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Why Spirulina Could Be the Protein Source of the Future

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Scientists are intensively searching for sustainable and nutritionally rich alternative protein sources due to global population growth placing increasing pressure on existing food systems. Spirulina (*Arthrospira platensis* and *Arthrospira maxima*), a blue-green cyanobacterium, has emerged as one of the most promising candidates. Containing 50-70% protein on a dry weight basis, together with essential amino acids, polyunsaturated fatty acids, vitamins, minerals, and the bioactive pigment phycocyanin, spirulina offers an unrivalled nutritional profile among plant-based foods. Beyond nutrition, spirulina exhibits potent antioxidant, anti-inflammatory, and immunomodulatory properties, positioning it as a valuable functional food and therapeutic agent. Its cultivation requires minimal land, produces no cellulose barrier limiting digestibility, and contributes to environmental sustainability through carbon dioxide sequestration. This article reviews the scientific evidence supporting spirulina as the protein source of the future, examining its nutritional composition, health benefits, sustainable production potential, food applications, and current challenges to widespread adoption.

Keywords: Spirulina, Arthrospira platensis, alternative protein, phycocyanin, sustainable food, nutraceutical

Introduction

The global food system faces an unprecedented challenge: feeding a world population that is projected to reach 10 billion by the year 2050, within the constraints of a planet with finite and increasingly stressed natural resources (Musa et al., 2025). At the same time, nearly 670 million people worldwide are still expected to remain undernourished in 2030 (Opiyo et al., 2024). These twin pressures are compelling researchers and policymakers alike to look beyond conventional protein sources such as meat, eggs, and legumes towards innovative and sustainable alternatives. Microalgae, including spirulina, are identified as an alternative source of protein for malnourished populations (Podgorska-Kryszczuk, 2024). As early as 1974, the cyanobacterium *Arthrospira platensis* was identified as the "food of the future" at the United Nations World Food Conference (Musa et al., 2025). Today, the World Health Organisation (WHO) has named spirulina a "superfood," and the US Food and Drug Administration (FDA) has granted it "generally recognised as safe" (GRAS) status. NASA has also recognized its potential for use in space missions (Musa et al., 2025). Spirulina offers several advantages over higher plants, including: the lack of need to occupy limited land areas; the possibility of cultivation in agriculturally unsuitable areas using non-potable or saline water; shorter growth periods; higher efficiency in the production of protein and bioactive compounds; and the ability to control the production of beneficial compounds by regulating growth conditions (Podgorska-Kryszczuk, 2024). Spirulina nutrients are also easily preserved and stored without extensive processing, further supporting its practical utility as a food source (Musa et al., 2025). This article reviews the scientific evidence underpinning spirulina's potential as the protein source of the future, examining its rich nutritional composition, diverse health-promoting properties, sustainable cultivation system, food fortification applications, and the challenges that must be overcome before it can fulfil its full global potential.

(https://adiva.com.vn/tao-spirulina-la-gi-tac-dung-tri-nam-cua-tao-spirulina-tao-mat-troi-nhu-nao/)

Nutritional Composition of Spirulina

Protein Content and Amino Acid Profile

Spirulina is primarily distinguished by its remarkable protein content, which constitutes 50-70% of its dry weight (Musa et al., 2025). When compared to conventional food protein sources, this figure is substantially higher than that of beef (17.4-22%), chicken (19-24%), fish (19.20-22%), soybeans (35.35-40.30%), and eggs (12.6%) (Podgorska-Kryszczuk, 2024; Musa et al., 2025). In addition, spirulina protein is highly digestible, with a digestibility rate of 85-95%, which is attributable to the structure of the microalga's cell wall, which consists mainly of proteins, carbohydrates, and lipids, in contrast to plant cell walls, which consist of cellulose indigestible to humans (Podgorska-Kryszczuk, 2024). Spirulina contains all essential amino acids required by the human body, including lysine, leucine, histidine, phenylalanine, methionine, threonine, tryptophan, and valine (Podgorska-Kryszczuk, 2024). It has sufficient composition of all essential amino acids that meet standard dietary recommendations (Musa et al., 2025). Importantly, the digestibility of individual spirulina amino acids consistently exceeds that of chickpeas and mung beans. For instance, the digestibility of phenylalanine in spirulina reaches 95.3%, compared to 60.5% in chickpeas and 65.2% in mung beans (Podgorska-Kryszczuk, 2024). The protein fraction of spirulina also contains up to 20% phycobiliproteins, which are blue-coloured proteins including phycocyanin and allophycocyanin (Podgorska-Kryszczuk, 2024).

Fats, Carbohydrates, Vitamins, and Minerals

Beyond protein, spirulina's macronutrient composition includes carbohydrates (15-20% of dry matter, mainly as polysaccharides) and lipids (6.4-14.3%, depending on growth conditions) (Musa et al., 2025). The lipid fraction is particularly valuable because it is rich in polyunsaturated fatty acids (PUFAs) such as palmitic acid, gamma-linolenic acid (GLA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) (Musa et al., 2025). The presence of high levels of PUFAs makes spirulina's use in food and feed extremely interesting from a nutritional standpoint (Opiyo et al., 2024).

Spirulina is also a valuable source of minerals, including calcium, magnesium, potassium, zinc, iron, and selenium (Musa et al., 2025). Its iron content, ranging from 106 to 1800 mg/kg, makes it an especially important supplement for individuals at risk of anaemia, particularly vegans and vegetarians (Musa et al., 2025; Podgorska-Kryszczuk, 2024). The vitamin profile of spirulina includes Vitamins B1, B2, B3, B6, B9, B12, Vitamin K, and Vitamin E (Musa et al., 2025). This comprehensive micronutrient profile makes spirulina an excellent addition to diets, especially those of vegans and vegetarians, who often struggle to meet their nutritional requirements from plant sources alone (Podgorska-Kryszczuk, 2024).

(https://www.ocregister.com/2023/02/18/what-home-gardeners-should-know-about-spirulina-and-sorghum/)

Phycocyanin and Other Bioactive Compounds

Among spirulina's diverse bioactive constituents, phycocyanin occupies a central place. This water-soluble, blue-coloured protein pigment is unique to spirulina and constitutes 94.9-251 g/kg of its dry mass (Musa et al., 2025). Phycocyanin is a natural blue dye with many valuable properties, including antioxidant, anti-inflammatory, immune-modulating, and anticancer properties. The phycocyanin chromophore, a tetrapyrrole molecule known as phycocyanobilin, is probably responsible for spirulina's high antioxidant activity and is more effective at inhibiting oxidation than natural antioxidants such as zeaxanthin, alpha-tocopherol, and caffeic acid (Podgorska-Kryszczuk, 2024). Phycocyanin has found wide application in the food, cosmetics, and pharmaceutical industries, increasing spirulina's market value considerably (Spínola et al., 2024). Several studies suggest that the phenolic compounds, flavonoids, and phycocyanins present in spirulina can mitigate oxidative stress and prevent chronic diseases such as cancer and diabetes (Spínola et al., 2024). Spirulina's total phenols range from 2 to 17.3 g/kg and total flavonoids from 1 to 9 g/kg, while its carotenoid content, including the provitamin A precursor beta-carotene, contributes further to its antioxidant capacity (Musa et al., 2025). Spirulina polysaccharides represent another important group of bioactive compounds, exhibiting immunomodulatory and anti-cancer properties. Chlorophylls and carotenoids add further antioxidant and pigmentation value to the biomass (Spínola et al., 2024). Due to these unique properties and widespread demand, numerous attempts are being made globally to improve methods for phycocyanin extraction and to increase production efficiency (Podgorska-Kryszczuk, 2024).

Health Benefits of Spirulina Supplementation

Antioxidant and Anti-Inflammatory Effects

The antioxidant capacity of spirulina has been extensively documented in both animal studies and clinical trials. Spirulina activates cellular antioxidant enzymes, inhibits lipid peroxidation and DNA damage, scavenges free radicals, and increases the activity of superoxide dismutase and catalase (Musa et al., 2025). Numerous animal studies and clinical trials have demonstrated that spirulina improves a variety of oxidative stress-induced symptoms by enhancing the body's antioxidant capacity, repairing neuronal injury, suppressing tumour activity, inhibiting inflammation, improving immunity, alleviating toxicity, improving organ functions, and relieving cardiovascular disease conditions (Spínola et al., 2024). A comprehensive systematic review and meta-analysis, which included 22 randomised clinical trials involving 5,385 participants, demonstrated that spirulina supplementation significantly reduced key inflammatory biomarkers, including C-reactive protein (CRP) levels (SMD: -0.972 mg/dl), interleukin-6 (SMD: -0.532), and tumour necrosis factor-alpha, TNF-alpha (SMD: -0.579 mg/dl) (Khorshidi et al., 2025). Furthermore, oxidative stress biomarkers showed a significant decrease in malondialdehyde (SMD: -0.929) and a notable increase in total antioxidant capacity (SMD: 1.086) (Khorshidi et al., 2025). These findings strongly advocate for spirulina as a valuable dietary supplement for both healthy individuals and patients, aiming to lower inflammatory markers and enhance antioxidant capacity (Khorshidi et al., 2025).

Immunomodulatory and Other Therapeutic Properties

Spirulina's immunomodulatory properties are well documented. It can stimulate macrophage activity, enhance natural killer (NK) cell function, activate T-cells, and strengthen the immune response against infections (Musa et al., 2025). Spirulina's rich nutritional makeup also provides several other health benefits, including activity against bacteria and viruses such as *Staphylococcus aureus*, *Escherichia coli*, influenza, measles, Herpes simplex virus (HSV-1), and human cytomegalovirus (Musa et al., 2025). Spirulina's potential to mitigate oxidative stress, enhance immune function, and inhibit tumour growth positions it as a promising candidate for preventing chronic diseases (Spínola et al., 2024). Among other therapeutic benefits, spirulina has been shown to support the treatment of cardiovascular diseases, lower blood pressure and glucose levels in diabetics, support weight loss, and prevent neurodegenerative diseases (Podgorska-Kryszczuk, 2024). It has also demonstrated utility as a functional food for anaemia prevention due to its high iron and calcium content, which is of particular relevance for vegetarian and vegan populations (Musa et al., 2025).

Spirulina as a Sustainable Protein Source

The environmental advantages of spirulina production are a key factor supporting its role as a future food. Spirulina contains up to 70% protein in its dry mass, grows faster than terrestrial plants, and has higher protein productivity per area than other crops such as soybean, legumes, or wheat (Opiyo et al., 2024). This means that spirulina can produce substantially more protein per unit of land than conventional agricultural crops, which is a critical consideration given the finite amount of arable land globally. Commercial spirulina farming began in the 1970s in Mexico, and today the Asia-Pacific region has witnessed a significant rise in spirulina production, with China accounting for approximately half of global annual production of roughly 10,000 tonnes of dry biomass (Musa et al., 2025). Commercially, spirulina is grown using raceway pond systems, and it can be processed by filtration, homogenization, pasteurization, and spray drying for commercialization (Musa et al., 2025). These open-system raceway ponds cost less to operate, can be easily maintained, are directly exposed to sunlight, and accumulate less dissolved oxygen than closed photobioreactors (Musa et al., 2025). An important environmental co-benefit of spirulina cultivation is carbon dioxide sequestration and the removal of nitrogenous and phosphorous waste from wastewater, meaning that spirulina can increase the sustainability of a whole food system (Opiyo et al., 2024). Small-scale farmers can also produce spirulina using animal manure available on the farm instead of costly commercial fertilizer, making it potentially affordable and accessible for low-income food producers in developing countries (Opiyo et al., 2024). Its cultivation has been described as more economical and environmentally sustainable than other microalgae used for biodiesel production, further underscoring its broad sustainability credentials (Musa et al., 2025).

Food Fortification and Application Potential

Spirulina's rich protein, pigment, and bioactive compound profile makes it an attractive ingredient for food fortification. Scientists are attempting to enrich many food products with the microalga, supported not only by the improved nutritional composition of the fortified product but also by spirulina's impact on sustainable food production (Podgorska-Kryszczuk, 2024). Spirulina supplementation has been shown to have a positive effect on many staple foods, including bread, pasta, biscuits, yoghurt, kefir, sauce, and meat products (Podgorska-Kryszczuk, 2024). Commercially, spirulina can be found in various forms, mainly dry powder, tablets, and capsules, with a recommended daily dose ranging from 0.25 g to 5 g (Podgorska-Kryszczuk, 2024). Spirulina protein has been shown to exhibit similar adsorption kinetics and surface tension reduction as whey protein isolate, one of the most popular food stabilisers (Podgorska-Kryszczuk, 2024). It has also been shown to exhibit promising techno-functional properties, including emulsifying activity, foaming properties, good solubility, and the capacity to retain water and oil (Podgorska-Kryszczuk, 2024). These properties are particularly desirable for food manufacturers looking to address the growing interest in vegan and vegetarian diets (Podgorska-Kryszczuk, 2024). Beyond human nutrition, spirulina has demonstrated significant promise in animal and aquaculture feed. Microalgae, including spirulina, can play an important role in sustainable aquaculture due to their high crude protein values (up to 50% dry weight) and an amino acid profile comparable to that of fish meal (Opiyo et al., 2024). Studies have found that tilapia fingerlings fed diets with spirulina, replacing up to 30% of fish meal protein, were not negatively affected in terms of growth performance compared to fish fed a commercial diet (Opiyo et al., 2024). Spirulina has also been shown to boost the reproductive performance of tilapia by increasing the number and size of eggs as well as their hatchability (Opiyo et al., 2024), demonstrating its utility across the food supply chain.

Current Challenges and Future Prospects

Despite its considerable nutritional and environmental merits, the large-scale adoption of spirulina as a mainstream food ingredient faces several significant challenges. These include its distinctive marine flavour and odour, relatively high production costs, low consumer awareness of its nutritional benefits, and limited consumer acceptance of the characteristic taste and colour imparted to enriched food products (Podgorska-Kryszczuk, 2024). Commercially, spirulina supplements remain relatively expensive compared to conventional protein sources, which restricts accessibility in lower-income populations and markets. From a production standpoint, the nutritional composition of spirulina varies greatly according to culture conditions and analysis methods, introducing variability in product quality that must be managed through standardized cultivation and processing protocols (Musa et al., 2025). Furthermore, thermal processing, which is commonly applied in food manufacturing, can degrade phycocyanin, affecting its functional properties, while the optimal conditions for maximizing spirulina's nutraceutical potential through fermentation remain subjects of active research (Spínola et al., 2024). Future research is needed to optimize production and cultivation methods, improve the bioavailability of spirulina's active compounds, and validate its efficacy through dose-effect relationships in large-scale clinical trials (Spínola et al., 2024). Scientists are already focusing on solving challenges by promoting nutritional knowledge, improving microalgae production methods, and modelling growing conditions (Podgorska-Kryszczuk, 2024). With targeted investment in these areas, spirulina's current limitations can be progressively overcome, accelerating its transition from a niche supplement to a mainstream global protein source.

Conclusion

Spirulina stands at the confluence of global nutrition challenges and the search for sustainable food systems. Its exceptionally high protein content (50-70% dry weight), complete essential amino acid profile, rich micronutrient composition, and potent bioactive compounds including phycocyanin collectively make it one of the most nutritionally dense foods available. Supported by a growing body of clinical and experimental evidence confirming its antioxidant, anti-inflammatory, and immunomodulatory effects, spirulina's value extends well beyond simple protein provision. When combined with its environmental advantages of minimal land use, rapid growth, carbon dioxide sequestration, and wastewater remediation capacity, the scientific case for spirulina as a key component of future food systems is compelling. Overcoming the remaining barriers of cost, consumer acceptance, and production standardization will be decisive in fulfilling its potential as the protein source of the future.

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