

Research Progress on the Nutritional Properties of Microalgae and Their Applications in Food

Yuqing Xing *

Department of Bioscience and Biotechnology, Beijing Forestry University, Beijing, 100091, China

* Corresponding Author Email: Xingyuqing16@bjfu.cn

Abstract. Microalgae are rich in nutrients and bioactive substances, which can provide nutrients to the human body and have functions such as antioxidant, antibacterial, and immunomodulation. Microalgae are receiving more and more attention as a potential new source of food ingredients. However, the application of microalgae in food is still immature. This paper reviews the physiological active functions of polysaccharides, proteins, unsaturated fatty acids, pigments and other bioactive substances in microalgae, summarizes the current status of the application of microalgae in meat foods, pasta, additives and functional foods. At the end of the article, the existing problems and challenges, such as microalgae with special odor, complex processing, insufficient experimental data, etc., are systematically elaborated, and the outlook and suggestions are put forward to express the confidence in the development of microalgae as a novel raw material in the food industry. The whole article aims to provide theoretical references for the development of microalgae food and the exploration of new food resources.

Keywords: Microalgae; nutrition; bioactive substance; food.

1. Introduction

Microalgae are a group of aquatic organisms with tiny morphology and simple structure, rich in proteins, lipids, polysaccharides, carotenoids and other nutrients, and are also a high-quality source of biologically active components, such as carotenoids (astaxanthin, salvinorin), omega-3 fatty acids and polyphenols. Currently, some of the bioactive substances in microalgae are being studied and developed, and some of them have been shown to have antioxidant, anti-inflammatory, antitumor, and antiviral effects [1]. As a high-quality food ingredient, microalgae have great potential for development in the field of food and health due to their wide distribution, short growth cycle, large biomass, high photosynthetic efficiency, rich nutrition, and strong environmental adaptability.

The industrialization of microalgae resources is relatively short, dating back to the World War II period, and after decades of development, it is still in its initial stage. In recent years, microalgae's great economic and environmental value has attracted extensive attention from various industries. As a natural source of phytonutrients, the application of microalgae in the food field has also been gradually recognized, and more and more countries and food enterprises have begun to engage in the production of microalgae research. At present, the artificial culture of microbial algae resources, including the cyanobacteria of *Spirulina*, *Chlorella*, *Chlorella*, *Rhodococcus* and *Duchenne*, etc., with the fermentation method of high-density cultivation of *Chlorella* technology to obtain a substantial breakthrough and to be able to promote the application of the scale of *Chlorella*, its quality and stability have been greatly improved worldwide, laying the foundation for the industrialization of microalgae development [2].

With the increase of consumers' demand for healthy diet, microalgae-based products gradually appear in the market. At present, microalgae are mainly used in the market as dietary supplements and biological factories to prepare all kinds of physiologically active ingredients, such as DHA alga oil, astaxanthin, etc., and the export of its product applications is relatively narrow. Due to bottlenecks in production technology, other nutrients in microalgae have not been fully developed and utilized, such as the production and utilization of microalgae proteins worldwide is still very limited, microalgae in high-quality protein isolation technology, there is still a lot of room for progress [3]; microalgae polysaccharides as well as unsaturated fatty acids extraction cost is too high and low yield,

the efficient upgrading of production technology has become an urgent problem to be solved, and so on.

Based on the current research status of microalgae, this paper will provide an overview of the nutritional functions of microalgae, the current status of microalgae application in the food field and the challenges faced, aiming to provide reference for the innovative application of microalgae resources in the food field and the research and development of microalgae food.

2. Nutrients in Microalgae

2.1. Microalgal Polysaccharides

Microalgal polysaccharides are mainly categorized into structural polysaccharides and extracellular polysaccharides, and different microalgal polysaccharides have different structures and compositions. Polysaccharides accounted for a relatively high proportion of the algal powder of *Chlorella vulgaris* and *Chondrus crispus*, amounting to 30% to 60% of the dry weight. Microalgal polysaccharides have a variety of functional properties such as antiviral, antioxidant, antibacterial and hypoglycemic [4], and have been used in food thickening, preservation and the development of probiotic foods. In terms of structural polysaccharides, blunt-topped *Spirulina* and *Chlorella vulgaris* polysaccharides have thickening properties, and blunt-topped *A. platensis* polysaccharides as can slow down the process of starch pasting. Not only that, but the extracellular polysaccharide also secreted by microalgae is a kind of high molecular weight chain polymer, which can form hydrocolloids with high molecular weight and high hydrodynamic volume in aqueous solution, thus it has high viscosity characteristics, and the sulfated polysaccharide contained in extracellular polysaccharide has the effect of inhibiting bacteria and fungi, so it can be applied as a natural preservative in food. Microalgae extracellular polysaccharides are also beneficial to human health with immunomodulatory, antioxidant and antibacterial effects [5]. Sulfated microalgae polysaccharide promotes NO production in mouse macrophages, and experiments using inhibitors of various kinases have revealed that only JNK inhibitors can inhibit microalgae polysaccharide-induced NO production, demonstrating that microalgae polysaccharide promotes macrophage NO production through the JNK pathway [6].

2.2. Microalgal Proteins

Protein is the primary metabolite of microalgae, and the protein content of microalgae is generally above 40%, which is one of the most important material components of microalgae. Microalgae proteins are rich in a variety of essential amino acids, such as leucine, arginine and lysine, and the essential amino acid index (EAAI) of *Chlorella* and Blunt Top Nodule *Spirochaetes* is higher than that of crop proteins, such as wheat and maize, and comparable to that of meat and soybeans in terms of WHO/FAO standards [7]. Among microalgae proteins, studies on phycocyanin are predominant. Algal cyanin is a water-soluble protein with high nutritional value, which can also be applied in the food field as a blue pigment, while algal cyanin has biologically active functions such as antitumor, antioxidant, anti-inflammatory, and immune enhancement, which can also be applied in the field of health care products and medical treatment [8]. Ramirez et al. [9] treated inflammatory mice with phycocyanin doses of 100, 200 and 300 mg/kg body weight. After waiting for 1 h for the action of phycocyanin to detect the inflammatory indexes of mice, it was found that the release of cellular histamine was significantly reduced and showed a concentration gradient effect with the dose of phycocyanin treatment, which further confirmed the anti-inflammatory effect of phycocyanin.

2.3. Unsaturated Fatty Acids from Microalgae

Lipids make up about 10% to 60% of microalgae, of which Ω -3 fatty acids can improve hypertension and congestive heart failure, and also have a positive effect on the development and composition of intestinal flora. In animal models, supplementation with Ω -3 fatty acids improves hepatic insulin sensitivity, adipocytokine production and has direct and indirect anti-inflammatory

effects [10]. Among the Omega-3 fatty acids, docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which together account for 40% of the polyunsaturated fatty acids found in the brain, stand out for their significant health benefits. DHA promotes short- and long-term memory by supporting neurons and helps to improve brain function; EPA limits the development of inflammation associated with chronic diseases. The combined action of EPA and DHA contributes to fetal development, prevent inflammation, and deal with cardiovascular disease. Today, dairy products and infant formulas supplemented with microalgae EPA and DHA are industrially produced.

2.4. Microalgal Pigments

Microalgal pigments are categorized as carotenoids, chlorophylls and phycobilins. Microalgae pigments have high health-promoting nutrients such as antioxidants, vitamin precursors, neuroprotective and immune boosters. Phycocyanin is often used as a coloring agent in foods such as ice cream, chewing gum, popsicles, jellies, dairy products and soft drinks. Alginin has antioxidant and anti-inflammatory activity, and is effective in alleviating Alzheimer's disease, liver and kidney toxicity, and diabetes. β -carotene has the ability to enhance immunity and prevent skin diseases and cataracts, and β -carotene extracted from *Duchenne* algae is often added to foods such as juices, cheeses, and canned foods. Lutein is a member of the carotenoid family with antioxidant and radiation protection, anti-cancer, prevention of cardiovascular diseases and eye protection [11].

2.5. Bioactive Components in Microalgae

There are a large number of bioactive substances in microalgae, such as pigments, vitamins, phenolic compounds, and minerals, which have a variety of physiological effects such as antioxidant, anticancer, alleviation of chronic diseases, immunomodulation, antidiabetic and anti-inflammatory effects. *Spirulina* sp. has been called a "superfood" by the WHO and is a photoautotrophic unicellular microalgae, which is an excellent natural source of vitamins A, B1, B2, and B12, as well as pigments (e.g., β -carotene and lutein) and minerals. 7 g of *Spirulina* sp. contains up to 11%, 15% and 4% of the human daily intake of vitamins B1, B2 and B3, and 21% and 11% of the daily intake of copper and iron in 7 g of dry matter [12]. *Duchenne* salina also contains vitamins B2, B12, E and β -carotene, while *Chlorella* sp. contains high concentrations of vitamin B7. Astaxanthin is a natural pigment with stronger antioxidant properties than vitamin C, E or other carotenoids and has been used in functional foods as well as beverages [13]. A good source of astaxanthin is *H. pluvialis*, a freshwater microalga that contains up to 4-5% astaxanthin.

3. Application of Microalgae in Functional Foods

3.1. Meat and Protein Foods

Microalgal PolysaMicroalgae can be used as meat protein substitutes to enhance the nutritional value of the product and improve the sensory characteristics. The outstanding protein content of *Spirulina* and *Chlorella*, which is much higher than common plant protein sources, and the protein utilization of a variety of microalgae is superior to that of common plant proteins, make microalgal proteins an ideal choice for meat substitutes in artificial meat production, and a potential source of future food proteins [5]. Fish products supplemented with *Spirulina* sp. showed significantly increased antioxidant activity, and the water and oil holding capacity of the products was significantly improved, exhibiting better textural and sensory attributes [14].

3.2. Pasta Products

Traditional pasta products as a staple food have a single raw material, high carbohydrate content and unbalanced nutrient composition, while algae are rich in nutrients, which can improve the nutritional value of pasta products when added to pasta products. Mostolizadeh S et al. [15] added spirulina powder to the preparation of pasta, which increased the essential amino acids and

unsaturated fatty acids content of pasta and improved the nutritional value of pasta. At the same time, microalgae have water retention properties and can delay the aging of starch in flour; the addition of chlorella can improve the elasticity, cooking characteristics, rheological properties and gluten network of dough. Graca C et al [16] added chlorella powder to bread, and by observing the microstructure of the dough, it was found that the addition of chlorella strengthened the structure of gluten network of the dough, which enhanced the viscoelasticity and toughness of the bread.

3.3. Microalgae-based Functional Foods

Microalgae are high in minerals and vitamins, rich in variety and balanced in composition, such as tocopherols, Vitamin A, Vitamin B, ascorbic acid, niacin, etc., potassium, calcium and magnesium as massive elements, and iron, zinc and selenium as trace elements [17]. In addition to this, microalgae contain algal polysaccharides, astaxanthin, unsaturated fatty acids, β -carotene, terpenoids, etc., which have diverse health functions and pharmacological effects, making them widely used in functional foods. Tertychnaya et al. [18] improved the nutritive value of bread using *D. salina* with an increase in phosphorus content by 2.8 to 3.6 times and calcium content by 2.25 to 3.25 times.

Meanwhile, chlorella polysaccharides can promote phagocytosis capacity and lymphocyte proliferation in mice with an effective dose of 50 mg·kg⁻¹ [19]. The health benefits of microalgal polysaccharides such as immunity enhancement, antiviral, tumor inhibition, anti-aging and antiviral make them highly sought after in the field of functional foods.

3.4. Use of Microalgae as Food Additives

Food additives are regarded as the soul of the modern food industry and the most active element in food innovation. Advocating natural, nutritious and multi-functional food additives has become the development trend in the food industry, which is exactly in line with the characteristics of microalgae. Phycocyanin in *Spirulina*, chlorophyll and lutein in *Chlorella proteolytica*, and β -carotene in *Micrococcus anthropophilus* and *Halophyceae* are all good natural food colorants. Microalgae pigments are more stable and *Chlorella vulgaris* can be used as a natural colorant in butter cookies, which showed a very stable color over a shelf life of 3 months [20]. Not only that, the color of microalgae is also rarer among natural pigments, for example, phycocyanin is the only natural blue pigment, which can make the food present a pure and clear blue color and bring a strong visual impact to consumers.

4. Challenges for the Microalgae Food Industry

Microalgae are rich in nutrients and have a variety of physiological activities and functions, and have great potential for application in food, but there are still many problems and challenges.

First of all, since microalgae have a special fishy taste, people need to strictly control the number of microalgae added during food processing, and if necessary, adopt β -cyclodextrin embedding method, fermentation and deodorization to obtain microalgae fruit and vegetable juices with good flavors. *Spirulina* can be used to make kiwi containing tablets, but the high thermal sensitivity of algal bile proteins may lead to darkening of the color. Second, although microalgae as dietary supplements have obvious health benefits, it is unknown whether food products with added microalgae are able to achieve similar results. The number of microalgae added to foods is usually very low, making it difficult to achieve dietary supplement intake from food sources.

More importantly, microalgae and food are both very complex matrices, and the interactions between the various components resulting from the added utilization of microalgae in food are not sufficiently well defined, and relevant experimental data are scarce. Therefore, a comprehensive assessment of the functionality and health benefits of microalgae-based foods is needed.

5. Conclusion

Microalgae are rich in proteins, polysaccharides, unsaturated fatty acids, vitamins and other nutrients, which can be digested, absorbed and utilized by the human body after treatment and processing, and have certain effects such as immune-enhancing, antioxidant, antibacterial, antiviral and anticancer. Based on the excellent characteristics of microalgae, it has been gradually entered into the food industry as a new type of ingredient. Microalgae can enrich the nutritional composition of food, improve the organoleptic properties of food, benefit human health and meet the demand for dietary diversity and health. Therefore, microalgae have been developed and utilized as novel raw materials in meat products, pasta, functional foods, food additives, etc., and research has been carried all over the world. However, the food industry of microalgae also faces some problems, such as the wide variety of microalgae species, high processing cost, and specific odor, which need to be further investigated. The use of microalgae in other food applications (dairy products, fruits and vegetables, etc.) is not discussed in detail in this paper, but it is believed that with the development of food science and technology in the future, microalgae with their "food" potential will be further introduced into the food market.

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