Spirulina platensis: Nutritional Composition, Fisheries Applications, and Emerging Potential in Sustainable Capsule Shell Production

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ABSTRACT

Spirulina platensis is a protein rich cyanobacterium known for its remarkable nutritional profile, comprising essential amino acids, vitamins, minerals and health promoting bioactive compounds such as phycocyanin and carotenoids. These characteristics have led to its extensive use as a functional ingredient in human diets, animal nutrition, and aquaculture feeds. In fisheries, Spirulina enhances growth performance, immunity, reproduction, pigmentation, and overall health of cultured aquatic species. Beyond its nutritional applications, *Spirulina platensis* has emerged as a promising biotechnological resource due to its content of polyhydroxybutyrate (PHB), a biodegradable and biocompatible polymer. PHB offers potential for the development of sustainable and animal-free capsule shells as an alternative to conventional gelatin-based capsules. This article reviews the composition of *Spirulina platensis*, its importance in aquaculture, and its emerging role in the pharmaceutical industry as a source of eco-friendly capsule materials.

INTRODUCTION:

One of the first forms of life on Earth, spirulina (Arthrospira or Limnospira) is a member of the phylum Cyanobacteria, formerly known as blue-green algae (Schopf, 1993). Algae are eukaryotic organisms characterized by the presence of a membrane bound nucleus, whereas cyanobacteria are prokaryotic microorganism and therefore lack true nucleus. Despite being a multicellular creature (filamentous cyanobacterium), spirulina lacks a nucleus and other cellular organelles. The cytoplasmic and outer membranes encircle the photosynthetic thylakoid membranes that make up spirulina cells. They have a single circular chromosome arranged in a nucleoid of the prokaryotic kind. Cyanobacterial colonies were discovered through studies of fossil microbes in Precambrian rocks (3.5-0.5 billion years ago) (Rozanov & Astafieva, 2009, Sergeev *et al*, 2002). Numerous species of cyanobacteria inhabit a broad spectrum of environment, ranging from terrestrial soils and freshwater ecosystem, as well as extreme habits such as hot spring and soda lakes. Historically, prior to its rediscovery and scientific characterization in the mid-20th century, it was utilized by the Aztecs in 16th-century Mexico, where it was harvested from Lake Texcoco and referred to as “Tecuitlatl” (Saranraj & Sivasakthi, 2014). Later, it was sold as "Dihe" for bread and broths by the Kanembu people around Lake Chad in Africa (Saranraj & Sivasakthi, 2014). A trans-Saharan expedition discovered diuge and spirulina once more in the 1960s. *Spirulina platensis*, a filamentous cyanobacteria, was the predominant component of what seemed to be dried purees in the Die samples (Leonard, 1966). According to the taxonomical pirouettes of spirulina, three types of organisms may currently be identified which include 12 (twelve) species of Spirulina, about 35 (thirty five) species of Arthrospira, and 4 (four) species of Limnospira, including *Limnospira fusiformis*, *Limnospira platensis*, *Limnosipra maxima* and *Limnosipra indica* (formerly classified under spirulina or Arthrospira), are widely cultivated on a commercial scale owing to their efferent biomass production and their extensive use in spirulina.



Fig. 1: Microscopic view of *Limnospira* (*Spirulina*) showing spiral and linear morphotypes. Strains IPPAS B-1526 (spiral) and IPPAS B-287 (linear) are from the Microalgae and Cyanobacteria Collection, K.A. Timiryazev Institute of Plant Physiology, Russian Academy of Sciences (IPPAS), Moscow, Russia (Sinetova *et al*., 2024).

The blue-green microalga *Spirulina platensis* is a naturally grown traditional food source used by ancient civilizations and considered as a modern "superfood". It is currently acknowledged as one of the earliest and most nutrient-rich life forms on Earth. It is a multicellular, filamentous cyanobacterium characterized by an exceptionally high protein content (460-630 g kg^{-1}, dry matter basis) (Lupatini *et al.,* 2017). Additionally, it serves as a rich source of vitamins, minerals, essential amino acids, essential fatty acids, and bioactive pigments such as phycocyanin and carotenoids, which contribute to its strong antioxidant, anti-inflammatory, and immunomodulatory properties (Jung *et al.,* 2019). Researchers discovered its high nutritional value and low risk of microbial contamination in alkaline, saline environments by the 1960s and 1970s. This led to large-scale cultivation and its promotion as a future food under the FAO and UN, while NASA

investigated its use as a compact, oxygen-producing food source for space missions in the 1990s (Seyidoglu *et al.,* 2017). *Spirulina platensis* is a prime example of how a primitive cyanobacterium can bridge ancient nutrition and modern biotechnology. It is currently widely used as a dietary supplement and animal feed, and its biopolymers, pigments, and bioactive compounds are being used in pharmaceuticals, nutraceuticals, and even in innovative capsule-shell systems.

Capsules are solid preparations, usually made of gelatin, that contain medications and other inert substances in powder, granule, liquid, or semisolid form. They are placed within shells or tiny containers. The public is still unsure about the halalness of gelatin, which is the primary ingredient used to make capsule shells. This is because 44.5% (136,000 tons) of the world's gelatin production comes from pig skin, followed by cow skin (27.6%, 84,000 tons), bone (26.6%, 81,000 tons), and another substance (1.3%, 4,000 tons) (Sari *et al.*, 2020). In addition to the halalness issue, viruses that cause swine influenza and foot mouth disease (FMD) can easily contaminate gelatin capsules. Furthermore, since gelatin is an animal-derived protein, the amine groups present in gelatin can react with aldehyde groups in the drug. In addition, gelatin exhibits properties that make it prone to brittleness under low-humidity conditions. Carrageenan, obtained from the red macroalgae Rhodophyceae, particularly *Eucheuma cottonii*, can serve as an alternative gelling agent to replace gelatin; however, capsule shells made solely from carrageenan are easily degraded in the stomach, leading to the release of active compounds that may irritate the gastric mucosa. This limitation can be addressed by employing alternative materials to develop capsule shells that are more stable and capable of controlling drug release (Sari *et al*., 2020). Cyanobacteria *Spirulina platensis* is another material because it contains polyhydroxybutyrate (PHB), a polymer compound. PHB is a derivative of polyhydroxyalkanoates (PHA), which are biodegradable and biocompatible substances that are often generated by bacteria and cyanobacteria (Sari *et al*., 2020). PHB degrades quickly structurally, has a high mechanical strength, and doesn't emit any hazardous byproducts.

Composition and nutrient content of *Spirulina platensis*

1. **Protein and amino acid:** Usually making up between 50 and 70% of its dry weight, *Spirulina platensis* is incredibly rich in high-quality protein. It is regarding as high quality, complete protein because it supplies all the essential amino acid required in the human diet, including leucine lysine, methionine, phenylalanine, threonine, and valine. In addition to this indispensable amino acid such as arginine glycine, serine and alanine, which contribute to enhancing its overall nutritional and protein value (Spinola *et al*., 2024).

2. **Lipid and fatty acids:** Spirulina platensis contains a relative low lipid content, accounting for approximately 5-10% of its dry biomass yet these lipids are nutritionally valuable because they are enriched with polyunsaturated fatty acids (PUFAs). The principal PUFA is γ-linolenic acid (GLA; 18:3n-6), which is widely recognised for its beneficial effects on lipid metabolism and its anti-inflammatory activity. Other important fatty acids identified in S platensis include oleic acid, palmitic acid, and linoleic acid (18:2n-6). In addition, the biomass contains smaller quantities of omega -3 fatty acids, particularly α-linolenic acid (ALA), further enhancing its nutritional and functional value (Spinola *et al*., 2024).

3. **Carbohydrate:** About 15-20% of *Spirulina platensis's* dry weight is made up of carbohydrates. These mostly take the form of polysaccharides, particularly sulphated polysaccharides like calcium spirulan (Ca-SP), which have been connected to immune-stimulating, anti-inflammatory and antiviral properties. Additionally, the biomass retains some glycogen as an energy reserve, and the polysaccharide component includes glucose, rhamnose, xylose, mannose, and galactose (Spínola *et al*., 2024).

4. **Pigments (phycocyanin, carotenoids, chlorophyll):** The diverse health-promoting effects of *Spirulina platensis* are largely attributed to its abundant pigment composition, which also imparts its distinctive blue-green appearance. Among these pigments, phycocyanin is the most prominent and is a blue, protein-bound pigment recognized for its potent antioxidant and anti-inflammatory activities. Depending on the cultivation and processing conditions, phycocyanin may account for up to 47% of the dry biomass. In addition, *S. platensis* contains chlorophyll, carotenoids (such as β-carotene, lutein, and zeaxanthin), along with other vitamin-like antioxidant compounds that contribute to protection against oxidative stress and light-induced cellular damage (Spínola *et al*., 2024).

5. **Vitamins:** *Spirulina platensis* is rich in both water-soluble and fat-soluble vitamins. It contains considerable amounts of B-complex vitamins, which play a crucial role in cellular functions and energy metabolism, including Thiamine (B1), Riboflavin (B2), Niacin (B3), and Folate (B9). Furthermore, it also provides vitamin B12; however, its bioavailability and physiological effectiveness are still under investigation. Additionally, spirulina includes vitamin E (α-tocopherol) and vitamin A (β-carotene), which boost the immune system and provide antioxidant protection (Spínola *et al*., 2024).

6. **Minerals:** Due to its high mineral content, *spirulina platensis* is a useful dietary supplement for addressing micronutrient deficiencies. With concentrations ranging from roughly 28 to 50 mg per 100 g of dry biomass, iron is one of the most prevalent minerals and is especially helpful for those with iron-deficiency anaemia. Additional essential minerals that maintain bone health, enzyme function, and redox balance include calcium, magnesium, zinc, potassium, and various trace elements like copper and selenium. When the cell wall is appropriately pre-treated (such as by milling, heating, or extrusion), the bioavailability of these minerals in spirulina is typically regarded as high (Spínola *et al*., 2024).

7. **Secondary metabolites and bioactive compounds:** *Spirulina platensis* has numerous secondary metabolites with biological action in addition to basic nutrients. These include phenolic acids, polyphenols, sterols, and flavonoids with antioxidant, anti-inflammatory, antibacterial, and anticancer properties, such as ferulic acid, caffeic acid, rutin, quercetin, catechin, and related chemicals. These substances enable the use of spirulina in pharmaceuticals, functional foods, and nutraceuticals by increasing its overall nutraceutical value (Spínola *et al*., 2024).

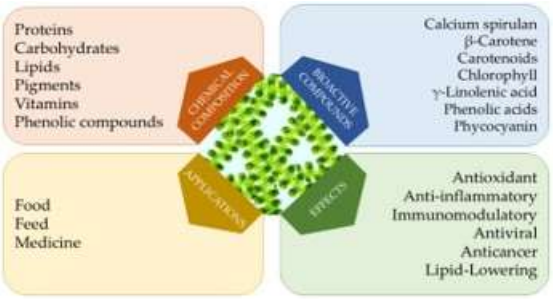


Fig.2: Overview of Chemical Constituents, Bioactive Components, and Functional Applications of *Spirulina* (Spínola *et al*., 2024)

***Spirulina platensis* in Fisheries**

Spirulina platensis has emerged as an important functional feed ingredient in fisheries and aquaculture because of its exceptional nutritional profile. The biomass contains approximately 60-70% protein on dry weight basis, together with a balanced supply of essential amino acid, vitamins, minerals, beneficial fatty acid, and a variety of bioactive constituents. These nutritional characteristics make *S. platensis* a promising alternative or complementary protein source for aquafeed formulation (Becker, 2007; Habib *et al*, 2008) numerous studies have demonstrated that dietary inclusion of spirulina can enhance growth performance improve feed and nutritional utilisation, and support the overall health, physiological condition, and productivity of cultured aquatic species.

Spirulina has gained considerable attention in the fisheries and aquaculture sectors as a valuable nutritional supplement and functional feed ingredient. Owing to its exceptionally high protein content, which ranges between 60-70% of its dry weight, along with a balanced composition of essential amino acids, vitamins, minerals, fatty acids, and bioactive compounds, Spirulina serves as an excellent alternative or supplement to conventional protein sources used in aquafeeds (Becker, 2007; Habib *et al*., 2008). The incorporation of Spirulina into aquaculture diets has been reported to enhance growth performance, improve feed utilization efficiency, and promote the overall health and productivity of cultured aquatic organisms.

One of the primary benefits of Spirulina supplementation is its positive effect on growth and feed conversion efficiency. Studies have demonstrated that the inclusion of Spirulina in the diets of commercially important fish species such as tilapia, carp, catfish, and various marine fishes significantly increases weight gain, specific growth rate (SGR), and biomass production. These improvements are largely attributed to the high digestibility of Spirulina proteins and its well-balanced nutrient composition, which facilitates efficient nutrient absorption and utilization by fish (Abdel-Tawwab & Ahmad, 2009). Furthermore, the presence of essential amino acids supports muscle development and tissue growth, leading to enhanced production performance.

In addition to its nutritional value, Spirulina functions as a natural immunostimulant that strengthens the immune system of aquatic organisms. The microalga contains several bioactive compounds, including phycocyanin, polysaccharides, carotenoids, and phenolic compounds, which have been shown to stimulate innate and adaptive immune responses. Dietary supplementation with Spirulina enhances macrophage activity, increases antibody production, improves lysozyme activity, and strengthens the overall defence mechanisms against bacterial, viral, and parasitic infections (Belay *et al.*, 1993; Watanuki *et al*., 2006). Consequently, fish and shrimp receiving Spirulina-enriched diets often exhibit higher survival rates and greater resistance to disease outbreaks, reducing the need for antibiotics and other chemotherapeutic agents.

Another important application of Spirulina in fisheries is its role in enhancing pigmentation. The microalga is naturally rich in pigments such as carotenoids, β-carotene, xanthophylls, chlorophyll, and phycocyanin. These pigments contribute significantly to the coloration of ornamental fish and commercially valuable species, including salmonids, koi carp, goldfish, and shrimp. Improved pigmentation not only enhances the aesthetic appeal of ornamental species but also increases the market value and consumer acceptance of food fish and crustaceans (Gouveia *et al*., 2003). As a result, Spirulina is widely used as a natural colour enhancer in aquaculture feeds.

Spirulina also plays a significant role in broodstock nutrition and reproductive performance. Research has shown that diets supplemented with Spirulina improve reproductive parameters such as gonadal development, fecundity, fertilization rates, hatchability, and larval quality in several fish species. These beneficial effects are mainly attributed to the presence of essential fatty acids, vitamins, antioxidants, and trace minerals that support reproductive physiology and embryonic development (James *et al*., 2006). Enhanced reproductive performance ultimately contributes to increased seed production and improved hatchery efficiency.

The microalga is further utilized as a live-feed substitute or supplementary feed for fish larvae and juvenile stages. Due to its microscopic size, soft cell structure, and high digestibility, Spirulina can be readily consumed by young aquatic organisms. Its inclusion in larval diets has been associated with improved growth, higher survival rates, better stress tolerance, and enhanced nutritional status during critical early developmental stages (Takeuchi *et al*., 2002). This makes Spirulina particularly valuable in hatchery operations where optimal larval nutrition is essential for successful aquaculture production.

Beyond its direct nutritional applications, Spirulina cultivation can contribute to the sustainability of aquaculture systems. The microalga is capable of utilizing dissolved nutrients, including nitrogen and phosphorus compounds present in aquaculture effluents. By assimilating these nutrients, Spirulina helps recycle waste materials, reduce nitrogenous compounds such as ammonia and nitrate, and improve overall water quality (Richmond, 2004). This bioremediation potential supports environmentally sustainable aquaculture practices while simultaneously generating valuable biomass that can be reused as feed.

Overall, *Spirulina platensis* represents a multifunctional resource in fisheries and aquaculture. Its ability to improve growth performance, enhance immune responses, promote pigmentation, support reproduction, aid larval development, and contribute to environmental sustainability makes it one of the most promising microalgal species for modern aquaculture systems. As the demand for sustainable and high-quality aquafeeds continues to grow, Spirulina is expected to play an increasingly important role in improving the productivity and ecological sustainability of the global aquaculture industry.

CONCLUSION

Spirulina platensis is a highly valuable microalga with exceptional nutritional, pharmaceutical, and biotechnological significance. It has rich distribution of essential amino acid, proteins, vitamins, minerals, pigments, fatty acid and bioactive compounds makes it an important resource for human nutrition, animal feed, and nutraceutical applications. According to aquaculture research, adding spirulina to the diet can improve pigmentation, immunological responses, gut health, and reproductive performance in a variety of fish species while partially replacing fish meal without compromising growth, survival, or feed efficiency where its also supporting environmentally sustainable farming practices. Furthermore, the presence of biodegradable and biocompatible polyhydroxybutyrate (PHB) highlights its potential as an innovative alternative to conventional gelatin-based capsule shells, addressing concerns related to animal-derived products and environmental sustainability. Therefore, *Spirulina platensis* represents a promising natural resource that bridges nutrition, aquaculture, and modern biotechnology, offering sustainable solutions for future food, feed, and pharmaceutical industries.

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