison and evaluation in application research [10,11]. Notably, in brown algae, fucoxanthin is primarily stored in the cuticle in the form of fatty acid esters, whereas in green algae, it exists in the cytoplasm in its free form. As marine biodiversity and resources are studied more deeply, an increasing number of fucoxanthin sources are being discovered, providing broader possibilities for its application and research.

2.2 Production Process of Fucoxanthin

The production process of fucoxanthin primarily includes traditional extraction methods and biotechnological methods [12]. In the traditional extraction method, the seaweed undergoes preliminary treatment, grinding, and leaching, followed by processes such as decolorization, desalination, filtration, and crystallization to obtain a high-purity fucoxanthin product. This method has disadvantages, including low extraction efficiency, long production periods, environmental impact, resource waste, and high costs.

Biotechnological methods involve synthesizing fucoxanthin using microorganisms, plants, and other organisms through genetic engineering, fermentation, metabolic engineering, and other biotechnological means. These methods offer advantages such as high extraction efficiency, high purity, shorter production periods, and no influence from seasonal or environmental factors. Common strains used in biotechnology for fucoxanthin production include Escherichia coli, yeast, and Brassica napus. Through genome modification and metabolic engineering regulation, efficient fucoxanthin production has been successfully achieved.

Currently, the engineering synthesis of fucoxanthin using Escherichia coli is predominant. By modifying its genome, E. coli can produce fucoxanthin. Additionally, optimization of culture conditions, fermentation time, and medium components has improved the production efficiency and quality of fucoxanthin. Furthermore, biotechnological methods can achieve the artificial synthesis of fucoxanthin, where key steps include building a fucoxanthin molecular skeleton from simpler molecules and completing the remaining steps through chemical reactions. Although this method incurs higher costs, it allows precise regulation and control of the fucoxanthin molecular structure, providing possibilities for developing novel fucoxanthin derivatives.

In summary, different production processes significantly impact the yield, purity, and cost of fucoxanthin, necessitating selection based on specific circumstances. With continuous advancements in biotechnology, innovative technologies are increasingly being introduced into fucoxanthin production, offering better prospects and development opportunities for its industrialization and commercialization.

3. Purification and Structure Identification of Fucoxanthin

3.1 Purification Method of Fucoxanthin

The content of fucoxanthin in marine algae is relatively low, necessitating purification to improve its purity and yield. Common purification methods include organic solvent extraction, chromatography, and crystallization [13,14].

Organic Solvent Extraction: This method uses organic solvents such as acetone, ethanol, n-butanol, and chloroform. Seaweed powder is mixed with the organic solvent and stirred to obtain a fucoxanthin extract. The extract is then centrifuged, and the supernatant is collected and concentrated using a rotary evaporator to obtain a concentrated fucoxanthin solution.

Chromatography: This method includes gel chromatography, reverse-phase high-performance liquid chromatography (RP-HPLC), and ion exchange chromatography. RP-HPLC is particularly effective for obtaining high-purity fucoxanthin. Using a C18 column with hydrophobic groups, fucoxanthin interacts with the column and is separated by changing the polarity and flow rate of the elution solvent.

Crystallization: This method can purify fucoxanthin to over 99%. Solvents such as acetone, ethanol, n-butanol, and water are used. By controlling the crystallization temperature and speed, fucoxanthin crystals with varying purity and morphology can be obtained.

3.2 Structural Identification of Fucoxanthin

The structural identification of fucoxanthin is crucial for determining its biological activity and application prospects. Fucoxanthin contains unique structural units, such as two 5,6-epoxides, two alkyl terminations, and conjugated systems, which require advanced analytical methods for accurate identification. Common methods include mass spectrometry, nuclear magnetic resonance spectroscopy, and infrared spectroscopy [15-18].

Mass Spectrometry (MS): MS is vital for structural identification, with electrospray ionization mass spectrometry (ESI-MS) and MALDI-Tof mass spectrometry being commonly used [19,20]. MS determines the molecular weight and molecular ion peak of fucoxanthin, aiding in structural elucidation.

Nuclear Magnetic Resonance Spectroscopy (NMR): NMR is essential for determining the molecular structure and three-dimensional configuration of fucoxanthin [21]. It can deduce the molecular structure by studying chemical shifts and dipolar coupling constants.

Infrared Spectroscopy (IR): IR analysis detects functional groups in molecules to determine molecular structure [22,23]. Fucoxanthin has functional groups like epoxy and alkyl terminals, whose positions and chemical properties can be identified using IR analysis.

By utilizing these methods comprehensively, the structure of fucoxanthin can be accurately identified, providing essential support for subsequent biological activity and application research.

4. Physiological Function and Application of Fucoxanthin

4.1 Physiological Functions of Fucoxanthin

Due to its unique chemical structure and biological characteristics, fucoxanthin exhibits a variety of physiological functions. Firstly, fucoxanthin is a potent antioxidant, capable of capturing free radicals, scavenging peroxides, and resisting oxidative stress. Studies have shown that the antioxidant capacity of fucoxanthin is 100 times that of carotene and 10 times that of vitamin E, effectively preventing and treating numerous diseases, such as cancer, cardiovascular disease, and diabetes [24,25]. Secondly, fucoxanthin also regulates immune function. Research indicates that fucoxanthin can enhance the activity of immune cells, such as T cells and natural killer cells, thereby promoting antibody production and improving the body's immunity, which helps in preventing and treating many immune-related diseases, including tumors and autoimmune diseases [26,27].

Additionally, fucoxanthin has anti-inflammatory effects. It can inhibit the production of inflammatory mediators like interleukin-1 and tumor necrosis factor, thus reducing inflammatory responses and effectively treating diseases such as rheumatoid arthritis and inflammatory bowel disease [28,29]. Furthermore, fucoxanthin protects eyesight by inhibiting the oxidation and damage of retinal pigments, reducing eye fatigue, improving vision, and preventing age-related macular degeneration and other vision-related diseases [30].

Therefore, fucoxanthin can be used as a natural and healthy food additive and health care product, offering wide application prospects and market value.

4.2 Individual Application of Fucoxanthin

In recent years, fucoxanthin has been widely used in medicine, health care, food, and cosmetics due to its biological activity and medicinal value.

Medicine: Fucoxanthin has certain biological activity in medicine, acting as an antioxidant and anti-inflammatory agent. It has preventive and therapeutic effects on cancer, obesity, cardiovascular disease, and other conditions.

Health Care Products: Fucoxanthin is used to regulate lipid metabolism, reduce blood lipids, combat obesity, and prevent cardiovascular diseases. It also has anti-cancer properties, inhibiting cancer cell growth, inducing cancer cell apoptosis, and preventing neurofibroma angiogenesis [31,32].

Food Industry: As a natural food pigment, fucoxanthin is added to various foods, such as juice, beverages, candy, and pastries. It enhances immunity and prevents gastric ulcers, serving as a natural food health ingredient [33,34].

Cosmetics: Fucoxanthin's antioxidant, anti-inflammatory, and anti-aging effects improve skin texture, fade spots, alleviate skin sensitivity, and address other skin issues. Many cosmetic companies use fucoxanthin as an active ingredient in products like masks, lotions, and serums, significantly improving skin elasticity and moisture content [35,36].

Overall, as research into marine organisms progresses, fucoxanthin, a natural, safe, and efficient bioactive substance, will have increasingly extensive application prospects.

4.3 Combined Application of Fucoxanthin and Other Natural Pigments

With the growing demand for natural food additives, studies increasingly focus on the application of natural pigments. As a natural pigment, fucoxanthin is often used in combination with other natural pigments. Some studies show that combining fucoxanthin with other pigments results in better tone and stability, as well as enhanced antioxidant and physiological activity [37,38]. Recent research has explored marine algae pigment mixtures in food, including fucoxanthin, phycobiliprotein, and chlorophyll. These mixtures can prepare sauces, breads, cakes, and other foods without negatively affecting their color, taste, or nutritional components [39-41].

Other studies have explored combining fucoxanthin with anthocyanins, producing brighter colors and stronger antioxidant activity suitable for beverages and juices [42,43]. Combining fucoxanthin with carotene also shows promise, as the combination can act as antioxidants to improve the color and freshness of meat products [44,45].

It is important to thoroughly study and test the combined application of different natural pigments to determine the optimal ratios and conditions. The stability of natural pigments must also be considered, as different pigments may degrade and discolor in various environments [30,46,47]. Ensuring the effectiveness and stability of natural pigments requires careful research and control.

In conclusion, the combination of fucoxanthin with other natural pigments has broad application prospects, significantly promoting the development and application of natural food additives.

5. Problems and Prospects in the Study of Fucoxanthin

5.1 Technical Issues and Challenges

Despite the extensive physiological functions and application prospects of fucoxanthin, several technical challenges impede its research and utilization.

Firstly, the extraction and purification process of fucoxanthin presents significant technical difficulties. The low concentration of fucoxanthin in marine algae necessitates highly efficient extraction and separation techniques. Currently, methods such as organic solvent extraction, supercritical fluid extraction, and ultrasonic-assisted extraction are employed. However, these methods have issues like environmental pollution and low extraction efficiency, requiring further enhancement [48,49].

Secondly, due to the complexity of fucoxanthin’s structure, structural identification poses challenges. Traditional spectroscopic methods have limitations for complex compounds, necessitating a combination of various spectroscopic techniques such as nuclear magnetic resonance, mass spectrometry, and infrared spectroscopy. Additionally, chemical degradation and chemical synthesis methods are needed for structural validation [50,51].

Moreover, the biological effects and mechanisms of fucoxanthin require further investigation. Although some studies indicate fucoxanthin's antioxidant, anti-inflammatory, and anti-tumor functions, the specific mechanisms of action remain unclear. Furthermore, the safety and toxicity of fucoxanthin necessitate comprehensive evaluation [52,53].

Finally, technical challenges in the application of fucoxanthin include stability and bioavailability issues during production and usage. These challenges limit the scope of fucoxanthin's applications, necessitating further exploration of application methods and performance improvement [54-56].

In summary, further exploration and research are essential in the areas of extraction and purification, structural identification, biological effects and mechanisms, safety and toxicity evaluation, and application methods to promote fucoxanthin's use in biomedicine, food, and cosmetics.

5.2 Development Direction and Prospect

The future research on fucoxanthin will focus on the following aspects:

Firstly, further exploration of fucoxanthin’s physiological functions and molecular mechanisms is needed to understand its relationship with human health. As a natural antioxidant, fucoxanthin aids in scavenging free radicals and maintaining health, offering significant potential in preventing chronic diseases and slowing aging. Additionally, fucoxanthin’s anti-inflammatory and anti-tumor functions warrant further molecular mechanism studies to provide a robust scientific basis for its applications.

Secondly, identifying more fucoxanthin-producing strains and enhancing their yields is crucial. Currently, fermentation and extraction are the primary production methods, but yields remain low. Future research should seek high-yield fucoxanthin microorganisms from wild strains and soil samples and develop new production technologies to improve yield and purity, better meeting market demand.

Lastly, improving the stability and bioavailability of fucoxanthin through nanotechnology and other new technologies will enhance its application efficacy. Current applications in drugs and health products face challenges like insufficient stability and low bioavailability. Future research can use nanotechnology to encapsulate fucoxanthin in nano-carriers, enhancing stability and bioavailability for better application outcomes.

In conclusion, fucoxanthin, as a natural antioxidant with various physiological activities, holds vast application prospects. With continuous technological advancements, research and applications of fucoxanthin will deepen, bringing more benefits to human health and economic development.

6. Conclusion

Fucoxanthin, an important carotenoid found in marine algae, has been extensively reviewed in terms of its biological sources, production techniques, purification methods, structure identification, physiological functions, and applications. Currently, fucoxanthin is utilized in various fields, including health care products, cosmetics, food, and medicine. However, several technical challenges and issues persist in fucoxanthin research, such as optimizing production processes, developing efficient purification methods, exploring the mechanisms of physiological functions, and studying dose effects. Future research should aim to address these problems and investigate the application prospects of fucoxanthin across a broader range of fields, to better harness its significant physiological functions and benefits.

7. References

[1] Chen Jiannan, Chen Youqiang, Xue Ting. Extraction and Purification of Fucoxanthin from Isochrysis galbana [J]. Fujian Agricultural Science and Technology, 2020, (04): 28-37.

[2] Sui Ji, Wang Hui, Liu Tianzhong. Research Progress on Characteristics and Biosynthesis of Diatomaceous Fucoxanthin [J]. Marine Science, 2019, 43(12): 130-138.

[3] Li Minlan, Gong Zehua, Sheng Yan, et al. Research Progress on Extraction and Analysis Methods of Fucoxanthin [J]. Food Research and Development, 2021, 42(03): 202-206.

[4] Pan Dongjin, Li Jiaying, Liang Lifen, et al. Research Progress on Fucoxanthin Lipid-lowering Activity and Its Mechanism [J]. Guangxi Science, 2021, 28(06): 588-598.

[5] Fang Jingping, Chen Qinchang, Huang Luqiang. Advances in Fucoxanthin Biosynthesis Pathway and Its Response to Light [J]. Journal of Fujian Normal University (Natural Science Edition), 2021, 37(05): 96-108.

[6] Hou Hongyan, Xiang Weipeng, Zhang Jinrong, et al. Screening of High Fucoxanthin Producing Marine Diatoms and Optimization of Light Condition [J]. Acta Hydrobiologica Sinica, 2020, 44(04): 912-919.

[7] Bi Kehai, Zhang Yuying, Sun Yufeng, et al. Study on Ultrasonic-assisted Enzymatic Extraction of Fucoxanthin from Laminaria japonica [J]. Food Research and Development, 2020, 41(16): 88-93.

[8] Li HY, Wang Y, Liu TH, et al. Study on Extraction and Purification of Fucoxanthin from Sargassum Horneri [J]. Advances in Biotechnology, 2020, 10(02): 205-213.

[9] Wu Suhuang. Isolation and Bioactivity of Fucoxanthin and Its Isomers from Laminaria Japonica [D]. University of Chinese Academy of Sciences (Institute of Oceanology, Chinese Academy of Sciences), 2019.

[10] Xu RJ, Gong YF, Wei FJ, et al. Correlation Analysis between Photosynthetic Physiological Indexes and Fucoxanthin Content of Phaeodactylum tricornutum under Different Light Quality [J]. Chinese Laser, 2020, 47(05): 471-479.

[11] Chen Ruoying, Xu Runjie, Gong Yifu, et al. Effects of Nitrogen on the Gene Expression and Metabolism of Key Enzymes in Fucoxanthin and Lipid Biosynthesis in Phaeodactylum Tricornutum [J]. Journal of Nuclear Agriculture, 2019, 33(09): 1734-1741.

[12] Huang Shousheng, Yu Jiangping, Deng Xia, et al. New Type DCS Application in the Production of Fucoxanthin [J]. Automation and Instrumentation, 2020, 35(11): 98-102.

[13] Hua Rufeng, Zhou Shuhua. Determination of Fucoxanthin in Concentrated Products of Laminaria Japonica by HPLC [J]. Journal of Food Safety and Quality Inspection, 2020, 11(19): 7114-7117.

[14] Zheng XY, Gong YF, Li SR, et al. Photosynthesis Inhibitor DCMU Effects on Fucoxanthin Content, Chlorophyll Fluorescence Characteristics and Key Gene Expression of Phaeodactylum tricornutum [J]. Journal of Nuclear Agriculture, 2020, 34(08): 1705-1712.

[15] Wei Fengjuan. Effects and Mechanisms of Four Elicitors on Fucoxanthin Accumulation in Phaeodactylum Tricornutum [D]. Ningbo University, 2021.

[16] Zhu Defei, Yang Runqing, Song Peiqin, et al. Effects of Light and Feeding Conditions on the Growth and Fucoxanthin Accumulation of Phaeodactylum tricornutum in an Indoor Tube Photobioreactor [J]. Journal of Guangdong Ocean University, 2021, 41(02): 18-26.

[17] Chen Jiannan, Chen Youqiang, Xue Ting. Use of UV and ARTP Screening Isochrysis galbana with Good Characters by Mutagenesis [J]. Fujian Agricultural Science and Technology, 2020, (02): 9-16.

[18] Zheng Lingzhi, Zhang Jie, Ren Ying, et al. Effects of Plant Hormones on the Growth and Fucoxanthin Accumulation of Thalassiosira Weisenbergii [J]. Journal of Fujian Normal University (Natural Science Edition), 2020, 36(04): 57-63.

[19] Zhang Heng, Zhao Qian, Chen Juanjuan, et al. Analysis of Pigments in Sargassum Horneri by Liquid Chromatography-Mass Spectrometry [J]. Journal of Nuclear Agriculture, 2019, 33(06): 1173-1180.

[20] Wang Li. Studies on Structure Identification and Microencapsulation of Carotenoids from Marine Algae [D]. Dalian Ocean University, 2015.

[21] Wang Shuhui. Isolation, Identification and Antitumor Activity of Fucoxanthin from Algae [D]. Ocean University of China, 2010.

[22] Li Donghui. Improvement of Stability and Intestinal Absorption of Fucoxanthin by Protein Noncovalently Bonded Micelles [D]. Jimei University, 2022.

[23] Tang Chen, Lu Wei, Qi Xiaoling, et al. Study on Extraction and Activity of Fucoxanthin from Laminaria Japonica [J]. Journal of Nantong Vocational University, 2017, 31(04): 93-97.

[24] Nur Aminai Maimaiti, Aishanjiang, Zhao Huixin. Research Progress on Pharmacological Effects of Fucoxanthin [J]. Yunnan Chemical Industry, 2021, 48(10): 4-8.

[25] Feng Jinxiu, Wu Jinhui, Wang Huiying, et al. Research Progress on Anti-inflammatory Activity of Fucoxanthin. Beijing, China: 2020: 6.

[26] Sun Xiaowen, Zhao Hailong, Zhao Lili, et al. Preparation, Antioxidant and Antitumor Activities of Fucoxanthin Nanocomposit [J]. Oceans and Lakes, 2019, 50(06): 1233-1240.

[27] Guo Kai. Fucoxanthin Anti-inflammatory and Regulation of Innate Immune Mechanism [D]. Fujian Normal University, 2019.

[28] Han Hui. Neuroprotective Effect of Fucoxanthin on Parkinson's Disease [D]. Ningbo University, 2021.

[29] Zhu Minmin, Li Yunpeng, Zhang Miao, et al. Fucoxanthin Resistance D-gal Induction SH-SY5Y Study on the Effect and Mechanism of Cell Senescence [J]. Guangxi Science, 2021, 28(03): 310-320.

[30] Guo Zixin, Liu Yunjun, Liu Yixiang, et al. Non-antioxidant Pathway of Fucoxanthin in Improving Phagocytosis of Retinal Pigment Epithelial Cells [J]. Food Science, 2022, 43(23): 168-173.

[31] Luan Heqi. Effect of Fucoxanthin on Epithelial-mesenchymal Transition in Lung Adenocarcinoma Cells and Its Mechanism [D]. Dalian Medical University, 2019.

[32] Wang Fei. Protective Effect of Fucoxanthin on Cardiotoxicity Induced by Adriamycin and Its Synergistic Antitumor Effect [D]. Zhejiang Ocean University, 2016.

[33] Li Bin. Study on Extraction and Preparation of Fucoxanthin and Polyphenols from Laminaria Japonica [D]. Jimei University, 2015.

[34] Wang Shuhui, Xue Changhu. Structure, Properties and Functions of Fucoxanthin [J]. Science and Technology of Food Industry, 2010, 31(06): 408-410.

[35] Xiao Lei, Chen Gang, Liu Chenguang. Research Progress on the Application of Active Components from Brown Algae in Cosmetics [J]. Science of Daily Chemicals, 2015, 38(11): 18-21.

[36] Xu Yaru. Study on Antioxidant Activity of Brown Alginate Polyphenol [D].

Ningbo University, 2014.

[37] Wang Bo, Gong Yifu, Ye Ben, et al. Key Enzymes of Fucoxanthin Biosynthesis in Phaeodactylum tricornutum PtHMGR: Studies on Cloning and Regulation of Inducible Expression of Genes [J]. Chinese Journal of Pharmacy, 2023, 58(03): 222-230.

[38] Liu Yan, Zhi Lichao, Wang Huirui, et al. Fucoxanthin of Sargassum Horneri: Inhibition of Glucosidase Activity and Its Hypoglycemic Effect [J]. Journal of Dalian Ocean University, 2023, (01): 120-128.

[39] Wang Xiao. Research Progress on Biological Function and Application of Fucoxanthin [J]. Western Leather, 2018, 40(11): 110.

[40] Li Bin. Study on Extraction and Preparation of Fucoxanthin and Polyphenols from Laminaria Japonica [D]. Jimei University, 2015.

[41] Hu Xiaojie. Study on the Preventive Effect of Fucoxanthin and Soybean Residue Dietary Fiber on Obesity and Its Mechanism [D]. Zhejiang University, 2013.

[42] Li DG, Chen N, Hong YL, et al. Research Progress on Culture Methods and Application of Isochrysis galbana [J]. Fisheries Research, 2022, 44(03): 294-300.

[43] Wang Shuhui, Xue Changhu. Structure, Properties and Functions of Fucoxanthin [J]. Science and Technology of Food Industry, 2010, 31(06): 408-410.

[44] Chen Xiaoli, Wang Shuhui, Zhu Junxiang, et al. Study on the Stability of Fucoxanthin in Water and Oil Model System [J]. Science and Technology of Food Industry, 2016, 37(14): 298-302.

[45] Yan Zhenling. Study on the Stability of Fucoxanthin in Laminaria japonica [J]. Modern Agricultural Science and Technology, 2016, (03): 315-319.

[46] Wei Fengjuan, Gong Yifu, Zhang Li, et al. Effects of Rapamycin on Fucoxanthin Content and Key Enzyme Gene Expression in Phaeodactylum tricornutum [J]. Journal of Biology, 2022, 39(03): 72-77.

[47] Hu Bianfang, Wang Yihua, Hao Huifang, et al. Effects of 2,4-Epibrassinolide on the Growth and Physiological Characteristics of Cyclotella sp. [J]. Journal of Shanxi University (Natural Science Edition), 2022, 45(05): 1385-1391.

[48] Li Minlan, Gong Zehua, Sheng Yan, et al. Research Progress on Extraction and Analysis Methods of Fucoxanthin [J]. Food Research and Development, 2021, 42(03): 202-206.

[49] Bi Kehai, Zhang Yuying, Sun Yufeng, et al. Study on Ultrasonic-assisted Enzymatic Extraction of Fucoxanthin from Laminaria japonica [J]. Food Research and Development, 2020, 41(16): 88-93.

[50] Jia Zeming, Gong Yifu, Zhang Li, et al. Fucoxanthin Synthesis in Phaeodactylum tricornutum: ZEP Bioinformatics, Subcellular Localization and Expression Analysis of Gene Family [J]. Chinese Journal of Pharmacy, 2022, 57(24): 2067-2076.

[51] Zhao Songhao, Tao Qiushuang, Shen Jianren, et al. Diatom Fucoxanthin: Chlorophyll a/c Protein-Revealing Erythroid Light-Harvesting Antenna Complex [J]. Nature Magazine, 2021, 43(03): 157-164.

[52] Pan Dongjin, Li Jiaying, Liang Lifen, et al. Research Progress on Fucoxanthin Lipid-lowering Activity and Its Mechanism [J]. Guangxi Science, 2021, 28(06): 588-598.

[53] Han Hui. Neuroprotective Effect of Fucoxanthin on Parkinson's Disease [D]. Ningbo University, 2021.

[54] Liang Ying, Xin Hongcui, Yan Yiyun, et al. Plasma Mutagenesis of Nitzschia closterium minutissima at Ambient Pressure and Room Temperature and Screening of High Fucoxanthin Producing Strain [J]. Journal of Ocean University of China (Natural Science Edition), 2022, 52(07): 39-48.

[55] Qiao Zichun, Liu Guangming, Cao Minjie, et al. Characteristic Spectral Changes of Fucoxanthin from Brown Algae during Processing [J]. Journal of Jimei

University (Natural Science Edition), 2018, 23(01): 27-32.

[56] Yan Zhenling. Study on the Stability of Fucoxanthin in Laminaria japonica [J]. Modern Agricultural Science and Technology, 2016, (03): 315-319.