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SPIRULINA AS FUNCTIONAL FOOD: INSIGHTS INTO CULTIVATION, PRODUCTION, AND HEALTH BENEFITS

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ABSTRACT
Background: *Spirulina (Arthrospira platensis)*, a filamentous cyanobacterium, is renowned as a superfood due to its rich nutritional composition, including proteins, carbohydrates, essential fatty acids, vitamins, minerals, and phytochemicals. Historically consumed by the Aztecs and the Kanembu people near Lake Chad, it gained renewed interest in the 20th century as a potential astronaut food. **Objective:** This review aims to trace *Spirulina*'s evolution from an ancient dietary staple to a modern superfood, emphasizing its immune support, antioxidant properties, and essential nutrients. It also highlights ongoing research on *Spirulina*'s potential to address various health concerns and nutritional needs. **Method:** The review adopts a comprehensive approach to evaluate *Spirulina's* pharmacological and therapeutic potential. It systematically examines existing literature, research studies, and clinical trials on *Spirulina's* health benefits and applications, focusing on its ability to combat malnutrition, boost economies, and offer novel therapeutic interventions. **Results:** *Spirulina* is identified as a valuable natural resource with significant potential in nutrition and medicine. The review underscores its pharmacological and therapeutic attributes, particularly in addressing malnutrition and contributing to economic development. **Conclusion:** *Spirulina's* role as an effective medicinal resource is discussed, highlighting its implications for novel therapeutic interventions. Overall, the findings underscore *Spirulina's* nutritional significance, enduring appeal, and promising role in tackling contemporary health challenges.

INTRODUCTION

Spirulina (Arthrospira platensis) is a filamentous cyanobacterium, often called blue-green algae, valued for its potential health benefits and rich nutritional profile. Classified as microalgae by botanists due to its chlorophyll a, and as a bacterium by bacteriologists because of its prokaryotic structure, *Spirulina* features a helical, filamentous shape, measuring 50-60 µm in diameter and 200-300 µm in length. Historically, Native Americans made sun-dried cakes from *Spirulina*, a practice still echoed in regions like Nigrita and Serres in Greece, Japan, India, the United States, and Spain [1]. *Spirulina* is marketed as a dietary supplement and is available in health food stores as

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drinks or tablets. Known as a "superfood," it contains high levels of proteins (60-70%), carbohydrates (15-25%), and essential fatty acids (18%), including omega-3 and omega-6, with low fat and cholesterol content. It also contains vitamins, minerals, and pigments like carotenes, chlorophyll a, and phycocyanin. *Spirulina* thrives in alkaline environments but can grow across various pH levels using cultivation methods such as seas, ponds, and lakes [2]. Its nutritional composition includes gamma-linolenic acid, iron, vitamin B12, beta-carotene, and trace minerals, making it a significant food source declared optimal by the FDA. The presence of carotenoids, phenols, polysaccharides, phycocyanins, sterols, and polyunsaturated fatty acids (PUFAs) in *Spirulina* is linked to treating inflammatory diseases, tumors, hypertension, obesity, high cholesterol, and cardiovascular diseases (CVDs). In the food industry, *Spirulina* is processed into powder, liquid, oil, pills, or capsules for use in confectioneries, snacks, and baked goods, addressing child nutrition and malnutrition while offering market diversity [3]. This review summarizes *Spirulina's* mechanisms of action, potential health benefits, and current and future clinical applications, highlighting its promise as a nutritional supplement and medicinal resource [4]. With its high demand and extensive availability, *Spirulina* supports nutrition, livelihoods, and environmental sustainability, addressing contemporary health challenges and offering novel therapeutic interventions [5][6]. *Spirulina* as a superfood with marvelous health benefits: Insights into cultivation, production, and health benefits are presented in Figure 1.

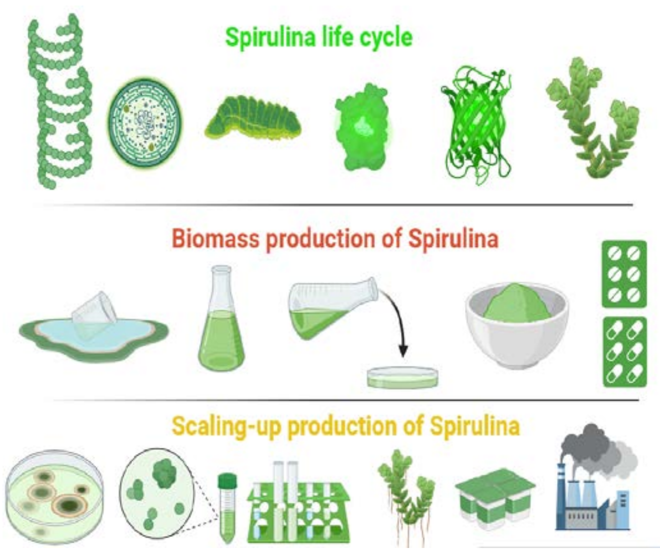

Figure 1: *Spirulina* as a superfood with marvelous health benefits: Insights into cultivation, production, and health benefits [1]

Historical background and Fundamental attributes of *spirulina*

History and cultivation of *spirulina*

Spirulina has been a dietary staple across civilizations and continents throughout history. The Aztecs in Mexico and the Kanembu people near Lake Chad revered it as "tecuitlatl," drying it into cakes for easy storage. This practice highlights *Spirulina's* enduring cultural and nutritional significance in diverse regions, spanning ancient civilizations and sustaining communities through its rich nutritional content [7]. The Kanembu people gather fresh algae from Lake Chad, filling clay pots with wet algae that drains through cloth bags. They spread the algae on the lakeshore to partially dry in the sun, then chop it into small squares. These squares are brought to villages like Abdulqader, Barsanti, and Tredici, where they finish drying on mats in the sun. Once completely dry, women sell the algae cakes in nearby markets, where they serve as a vital source of nutrition in daily life [8].

The Kanembu people often crumble "Dihé" and mix it with a tomato-and-pepper sauce, serving this mixture with millet, beans, fish, or meat, forming a substantial part of their diet. Pregnant women especially consume "Dihé" cakes directly, believing that the dark color protects their unborn babies from sorcerers' malevolent gazes [9].

In the 20th century, *Spirulina* saw a resurgence of interest as a potential food source. Rediscovery in the 1960s and 1970s led scientists to scrutinize its nutritional composition and health benefits. By the 1970s, commercial cultivation began, driven by its recognized potential as a highly nutritious food. *Spirulina's* suitability for mass production caught the attention of organizations and companies, prompting the development of cultivation techniques. It even drew interest from NASA, which explored its use as a viable food source for astronauts during extended space missions [10].

Spirulina's high protein content and nutrient-rich profile made it a promising addition to space food rations. In recent decades, *Spirulina* has surged in popularity as a dietary supplement, available in powder, capsules, and tablets, marketed for its nutritional benefits and recognized as a superfood. It is now widely incorporated into various food products and continues to gain attention for its ample protein, vitamins, minerals, and essential nutrients [11]. People rely on *spirulina* for its potential health benefits, including immune system support, antioxidant properties, and its nutrient-rich composition. Once primarily a food source in specific regions, its recognition as a valuable nutritional supplement has expanded its use worldwide. Ongoing research explores its applications in addressing various health concerns and nutritional deficiencies, ensuring *spirulina* remains a subject of continued fascination and study in the modern era [12].

Spirulina cultivation in India thrives in states like Tamil Nadu (Madurai), Karnataka (Mysuru, Bengaluru), Andhra Pradesh (Visakhapatnam), and Maharashtra (Pune, Mumbai). These areas are selected for their conducive climates, freshwater availability, and suitable land. Gujarat (Vadodara, Surat) and Rajasthan (Bikaner, Jodhpur) employ innovative techniques to overcome desert challenges. Puducherry utilizes coastal advantages, while Odisha (Puri, Bhubaneswar) taps coastal resources. These efforts highlight *Spirulina*'s adaptability across varied Indian landscapes, supporting local economies through nutrition and sustainable agriculture in Figure 2 [4].

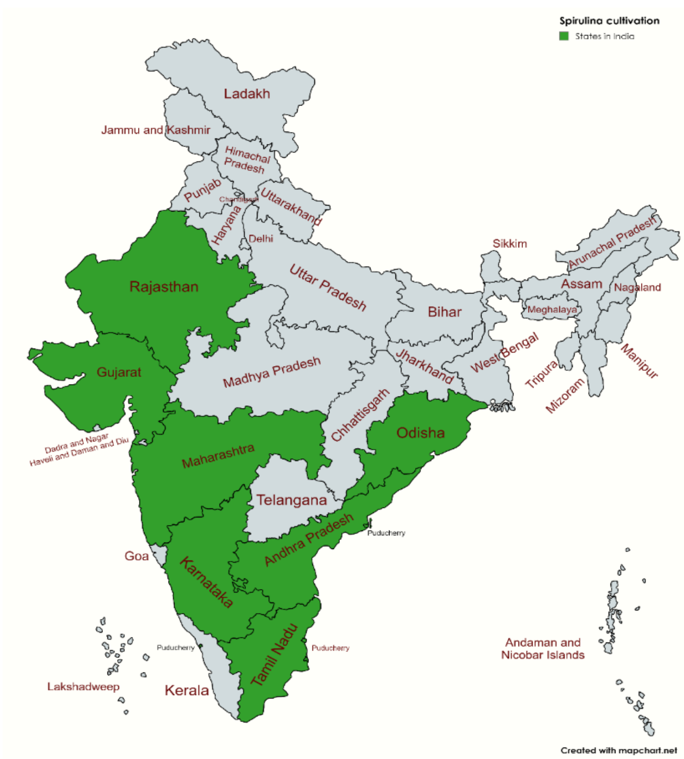

Figure 2: *Spirulina* cultivation in various states in India [4]

Fundamental attributes of *spirulina*

Taxonomy and Morphology

Turpin first proposed the genus *Spirulina* in 1827 for SL oscillarioides. It is a genus under the phylum Cyanobacteria and is classified under the kingdom Monera and division Cyanophyta. There are currently about 39 recognized species of *spirulina*, the most studied of which are *S. platensis*, *S. fusiformis*, and *S. maxima* due to their significant nutritional and medicinal value. *S. platensis* is by far the most accessible and extensively used species, especially in the food and medical industries. Table 1 contains comprehensive descriptions [13].

Table 1: The taxonomy of *Spirulina* [50-53]

Scientific classification	
Kingdom	Archaeplastida
Division	Cyanobacteria
Class	Cyanophyceae
Order	Oscillatoriales
Family	Pseudanabaenaceae
Subfamily	Spirulinoideae
Genus	*Spirulina*
Species	*Spirulina plantesis*

Spirulina is a symbiotic, multicellular, filamentous blue-green microalga linked to nitrogen-fixing bacteria. It features cylindrical trichomes in a left-hand helix and contains phycocyanin, giving it a blue color. Some strains have phycoerythrin, imparting a reddish-pink hue. Photosynthetic and autotrophic, *Spirulina* reproduces by binary fission. Its gas-filled vacuoles and helical structure create floating mats with 50-500 μm long filaments and 3-4 μm wide. *Spirulina* has gram-negative bacteria-like cell walls. SL is photosynthetic, making it autotrophic, and it reproduces through binary fission. It's worth noting that cyanobacteria, such as *Spirulina*, possess cell walls that resemble those of gram-negative bacteria. In addition to other components that resist lysozyme, these cell walls contain peptidoglycan, a lysozyme-sensitive heteropolymer that provides structural support and osmotic protection to the cell. Table 2 lists further morphological characteristics of SL [14].

Spirulina growth phases

The life of *Spirulina* involves three stages: Trichome Fragmentation, where trichomes break into chains of cells; Hormogonia Enlargement and Maturation, where cells enlarge and mature; and Trichome Elongation, where mature trichomes elongate to form new filaments, growing lengthwise and adopting a helical form through binary fission [15]. Various stages of the SL life cycle are resented in Figure 3.

Table 2: The morphology of *Spirulina* [1,12,32]

SNo.	Characteristic	Description
1	**Shape**	Filamentous, spiral, or helical -Spirulina typically has a filamentous, spiral, or helical shape, which gives it its distinctive appearance. The filaments are composed of single cells joined together, forming long, thread-like structures.
2	**Size**	Diameter: Each individual *Spirulina* cell is quite small, ranging from 5 to 10 micrometers (μm). These cells are elongated, and the overall length of a filament can vary.
3	**Color**	*Spirulina* appears blue-green due to pigments like chlorophyll and phycocyanin. These pigments are responsible for the characteristic coloration.
4	**Structure**	*Spirulina* is a multicellular organism with cells arranged linearly along the filament. These cells are prokaryotic, meaning they lack a true nucleus, as do other membrane-bound organelles found in eukaryotic cells.
5	**Filament Shape**	*Spirulina* filaments have a distinctive helical or spiral shape, resembling a coiled spring or corkscrew. This spiral morphology allows for the efficient absorption of light and nutrients.
6	**Trichomes**	The filaments of *Spirulina* are often referred to as trichomes, chains of individual cells that form the characteristic spiral structure.
7	**Habitat**	*Spirulina* is often found in alkaline water bodies such as lakes, ponds, and alkaline, brackish waters. It can also be cultivated in controlled environments for commercial purposes.
8	**Mobility**	*Spirulina* cells are non-motile, meaning they do not possess structures like flagella for movement. They rely on water currents to disperse and grow.
9	**Growth**	*Spirulina* can reproduce through binary fission, dividing one cell into two daughter cells. This type of reproduction allows it to multiply under favorable conditions rapidly.

Figure 3: Life cycle of *Arthrospira platensis* [10-15]

Spirulina has a relatively simple life cycle characterized by a process of asexual reproduction through binary fission. Here is an overview of the life journey of SL Algae.

Cell Division: *Spirulina's* life cycle begins with cell division, where individual cells within multicellular filaments (trichomes) grow and divide through binary fission.

Binary Fission: *Spirulina* primarily reproduces through binary fission, where a single cell within the filament divides into two daughter cells, each inheriting a copy of the parent cell's genetic material.

Formation of Filaments: During binary fission, cells within a filament elongate, causing the trichomes (chains of cells) to grow longer, with each cell contributing to the filament's overall length [16].

Maturation: As filaments grow and new cells form through binary fission, they mature, becoming fully functional and capable of photosynthesis and other metabolic processes.

Photosynthesis: *Spirulina* uses sunlight to convert CO_2 and H_2O into energy-rich compounds like sugars through photosynthesis. Chlorophyll a and other pigments capture light energy to facilitate this process.

Harvesting: In commercial cultivation, mature *Spirulina* filaments are harvested upon reaching the desired biomass. Methods vary but typically involve separating the *Spirulina* biomass from the culture medium [17].

Processing: After harvesting, the biomass can be processed into powder, flakes, tablets, or capsules, tailored as a dietary supplement or food ingredient.

Cultivation Continues: In natural or controlled cultivation settings, *Spirulina's* life cycle persists under favorable environmental conditions like temperature, pH, and nutrient availability, enabling continuous growth and reproduction [18].

Natural habitat, source, and growth

Spirulina (SL), a cyanobacteria or blue-green microalgae, thrives in alkaline and brackish waters, commonly found in lakes and ponds. It naturally occurs in environments like Lake Texcoco in Mexico, which the Aztecs historically harvested. In India, it inhabits saline lakes and regions with tropical and subtropical climates, adapting well to warm, sunny conditions [19]. *Spirulina* (SL) can be sourced from natural aquatic habitats or cultivated commercially. SL is often grown commercially in controlled environments like large, shallow ponds or closed photobioreactors. These systems maintain precise pH, temperature, and nutrient levels, which are crucial for optimal growth. *Spirulina* requires intense sunlight, warm temperatures (30°C to 35°C), alkaline pH (9 to 11), and aeration for photosynthesis and growth [20].

Exploring the Nutritional and Biochemical Components of *Spirulina*

The body gets most of its essential nutrients from foods needed for growth, vital biological functions, and overall health maintenance. The season, the location of the facility where the algae is produced, and the source of the algae used for culture all impact the *spirulina*'s composition. SL is mainly composed of proteins, which account for between 55% and 70% of its weight, with carbohydrates making up the remaining 15% to 25%. Minerals range from 7% to 13%, fats from 6% to 8%, moisture from 3% to 7%, and dietary fibers from 8% to 10% make up dried algae [21]. Notably, polyunsaturated fatty acids (PUFAs) account for 1.5% to 2% of the total fat content, with linolenic acid accounting for 36% of the total PUFAs. B1, B2, B3, B6, B9, B12, C, D, and E vitamins, vital minerals (K, Ca, Cr, Cu, Fe, Mg, Mn, P, Se, Na, and Zn), and a variety of pigments (such as chlorophyll A, xanthophylls, beta-carotene, and others) are also present in SL. Figure 4 displays some essential *spirulina* biochemical elements [22]. Spirulina is abundant in essential bioactives, including phycocyanin, carotenoids such as beta-carotene, chlorophyll, Vitamin B12, Vitamin E, calcium, iron, magnesium, phosphorus, potassium, sodium, zinc, omega-3 fatty acids, and gamma-linolenic acid (GLA). The latest human clinical trials on *Spirulina* demonstrate its potential nutraceutical benefits due to its antioxidant, anti-inflammatory, and antiviral effects. A randomized trial on COVID-19 ICU patients found that *Spirulina* supplementation significantly reduced hospital and ICU stays, suggesting anti-inflammatory benefits that may help manage critical illness. However, *Spirulina* did not significantly impact survival rates or other clinical scores such as the NEWS2 and APACHE scores, which assess organ function and disease severity [1].

In sports nutrition, *Spirulina*’s antioxidant properties have been noted to reduce oxidative stress and improve markers like plasma malondialdehyde (MDA) and superoxide dismutase (SOD) activity in athletes, demonstrating its role in protecting against exercise-induced oxidative damage. These studies, involving various sample sizes and designs, affirm that *Spirulina* supplementation can bolster redox balance and immune function. These studies highlight *Spirulina*'s multifaceted health benefits and reinforce its role in nutraceutical applications, though further large-scale trials are warranted for more conclusive evidence. These components contribute to its nutritional profile and potential health benefits Table 3.

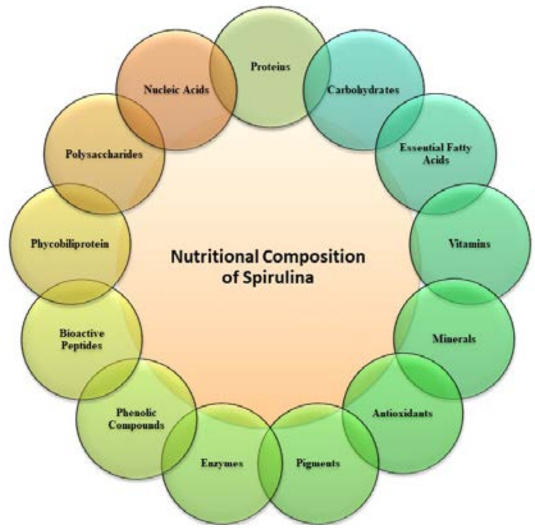

Figure 4: Nutritional Composition of *Spirulina* [22, 35]

Lipids/Fats and Fatty Acids

The essential lipids, which primarily consist of unsaturated fatty acids, make up approximately 1.3% to 15% of the total lipid content in SL, accounting for about 6% to 6.5% of its composition. Interestingly, gamma-linolenic acid (GLA) makes up a sizable amount—roughly 30% to 35% of the total fat content. Furthermore, between 25% and 60% of the total fatty acids in SL can be composed of polyunsaturated fatty acids (PUFAs) [23-28]. Additionally present are essential fatty acids, such as linoleic and linolenic acid, at concentrations of up to 1.0 g per 100 g of dry biomass of SL. *Spirulina*'s primary fatty acids include palmitic acid (44.6% to 54.1%), oleic acid (1% to 15.5%), linoleic acid (10.8% to 30.7%), and gamma-linolenic acid (8.0% to 31.7%). Notably, gamma-linolenic acid (GLA) is an essential fatty acid rarely found in other dietary sources. Adults should aim for 1% to 2% of their daily energy intake to come from essential fatty acids, while children need slightly more at 3% [23]. Regarding cholesterol, *spirulina* contains around 32.5 mg per 100 g. To put this in perspective, a 10 g serving of SL powder (equivalent to a soup spoon) supplies just

1.3 mg of cholesterol and 36 kcal of energy. For comparison, a comparable amount of protein from an egg provides 300 mg of cholesterol and 80 kcal. Consequently, SL powder is a popular choice for supplementing protein intake while managing weight, with the typical daily dose ranging from 2 to 8.5 g [24].

Table 3: Nutritional and Bioactive Components of *Spirulina* [21][22][76]

Bioactive Name	Concentration (mg/g)	Pharmaceutical Application
Phycocyanin	10-20% (100-200 mg/g)	It has antioxidant and anti-inflammatory properties, making it useful for treating conditions like arthritis and cardiovascular disease. It also has potential anti-cancer properties.
Chlorophyll	1-2% (10-20 mg/g)	Detoxification, immune support. Wound healing and skin protection due to its antimicrobial and anti-inflammatory properties. Potential anti-cancer properties.
Beta-Carotene	4 - 5	Antioxidant, vision health
Gamma-Linolenic Acid (GLA)	1 - 2	Anti-inflammatory, cardiovascular health. Making it useful for treating conditions like arthritis and autoimmune disorders.
Iron	0.05-0.15 mg/g	Anemia prevention, energy production. Treatment of iron-deficiency anemia. Essential for healthy red blood cells.
Vitamin B12	0.001 - 0.01	Energy production. Essential for nerve function, red blood cell formation, and DNA synthesis. Treatment of vitamin B12 deficiency and anemia.
Polysaccharides	8 - 15	Immune modulation, anti-tumor
Essential Amino Acids	60 - 70% of total protein	Muscle repair, overall health
Protein	60-70%	Anemia prevention, energy production
Carotenoids (e.g., beta-carotene)	0.2-0.5 mg/g	Vitamin A precursor, essential for healthy vision, immune function, and skin health. Antioxidant properties, protecting against cell damage and reducing cancer risk.
Vitamin E	1.5-3.5 mg/g	Antioxidant properties, protecting against cell damage and reducing cancer risk. Skin and hair care, due to its moisturizing and protective properties.
Calcium	1.5-2.5% (15,000-25,000 ppm)	Bone health and osteoporosis prevention. Muscle function and nerve transmission.
Magnesium	1.5-2.5% (15,000-25,000 ppm)	Muscle relaxation and cramp relief. Heart health, blood pressure regulation, and stroke prevention.
Phosphorus	1-2% (10,000-20,000 ppm)	Bone health and osteoporosis prevention. Essential for nerve function and DNA synthesis.
Sodium	0.5-1.5% (5,000-15,000 ppm)	
Zinc	0.1-0.5% (1,000-5,000 ppm)	Immune system support and wound healing. Treatment of zinc deficiency and related conditions (e.g., acne, diarrhea).
Omega-3 fatty acids	2-4% (20,000-40,000 ppm)	Heart health, inflammation reduction, and triglyceride lowering. Potential treatment for depression, anxiety, and ADHD.
Potassium	2-3% (20,000-30,000 ppm)	Heart health, blood pressure regulation, and stroke prevention. Muscle function and nerve transmission.

Carbohydrate

Studies have reported varying proportions of carbohydrates in *spirulina* spp. Some suggest it contains around 13.6% carbohydrates, while others indicate a range from 15% to 25% of its dry weight. It's important to note that *spirulina*'s carbohydrates are not uniform; they consist of different sugars, including glucose, mannose, galactose, xylose, and glycogen. This diverse carbohydrate composition makes SL highly digestible and nutrient-rich, making it suitable for consumption by the elderly and those with intestinal malabsorption [25]. Among these sugars, rhamnose is the dominant component, constituting roughly 52.3% of the total sugars in SL. *Spirulina*'s biomass contains 1.22g/L of these sugars, with its polysaccharide content comprising 2.590% of its biomass. The total sugars in SL represent approximately 17.275% of its polysaccharides. These carbohydrates include polymers like glucosamine (1.9%), rhamnosamine (9.7%), glycogen (0.5%), and smaller amounts of glucose, fructose, sucrose, glycerine, mannitol, and sorbitol. Additionally, *spirulina*'s cell wall contains sugars similar to those found in Gram-negative bacteria cell walls, such as glucosamine, muramic acid, and glucosamine bound to peptides [26]. It is worth mentioning that the percentage of carbohydrates in SL can vary depending on the nitrogen source in the medium. Substituting the nitrogen source with urea increases the carbohydrate percentage from 13.20% to 16.01%. This underscores the significance of cultivation conditions in determining *spirulina*'s nutritional composition [27].

Protein

SL boasts notably high protein content, ranging from 55% to 70% of its dry weight, with variations depending on its source. Notably, it qualifies as a complete protein, encompassing all essential amino acids (EAAs), albeit with slightly reduced quantities of methionine, cystine, and lysine compared to conventional protein sources like meat, eggs, or milk. Nonetheless, it surpasses standard plant-based proteins, including those from legumes. Proteins play a pivotal role in shaping the body's structure, functions, and the arrangement of tissues and organs. When the ingested food contains all EAAs, the body can synthesize the necessary proteins [28]. *Spirulina* exhibits remarkable protein content, ranging from 60% to 70% of its dry weight, starkly contrasting to beef, which contains only 22% protein. In plant sources, *spirulina* stands out with its exceptionally high protein content, doubling the protein levels found in the finest vegetable sources. This surpasses the protein percentages typically present in animal meats and fish (15%-25%), soybeans (35%), powdered milk (35%), peanuts (25%), eggs (12%), cereals (8%-14%), and whole milk (3%). The protein content in *spirulina* fluctuates by approximately 10% to 15%, depending on the harvest time, with the highest protein concentration occurring during the early morning hours [29].

Minerals

SL is a rich source of essential minerals, constituting approximately 7% of its total weight under laboratory conditions, with commercial *spirulina* production also typically aligning with this figure. Its mineral content can vary depending on growth media, temperature, pH, and salinity. This remarkable microorganism offers diverse minerals, including potassium, calcium, chromium, copper, iron, magnesium, manganese, phosphorus, selenium, sodium, boron, molybdenum, and zinc. Additionally, *spirulina* contains other vital nutritional components such as boron, phosphorus, and selenium. *Spirulina*'s mineral-rich composition extends to macro- and micronutrients, making it a versatile resource with applications in agriculture, the food industry, pharmaceuticals, perfumery, and medical practice [30].

Amino acid

Proteins are composed of amino acids, which serve as the fundamental building blocks of proteins and are essential components of various coenzymes, hormones, and nucleic acids. Foods containing all EAAs are crucial for addressing a wide range of dietary and health concerns, as EAAs fulfill diverse structural and functional roles in the body [31-37]. SL contains a comprehensive array of amino acids, including methionine, lysine, threonine, tryptophan, isoleucine, leucine, phenylalanine, valine, alanine, arginine, cysteine, glutamine, glycine, histidine, proline, serine, and threonine. Siva et al. found spirulina particularly rich in EAAs, with leucine and valine reaching 5400 and 4000 mg/100 g, respectively. Additionally, non-EAAs like glutamic acid and aspartic acid were found at high concentrations, with 9100 mg/100 g values and 6100 mg/100 g, respectively [31]. Another study by Salmean et al. reported substantial quantities of EAAs, with leucine (5380 mg/100 g), valine (3940 mg/100 g), and isoleucine (3500 mg/100 g) standing out prominently. Non-EAAs such as glutamic acid, aspartic acid, and alanine were also present in significant amounts, with 9130 mg/100 g, 5990 mg/100 g, and 4590 mg/100 g, respectively. Dry SL algae were found to contain EAAs, with quantities measured as follows: isoleucine (3.209 g/100 g), leucine (4.947 g/100 g), lysine (3.025 g/100 g), valine (3.512 g/100 g), arginine (4.147 g/100 g), alanine (4.515 g/100 g), aspartic acid (5.793 g/100 g), glutamic acid (8.386 g/100 g), and glycine (3.099 g/100 g) [32].

Vitamins

Spirulina is rich in vitamins, including B1 (thiamine), B2 (riboflavin), B3 (nicotinamide), B6 (pyridoxine), B9 (folic acid), B12 (cyanocobalamin), vitamin C, vitamin D, and vitamin E. Among these algae, SL stands out for its role in developing functional foods. It is an economical source of vitamin production, yielding a significant quantity of SL at a reasonable cost. Research has shown that SL contains high vitamin concentrations, making it an excellent addition to various food products such as beverages and juices [38-42]. This supplementation enhances the product's vitamin content while improving its nutritional and health-related benefits [33].

Spirulina vs. Other Superfoods

Spirulina, quinoa, and chia seeds each offer a distinct nutrient profile that makes them valuable for addressing malnutrition, cardiovascular health, and immune support. *Spirulina* stands out for its high protein content, containing approximately 60-70% protein by weight. It is also rich in essential vitamins (A, B-complex, and K), minerals (iron and magnesium), and antioxidant compounds like phycocyanin. These attributes make it particularly effective in combating malnutrition, especially protein deficiency [21]. Quinoa and chia seeds, on the other hand, are rich in fiber, omega-3 fatty acids, and complex carbohydrates, which contribute to their benefits for cardiovascular health by reducing cholesterol and improving heart function. While chia seeds are exceptionally high in alpha-linolenic acid (ALA), an essential omega-3 fatty acid, quinoa contains all nine essential amino acids, making it a complete protein source ideal for supporting muscle maintenance and general health. Regarding immune support, *Spirulina*'s unique compounds, like phycocyanin and beta-carotene, provide potent antioxidant and anti-inflammatory benefits, which may be more effective in immune modulation than the nutrient profiles of quinoa and chia. This comparison demonstrates that while all three superfoods are beneficial, *Spirulina* is especially valuable in malnutrition and immune support, while quinoa and chia shine in cardiovascular benefits [20]. A Nutritional Profile Comparison of Spirulina with Other Superfoods is given in Table 4.

Table 4: Nutritional profile comparison of *spirulina* with other superfoods [21]

Nutrient	***Spirulina***	**Quinoa**	**Chia Seeds**
Protein	60-70%	14-16%	16-18%
Fiber	0.5g per 10g	2.8g per 10g	3.4g per 10g
Omega-3 Fatty Acids	0.3g per 10g	0.1g per 10g	1.8g per 10g
Iron	28.5 mg per 100g	4.6 mg per 100g	6.1 mg per 100g
Antioxidants	High (phycocyanin, beta-carotene)	Moderate (quercetin, kaempferol)	Moderate (polyphenols)

Spirulina's bioactive compounds, such as phycocyanin, gamma-linolenic acid, and polysaccharides, can be isolated through solvent extraction or enzymatic hydrolysis. These compounds can be modified for targeted therapeutic applications, such as drug delivery systems or immune modulation. For example, phycocyanin's antioxidant and anti-inflammatory properties can be enhanced in cancer therapies or inflammatory conditions. These modifications increase the potential for *Spirulina*-based products in pharmaceutical development.

Assessing *spirulina*'s health risks: a comprehensive toxicity profile

Aquatic algal toxins, a group of toxic chemicals, encompass a wide range of naturally occurring poisonous substances produced by microalgae and blue-green algae. These substances pose a threat to human health and have environmental implications. These harmful compounds, known as cyanotoxins or blue poisons, are generated by cyanobacteria and are hazardous to humans and the environment. The sources of these toxins can be drinking water and dietary supplements containing algae. The specific chemical composition and level of toxicity of these toxins can vary depending on the affected parts of the body. Microcystins are one of the most common types of cyanotoxins, and their consumption can lead to symptoms such as abdominal discomfort, vomiting, diarrhea, skin irritation, weakness, and a sore throat, a condition referred to as cyanotoxicosis [43-51]. These symptoms can be attributed to cyanotoxins. Blue-green algae naturally produce three distinct types of cyanotoxins: alpha-anatoxin and methylamino-L-alanine, microcystin-LR, and cylindrospermopsin (CYL) [34]. The World Health Organization (WHO) has recommended a limit of 1 μg/L of MC-LR in drinking water.In summary, aquatic algal toxins encompass a range of poisonous substances produced by microalgae and blue-green algae, with cyanotoxins posing significant health and environmental risks. Cyanotoxicosis, caused by cyanotoxins like microcystins, can result in various distressing symptoms. Therefore, it is crucial to monitor and regulate these toxins in drinking water sources and other potential exposure routes [35]. Blue-green algae, including *spirulina*, have the potential to produce toxins known as cyanotoxins under certain conditions. These toxins can pose health risks to humans and animals when ingested, inhaled, or come into contact with the skin. It's important to note that not all blue-green algae or SL products contain toxins, but cyanotoxins are a concern in some cases. Toxicity from blue-green algae, including SL, can lead to various symptoms and health issues, including.

Gastrointestinal Distress: Ingesting contaminated blue-green algae can cause symptoms such as diarrhea, vomiting, abdominal pain, and nausea [36].

Skin Irritation: Contact with water contaminated by blue-green algae can lead to skin rashes, hives, or irritation.

Respiratory Issues: Inhaling aerosolized toxins from contaminated water bodies can result in symptoms like coughing, sneezing, sore throat, or difficulty breathing.

Liver and Nervous System Effects: Some cyanotoxins, like microcystins and anatoxins, can adversely affect the liver and nervous system. These effects can range from mild to severe, with potential long-term consequences.

Neurological Symptoms: Exposure to certain cyanotoxins may cause neurological symptoms such as headaches, dizziness, weakness, or muscle pain [37].

It is crucial to be cautious when consuming *spirulina* or any blue-green algae product. To minimize the risk of toxicity, Choose Reputable Sources and purchase SL products from trusted and reputable suppliers who regularly test for cyanotoxins and other contaminants. Avoid wild-harvested algae because wild-harvested blue-green algae may have a higher contamination risk than controlled cultivation. Adhere to recommended dosages provided on product labels to prevent excessive consumption. Stay informed about potential cyanobacterial blooms in natural water bodies where you swim or recreate, as these can pose health risks. If you experience symptoms of blue-green algae toxicity after consuming a product containing SL or being in contact with contaminated water, seek medical attention promptly [38].

Cultivation and Commercial production of *spirulina*

SL, a nutrient-rich blue-green microalgae, has gained popularity for its potential health benefits and versatile applications in various industries. Commercial production of SL in India has gained significant attention due to its nutritional benefits and potential as a sustainable food source. SL is typically cultivated in open ponds, raceway systems, or closed bioreactors. It thrives in alkaline freshwater environments with a pH range of 8-11. These systems require ample sunlight and controlled temperature conditions. *Spirulina* cultivation in India primarily occurs in regions with favorable climate conditions [39]. Tamil Nadu, Karnataka, Andhra Pradesh, Gujarat, and Rajasthan have become crucial cultivation hubs. SL can grow in various nutrient-rich media, including natural sources like lakes and artificial growth media. Common nutrients include nitrogen, phosphorus, potassium, and trace minerals. Some producers use organic waste materials as nutrient sources. Small- and large-scale SL production units exist in India [52-59]. Open pond systems, raceway ponds, and closed photobioreactors are commonly used cultivation methods. Open ponds are cost-effective and suitable for small-scale production, while closed systems offer better control over environmental factors. *Spirulina* is typically harvested when it forms dense biomass in the cultivation system. Harvesting methods include filtration, centrifugation, and sedimentation. After harvesting, the biomass is concentrated and prepared for further processing [5]. Once harvested, the SL biomass is dried to reduce its moisture content. Spray drying, freeze-drying, or sun drying are standard methods. Drying preserves the nutrient content and increases shelf life. Dried SL is ground into a fine powder or processed into various forms such as tablets, capsules, flakes, or liquid extracts. This processing allows for easy incorporation into a wide range of products. Quality control measures are crucial throughout the cultivation and production process. Regular testing ensures SL products meet safety and quality standards, including low heavy metal and microbial contamination.SL is commercially produced on a large scale by industrial and small-scale producers worldwide [7]. Countries like India, China, and the United States are significant producers of SL. *Spirulina* is used as a dietary supplement, functional food ingredient, and in various industries, including cosmetics and pharmaceuticals. Its rich nutritional profile, high protein content, vitamins, and antioxidants make it a valuable resource.SL cultivation is often praised for its eco-friendly nature. It can be grown using wastewater and CO_2, reducing environmental impact. Additionally, it has a higher yield per unit area than traditional crops. Indian research institutions and organizations are actively involved in SL research. They focus on improving cultivation techniques, enhancing product quality, and exploring new applications in malnutrition alleviation and sustainable agriculture. The Indian government has promoted SL cultivation to combat malnutrition and enhance food security, particularly in rural areas. Some states offer subsidies and support to encourage *Spirulina* production. India exports SL products to various countries, contributing to its international trade. Commercial production of SL in India continues to evolve, with ongoing efforts to increase production efficiency, product diversification, and sustainable cultivation practices. *Spirulina*'s role in addressing malnutrition and promoting health makes it a valuable resource in India's food and nutrition landscape [60]. SL is commercially cultivated on a large scale in over 22 countries. These countries include Benin, Brazil, Burkina Faso, Chad, Chile, China, Costa Rica, Côte d'Ivoire, Cuba, Ecuador, France, India, Madagascar, Mexico, Myanmar, Peru, Israel, Spain, Thailand, Togo, the United States of America, and Vietnam, as documented by Ravi et al. in 2010 [19].

Commercial production technologies of *Spirulina*

Two primary technologies for cultivating Spirulina are closed photobioreactors (PBR) and the open pond method. Laboratory cultivation is another method used to grow spirulina.

Closed Photobioreactors (PBR)

A photobioreactor is a closed system that enhances algae productivity by controlling environmental factors like carbon dioxide, water supply, temperature, light intensity, pH, gas exchange, and aeration. It can use artificial or natural light and various designs such as flat-plate, tubular, vertical column, and internally illuminated systems to optimize algae cultivation, addressing the challenges of open pond systems [15]. Efforts have focused on designing temperature-controlled photobioreactors like double-walled, internally illuminated systems with heating and cooling water circuits to improve efficiency and flexibility in large-scale algal cultivation for diverse applications [18].

Advantages

Closed photobioreactors (PBRs) are a prominent technology for cultivating *Spirulina* and various other microalgae and cyanobacteria. These systems provide a controlled and contained environment for algae growth, offering several advantages and features, as shown in Figure 5.

Closed photobioreactors (PBRs) precisely control light intensity, temperature, pH, and nutrient concentrations, optimizing conditions for high productivity. These systems also protect *Spirulina* from contaminants, ensuring purity and reducing the risk of microbial contamination. PBRs support year-round cultivation independent of weather conditions, ensuring consistent production. They conserve water through reduced evaporation and facilitate efficient harvesting and scalability from small research setups to large industrial operations. PBRs are crucial for research and development, enhancing the study and optimization of *Spirulina* growth parameters, making them essential for meeting increasing global demand in food, pharmaceutical, and cosmetic industries [62][33][28].

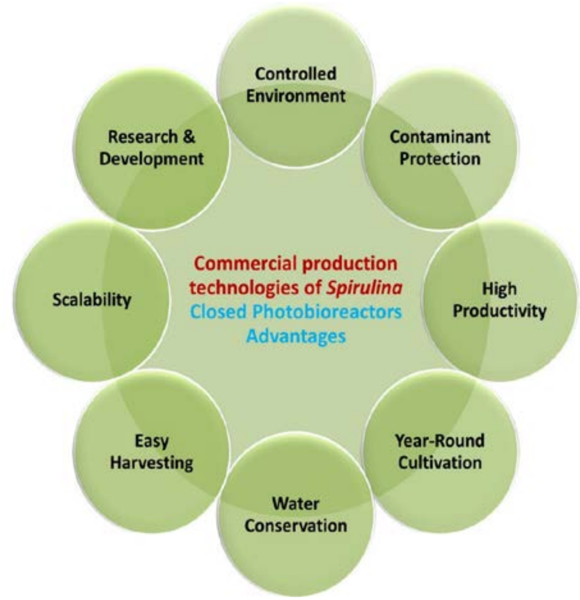

Figure 5: Advantages of the Closed Photobioreactors in commercial production technologies of *spirulina* [62]

Open Pond Method

The Open-Pond Method involves using open, shallow ponds or raceways to cultivate Spirulina, a type of blue-green microalgae. These ponds can be natural bodies like lakes or artificial containers such as circular ponds, tanks, and raceways, facilitating its growth in various environments. Cultivation is typically carried out in two ways: a) concrete ponds and b) pits lined with PVC or other plastic sheets [37].

Open ponds used for cultivating *Spirulina* often suffer from inefficiencies such as poor light utilization, evaporation losses, carbon dioxide diffusion, and large land area requirements. These systems also face challenges like inadequate aeration, which lowers mass transfer rates and biomass productivity. Location, season, temperature, pH, and nutrient availability further influence *Spirulina* growth in these shallow, rectangular ponds, typically 20-30 centimeters deep to maximize sunlight penetration [25]. Based on the Spirulina strain's requirements, the ponds are filled with freshwater, brackish water, or seawater. Water quality is crucial, necessitating freedom from contaminants. Essential nutrients like nitrogen and phosphorus are added and sourced from natural or synthetic fertilizers. Maintaining pH around 9-11 is optimal. Mechanical mixing or aeration ensures uniform distribution of nutrients and gases for *Spirulina* growth [9]. Open ponds maximize sunlight exposure, which is crucial for photosynthetic *Spirulina* growth. Harvesting occurs at peak cell density, often by skimming, followed by drying and processing into products like powder, flakes, or tablets, retaining nutritional integrity [63]. In eco-friendly practices, water recycling minimizes SL cultivation's environmental footprint. Rigorous quality control ensures SL products meet safety and dietary standards through contamination testing and consistency maintenance [16]. The Open Pond Method is known for its simplicity and cost-effectiveness, making it accessible to various cultivators. However, it also comes with challenges, such as susceptibility to contamination, variable climatic conditions, and the need for large land areas. As a result, alternative cultivation methods like closed photobioreactors have gained popularity for more controlled and efficient SL production in specific contexts [34]. The Open Pond Method of *Spirulina* Cultivation's several advantages are depicted in Figure 6.

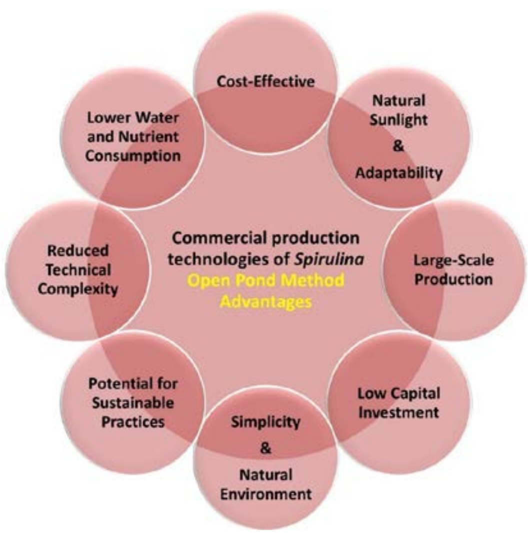

Figure 6: The advantages of the open pond method of *spirulina* cultivation [33][28]

Open pond systems offer cost-effectiveness and simplicity in cultivating *Spirulina*, utilizing natural sunlight for photosynthesis and supporting large-scale production to meet commercial demands [64]. They require lower capital investment and are adaptable to various climates, reducing technical complexity and water/nutrient consumption compared to closed photobioreactors [65]. However, challenges include susceptibility to contamination, less control over environmental factors, and the need for extensive land. Effective management is crucial to optimize growth and ensure product quality [2][1][66].

Open pond and photobioreactor (PBR) systems are two standard methods for cultivating Spirulina, each with distinct impacts on its nutrient density, bioactive compound retention, and environmental sustainability. Open pond systems are cost-effective but more vulnerable to contamination and environmental fluctuations, which can reduce the consistency of nutrient profiles and bioactive compounds like C-phycocyanin (C-PC) and gamma-linolenic acid (GLA) [2]. In contrast, photobioreactors provide a more controlled environment, leading to better retention of bioactive and enhanced nutrient density, particularly in terms of protein and essential fatty acids, due to optimal light and temperature regulation. However, PBR systems are more expensive and energy-intensive. Both systems offer the potential for sustainable Spirulina production, with PBRs generally having a lower environmental impact regarding water usage and land footprint [66].

Laboratory cultivation

Laboratory cultivation of SL occurs in controlled environments like growth chambers or clean rooms, ideal for research and small-scale production. Closed photobioreactors (PBRs) ensure precise control over light, temperature, pH, and nutrients, isolating from contaminants for optimal SL growth and experimentation [8]. In laboratory cultivation, maintaining sterile conditions is essential to prevent contamination. Standard practices include sterilizing equipment, culture media, and surfaces. Researchers adjust nutrient concentrations precisely to provide *Spirulina* with optimal levels of nitrogen, phosphorus, and trace elements for growth [67]. In laboratory cultivation, precise light sources like fluorescent lamps or LED panels are used for photosynthesis, with adjustable intensity, duration, and spectral composition. Temperature is meticulously controlled for optimal growth, while pH levels in the culture medium are closely monitored and adjusted. Aeration systems ensure sufficient carbon dioxide and oxygen for photosynthesis, preventing oxygen deficiency [10]. Laboratory cultivation involves rigorous monitoring of parameters such as cell density, biomass production, and biochemical composition to assess

Spirulina growth and adjust conditions as needed. It serves primarily for research, allowing the study of growth kinetics, nutritional content, and responses to varied situations. Stringent quality controls ensure biomass meets standards. This controlled environment supports scientific research in nutrition, biotechnology, and environmental science [18]. In assessing growth and biochemical traits under controlled conditions, three *Spirulina* species—*S. platensis, S. laxissima,* and *S. lonar*—were cultured. *S. platensis* showed the highest growth rate, biomass production, and pigment concentration, with lower intracellular phenolics. These results underscore *S. platensis* as ideal for large-scale cultivation due to its rapid growth and favorable biochemical profile [15].

Growth conditions and factors affecting the cultivation of *spirulina*

Various conditions and factors influence Spirulina's growth, all of which play crucial roles in its successful cultivation. Siting SL production facilities for large-scale cultivation requires careful consideration of climatic conditions, especially, consistent year-round sunshine. Achieving optimal growth can be challenging due to various environmental variables, including solar radiation, rainfall, wind, and temperature fluctuations [14]. These are multiple growth conditions and the key factors that affect the cultivation of *Spirulina*:

Temperature: SL thrives in warm temperatures. The ideal temperature range for its growth is typically between 30°C to 35°C (86°F to 95°F). However, it can tolerate a broader range, but growth rates may vary. A temperature range of 30-35°C, even when the outside temperature reached 38°C, was ideal for achieving the highest yield of *Spirulina*. Temperatures exceeding 35°C resulted in culture bleaching. Partial shading was employed to maintain a culture temperature of approximately 30°C, even when the external temperature soared to 38°C [24].

Light Intensity: *Spirulina* is photosynthetic, which relies on light for energy production through photosynthesis. Adequate light intensity is essential. Natural sunlight or artificial lighting systems can provide the necessary illumination. SL necessitated specific light intensities during its growth phase, with the optimal range falling between 20 and 30 K (Kelvin). Light exposure for 10 hours at an intensity of 2 K lux was achieved using colored cellophane paper to cover the fluorescent bulbs. Blue light produced the highest protein content, followed by yellow, white, red, and green light. It became apparent that white fluorescent light containing a red-orange component provided incredible energy for improved protein and pigment synthesis [34].

pH Levels: SL prefers alkaline conditions, with an optimal pH range of approximately 9 to 11. Maintaining pH within this range is crucial for its growth and overall health [68].

Nutrient Availability: SL requires a consistent supply of essential nutrients, including nitrogen, phosphorus, potassium, and trace minerals. The nutrient composition of the growth medium should be carefully controlled to ensure proper nutrition. SL demands higher nutrient inputs and salt concentrations compared to Scenedesmus and Chlorella. This could explain why *Spirulina* is primarily found in natural salt lakes. The challenging growth media currently utilized in various production centers are minor modifications of the medium initially developed by Zarrouk for SL cultivation. SL thrives in a high-alkalinity environment with a continuous provision of bicarbonate ions [39].

Carbon Dioxide (CO_2): *Spirulina* utilizes carbon dioxide for photosynthesis. Adequate CO_2 levels in the growth medium or air supply are essential for its growth. Ogawa and Terui observed that SL did not thrive when organic compounds were the sole carbon source. To enhance cyanobacteria production in large-scale cultivation, they utilized a minimal medium devoid of sodium chloride and enriched it with extracts from various organic fertilizers. This led to a 5 to 30 percent increase in the dry matter production of *Spirulina platensis* [69].

pH: pH directly impacts the physiological characteristics of algae and the accessibility of nutrients. pH influenced the solubility of carbon sources and minerals in the culture, either directly or indirectly. SL thrived at pH levels ranging from 9 to 11. The optimal pH of the *Spirulina* nutrient medium shifted from 8.4 to 9.5 during mass cultivation, primarily due to the consumption of bicarbonate and sodium ions [17].

Mixing and Aeration: Proper mixing of the culture medium helps prevent settling *Spirulina* cells, ensuring they receive even exposure to light and nutrients. Aeration is necessary to keep the cells suspended and to facilitate gas exchange. Agitating algal cultures offered several advantages, including the uniform distribution of CO_2 and the prevention of thermal stratification. Numerous agitation methods and devices have been reported, ranging from motor-driven paddles, pumps, gravity-flow systems, and air-light systems to manual agitation [70].

Contamination Control: *Spirulina* cultures are vulnerable to contamination by other microorganisms, including bacteria and fungi. Strict hygiene practices and sterile equipment are essential to prevent contamination.

Harvesting Techniques: The method used to harvest *Spirulina* biomass can affect its quality and yield. Effective and efficient harvesting techniques are essential for commercial-scale production [20].

Water Quality: High-quality water sources are critical, with considerations for purity, salinity, and the absence of heavy metals and toxins. Water sources should be selected and treated carefully. Water quality characteristics played a significant role in the production of algal biomass. They had a dual influence: first, they affected the solubility of nutrients added to the medium, and second, they selectively accumulated certain heavy metals during the algae's growth phase.

Strain Selection: Different strains or species of *Spirulina* may have varying growth rates, nutrient requirements, and environmental tolerances. It is important to choose the right strain for specific cultivation conditions.

Scale of Production: The scale of *Spirulina* cultivation, whether small-scale or large-scale, can impact the choice of cultivation systems, equipment, and nutrient management strategies. Climate and Location: The cultivation facility's location can influence temperature, light availability, and climate-related challenges. Some regions may be better suited for *Spirulina* cultivation than others [16].

Water Management: Efficient water management practices, such as recycling and minimizing water loss, can reduce operational costs and environmental impact [71].

Disease and Pest Management: While SL is relatively resistant to diseases and pests, monitoring and management strategies should be in place to address any issues that may arise. Optimizing these growth conditions and effectively managing these factors are essential for successful SL cultivation. Researchers and cultivators continually work to refine these conditions and factors to maximize *Spirulina*'s growth, nutritional value, and potential as a sustainable food source [11]. The cost-effectiveness and scalability of *Spirulina* production technologies, particularly in developing regions, play a crucial role in addressing malnutrition and food insecurity. Open pond systems are highly scalable and cost-efficient, making them suitable for resource-limited areas, as they require minimal infrastructure and can produce large quantities of *Spirulina.* While photobioreactors offer enhanced control over nutrient density and bioactive compound retention, they are more expensive and energy-intensive, limiting their applicability in developing regions. Despite these challenges, *Spirulina* remains a promising low-cost, high-nutrient food source, primarily when open pond cultivation is implemented in suitable climates [8].

Harvesting and processing of *Spirulina*

Harvesting and processing SL involves several vital steps to obtain the final product. These steps are crucial to ensure the quality and safety of SL for various applications. SL is typically harvested from large cultivation tanks or open ponds once it reaches the desired biomass concentration [72]. Harvesting can be done using various methods, including filtration, centrifugation, or sedimentation [6]. Harvesting and processing *Spirulina* (SL) involves several critical steps to ensure the production of high-quality, safe, and nutritious products [23]. Filtration is a crucial initial step, employing methods like Microfiltration (MF) and Ultrafiltration (UF), drum filters, centrifugal separators, press filters, and gravity filters to separate SL biomass from the culture medium and remove impurities. Following filtration, the biomass undergoes concentration to reduce water content, typically through centrifugation or further filtration. Subsequent washing ensures the removal of contaminants, preparing the biomass for drying. Drying methods such as spray drying, freeze drying, or sun drying reduce moisture content to around 5-7%. The dried SL is then milled into a fine powder for consistency and ease of use in dietary supplements, foods, and cosmetics. Throughout these stages, stringent quality control measures are applied to test for contaminants, heavy metals, and microbial presence, ensuring safety and nutritional standards compliance. Packaged in appropriate containers to preserve freshness, SL products are stored in controlled environments before distribution to health food stores, pharmacies, and online retailers. Consumers utilize SL by incorporating it into smoothies, as a dietary supplement, or as an ingredient in various recipes. The processing methods are tailored to the intended application and market demand, emphasizing hygiene and quality to deliver a safe and nutritious final product [5].

Pharmacological actions of *Spirulina*

Spirulina, a type of blue-green microalga, has been studied for its potential pharmacological actions and health benefits. While more research is needed, several pharmacological actions have been reported in *Spirulina*:

Antioxidant activity and antiproliferative activity

Spirulina is rich in antioxidants, including phycocyanin and beta-carotene, which can help neutralize harmful free radicals in the body, potentially reducing oxidative stress and protecting cells from damage [20]. Liver fibrosis, a persistent liver ailment that can advance to cirrhosis if left untreated, can be managed by restraining the proliferation of activated hepatic stellate cells (HSC) or prompting HSC apoptosis. Research has highlighted *Spirulina*'s antioxidant capabilities, primarily attributed to C-phycocyanin, which have been demonstrated to hinder HSC proliferation within the G2/M phase. This study employed HepG2 cells derived from the human liver to investigate these effects further. *Spirulina*, a type of blue-green microalgae, has been found to exhibit antiproliferative activity. This means that SL can inhibit the excessive growth and multiplication of specific cells, particularly cancer cells.

One of the key components responsible for this activity is C-phycocyanin, a natural pigment found in SL (Martins and Marto, 2023). Research studies have shown that *Spirulina*'s antiproliferative properties can be particularly relevant in inhibiting the proliferation of cancer cells, making it a subject of interest in cancer research. While more research is needed to understand the mechanisms involved fully, these findings highlight the potential health benefits of SL in preventing the uncontrolled growth of cells associated with diseases like cancer [22].

Anti-Inflammatory Properties

Some studies suggest that SL may have anti-inflammatory effects, which could benefit chronic inflammation conditions like arthritis and inflammatory bowel disease. SL, a type of blue-green microalgae, has demonstrated anti-inflammatory activity in various studies. This property is attributed to its unique composition, which includes bioactive compounds like phycocyanin, beta-carotene, chlorophyll, and various polysaccharides. Research has shown that SL can modulate the body's immune response and reduce the production of pro-inflammatory cytokines and mediators. Doing so helps alleviate inflammation and its associated symptoms [7].

This anti-inflammatory activity has been observed in both in vitro and in vivo studies. One of the primary mechanisms through which SL exerts its anti-inflammatory effects is inhibiting the activation of nuclear factor-kappa B (NF-κB). This transcription factor plays a crucial role in the inflammatory response. By blocking NF-κB activation, SL helps regulate the expression of genes involved in inflammation. *Spirulina*'s anti-inflammatory properties have been investigated in various health conditions, including allergies, arthritis, and inflammatory bowel disease. While it shows promise as a natural anti-inflammatory agent, more research, including clinical trials, is needed to fully understand its effectiveness and optimal dosages for specific health conditions [17].

Nonetheless, *Spirulina*'s potential as a dietary supplement for managing inflammation is an area of ongoing interest in nutrition and health. Immune System Support: *Spirulina* contains bioactive compounds that may enhance immune system function. It may help stimulate the production of immune cells and improve the body's defense against infections. *Spirulina* exhibits anti-inflammatory properties through the action of C-phycocyanin (C-PC), a Bili protein. This compound has been shown to inhibit the formation of proinflammatory cytokines, highlighting its role in reducing inflammation. *Spirulina*'s anti-inflammatory effects are contingent on inhibiting inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2) expression. The effectiveness of *Spirulina*'s anti-inflammatory actions is directly linked to the dose of Arthrosporic platensis, ensuring an adequate amount of C-phycocyanin to regulate these inflammatory molecules, thus contributing to the anti-inflammatory process [25].

Antiviral Activity

Research has shown that SL extracts may exhibit antiviral properties, potentially inhibiting the replication of certain viruses, although more studies are needed to confirm these effects. SL has demonstrated antiviral activity in various studies. One key mechanism behind this antiviral effect is the inhibition of viral replication. SL contains compounds like sulfated polysaccharides and glycolipids that have been shown to interfere with the attachment and entry of certain viruses into host cells [6].

Additionally, *Spirulina*'s immunomodulatory properties can help enhance the body's immune response against viral infections. While *Spirulina*'s antiviral activity is promising, further research is needed to explore its specific effects against different viruses and potential applications in antiviral therapies [22].

Cholesterol Management

Spirulina has been investigated for its potential to lower total cholesterol and triglyceride levels in the blood. Some studies suggest it may help improve lipid profiles, reducing the risk of heart disease. SL has been studied for its potential role in cholesterol management. Some research suggests that regular consumption of SL may help lower total cholesterol levels and improve the lipid profile. This effect is attributed to SL's bioactive compounds like phycocyanin, beta-carotene, and gamma-linolenic acid (GLA). Phycocyanin, the blue pigment in SL, has antioxidant and anti-inflammatory properties that may contribute to its cholesterol-lowering effects [31]. It is believed to inhibit the activity of an enzyme called HMG-CoA reductase, which plays a key role in cholesterol synthesis in the body. Gamma-linolenic acid (GLA), an omega-6 fatty acid found in SL, has been associated with reducing cholesterol levels and improving cardiovascular health [73]. While SL shows promise in managing cholesterol, it should not be considered a standalone treatment for individuals with high cholesterol. It can be part of a balanced diet and healthy lifestyle to support overall cardiovascular health. As with any dietary supplement, it is important to consult with a healthcare professional before incorporating *Spirulina* into your regimen, especially if you have existing medical conditions or are taking medications) [32].

Blood Pressure Regulation

Limited research indicates that *Spirulina* may have a modest effect in lowering blood pressure, which can benefit individuals with hypertension. *Spirulina* has been investigated for its potential to help regulate blood pressure, particularly in individuals with hypertension (high blood pressure). Some studies suggest that *Spirulina* may have a modest antihypertensive effect. SL contains bioactive compounds such as peptides, phycocyanin, and gamma-linolenic acid (GLA), possibly contributing to its blood pressure-regulating properties [21]. Certain peptides derived from SL have been shown to have ACE (angiotensin-converting enzyme) inhibitory activity. ACE inhibitors are commonly prescribed medications for lowering blood pressure. Phycocyanin, the blue pigment in SL, has antioxidant and anti-inflammatory properties. It may help relax blood vessels and improve blood flow, contributing to blood pressure regulation [8]. SL is a good source of potassium, an essential mineral that helps maintain healthy blood pressure levels. Adequate potassium intake is associated with lower blood pressure. Some research suggests that SL may stimulate the production of nitric oxide (NO), a molecule that relaxes blood vessel walls, leading to vasodilation and potentially lower blood pressure [74].

Anticancer Potential

Some preclinical studies have explored *Spirulina*'s potential to inhibit the growth of cancer cells and reduce the risk of cancer development. However, more research, including clinical trials, must establish its efficacy. SL has been studied for its potential anticancer properties, although more research is needed to understand its effects and mechanisms fully. The potential role of SL in cancer prevention has been attributed to its combined antioxidant and immune-modulating properties, which could contribute to tumor suppression. This study focused on its impact on oral carcinogenesis, specifically leukoplakia. Human studies in cancer prevention, particularly those aiming to lower cancer incidence as an endpoint, face logistical challenges, resulting in limited research in this area [34].

Antimicrobial activity

SL has demonstrated antimicrobial activity in various studies, highlighting its potential as a natural antimicrobial agent. It has exhibited inhibitory effects against different microorganisms, including bacteria, fungi, and viruses. The antimicrobial properties of SL are often attributed to its bioactive compounds, such as phycocyanin and other secondary metabolites. These properties make SL a promising candidate for combating microbial infections and promoting overall health [1].

Neuroprotective Effects

SL has garnered significant attention in scientific research due to its potential neuroprotective properties, which are particularly evident in experimental models of neurodegenerative conditions such as Parkinson's disease and Alzheimer's disease. These studies suggest that SL may hold promise in safeguarding the delicate neurons in the brain from various forms of damage. Its neuroprotective effects are thought to be attributed to a combination of factors, including its rich antioxidant content and anti-inflammatory properties. By shielding against oxidative stress and reducing inflammation in neural tissues, *Spirulina* exhibits the potential to enhance brain cell resilience and longevity, thereby offering a glimmer of hope for those grappling with neurodegenerative disorders. Further research in this area is essential to unravel the full extent of *Spirulina*'s neuroprotective mechanisms and its applicability in clinical settings [22].

Anti-anemic effect

SL exhibits anti-anemic effects, which means it can help alleviate conditions associated with anemia. Anemia is characterized by a deficiency of red blood cells or hemoglobin in the blood, leading to symptoms like fatigue, weakness, and pale skin. SL is rich in iron, a vital component for producing red blood cells and hemoglobin. Its iron content and other nutrients like vitamin B12 and folic acid make SL a potential dietary supplement for individuals with anemia. By boosting the body's iron levels and promoting red blood cell production, SL can help improve symptoms of anemia and enhance overall well-being. However, it is essential to consult a healthcare professional for proper diagnosis and guidance on using SL as a supplementary treatment for anemia [39].

Anti-fungal activity

SL has shown antifungal activity in several studies, indicating its potential as a natural antifungal agent. This activity is often attributed to its bioactive compounds, including phycocyanin and other secondary metabolites. SL's antifungal properties have been observed against various fungal strains, suggesting its effectiveness in inhibiting fungal growth [16]. These findings highlight *Spirulina*'s potential applications in combating fungal infections and supporting overall health [75-77].

Antidiabetic Effects

Studies have indicated that SL could significantly enhance insulin sensitivity and regulate blood sugar levels, offering potential advantages for individuals with diabetes. This effect is thought to be linked to *Spirulina*'s ability to improve glucose metabolism and reduce insulin resistance [31]. By doing so, SL may provide a valuable dietary supplement for individuals with diabetes, helping them manage their condition more effectively and potentially reducing the need for pharmacological interventions. However, it is crucial to note that further research, including clinical trials, is needed to fully comprehend the extent of *Spirulina*'s impact on diabetes management and its precise mechanisms of action [35].

Detoxification

SL shows promise in facilitating the elimination of heavy metals and toxins from the body, but its efficacy in detoxification processes necessitates additional exploration. Initial research suggests that *Spirulina*'s high content of chlorophyll and phycocyanin may contribute to its detoxifying potential by binding to and aiding in removing harmful substances [12]. However, more comprehensive studies and clinical trials are required to ascertain the extent of its detoxification benefits and to establish specific protocols for practical use in this context [36].

As Nutraceuticals and cosmetics

SL is increasingly being recognized for its applications in the nutraceutical and cosmetics industries. *Spirulina* is rich in essential nutrients, including proteins, vitamins, minerals, and antioxidants. These bioactive compounds make *Spirulina* a valuable ingredient in dietary supplements, functional foods, and health products. It is often incorporated into capsules, tablets, powders, and liquid formulations to provide various health benefits, such as immune support, antioxidant protection, and nutritional supplementation. SL is used in cosmetic and skincare products due to its potential benefits for the skin [24]. It is believed to help promote healthy skin by reducing inflammation, improving moisture retention, and protecting against UV radiation. SL extracts are found in creams, lotions, serums, and masks designed to nourish and rejuvenate the skin. It is important to note that while SL shows promise in these areas, more rigorous clinical studies are needed to confirm its pharmacological actions and therapeutic benefits [1]. Table 5 lists the multifaceted pharmacological effects of SL.

To profile *Spirulina's* nutrients and bioactives, several analytical techniques are commonly employed, including high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and nuclear magnetic resonance (NMR) spectroscopy. HPLC is beneficial for quantifying carotenoids, phycocyanin, and other pigments, while GC-MS is employed for fatty acid profiling, identifying omega-3 fatty acids and other lipids. NMR spectroscopy, often coupled with advanced metabolomics approaches, allows for the detailed identification of bioactive compounds, such as peptides and polysaccharides.

Recent studies have also utilized advanced techniques like near-infrared spectroscopy (NIRS) to assess *Spirulina's* chemical composition non-invasively, offering a faster and more efficient alternative for large-scale quality control actively provide comprehensive insights into *Spirulina's* nutrient profile and bioactive compounds, supporting its use in various therapeutic and nutraceutical applications.

Table 5. Multifaceted pharmacological effects of *Spirulina* [65-75]

Objective	Method	Key findings	Application
Investigate its antioxidant, immunomodulatory, and anti-inflammatory activities in animals and humans	*Spirulina* is rich in protein and vitamins, inhibits lipid peroxidation and DNA damage, Involves phycocyanin and β-carotene as important molecules	Used as a nutraceutical food supplement, Potential role in preventing oxidative stress-related diseases	Antioxidant, immunomodulatory, and anti-inflammatory Activities. [65]
Treatment for Ulcerative colitis and Crohn's disease	*Spirulina* and Dunaliella at 500 mg/kg assessed for modulating effects on acetic acid-induced ulcerative colitis in rats.	Both *Spirulina* and Dunaliella showed significant modulation of acetic acid-induced colitis in rats, attributed to increased antioxidant activity& reduced lipid peroxidation & inflammation markers	*Spirulina* demonstrated superior therapeutic & safety profiles compared to Dunaliella in acetic acid-induced ulcerative colitis, surpassing Sulfasalazine [66]
Management of blood pressure and reducing the risk of stroke through antihypertensive actions	Peptides with elevated levels of branched and aromatic amino acids like Ile, Val, Phe, and Tyr, positioned at both N and C-terminal ends, are well-suited for binding to ACE (angiotensin-converting enzyme) as competitive inhibitors	Controlling cardiovascular diseases, specifically hypertension, through blood pressure regulation, ACE-I enzyme inhibition, arterial wall relaxation, and fluid volume reduction by inhibiting angiotensin-II. Enhancing blood and oxygen flow to vital organs like the heart, liver, and kidneys	Antihypertensive actions [67]
formulate stable protein-rich emulsions	This study aimed to create a vegan oil-in-water emulsion incorporating varying *Spirulina* RB content, aligning with contemporary food preferences. Emulsions containing 3.0% (w/w) proteins were prepared with diverse chickpea and *Spirulina* RB ratios, assessing emulsifying properties, including texture, rheology, color, antioxidant activity, and droplet size distribution	The findings demonstrate the feasibility of creating stable, protein-rich emulsions utilizing protein-rich recovered material from *Spirulina* as an innovative food ingredient	Protein source to increase health benefits [68]
Addressing Skin Problems	Various natural compounds used for skin issues, growing interest in natural products.Ethanol extract of *Arthrospira platensis* is a more effective tyrosinase inhibitor.	Ethanol and water extracts of *Arthrospira platensis* evaluated for tyrosinase inhibition.Ethanol extract displayed higher tyrosinase inhibitory activity (IC50: 1.4×10^{-3} g/mL).Water extract showed lower inhibitory activity (IC50: 7.2×10^{-3} g/mL).Phenolic compounds may not be the main contributors to antioxidant capacity.	Cosmetic applications [69]

Objective	Method	Key findings	Application
Anti-Obesity Effects	*Spirulina* platensis has demonstrated an anti-obesity effect in clinical trials, improving various comorbidities.	This suggests its role in treating obesity rather than solely preventing it.	Anti-Obesity [70]
Exploring the Impact of *Spirulina* Supplementation on Pro/Antioxidant Status, Inflammation, and Muscle Damage	Seventeen elite male Rugby Union players were randomly assigned to *Spirulina* (SPI) or placebo (PLA) groups for 7 weeks. Blood samples were collected before, immediately after, and 24 hours after exhaustive exercise to assess pro/antioxidant status, inflammation, and muscle damage markers	study suggests that *spirulina* supplementation has the potential to mitigate exercise-induced lipid peroxidation, inflammation, and muscle damage, aiding recovery, especially for athletes with insufficient antioxidant intake and high training loads, potentially improving performance and post-exertion recovery	*Spirulina* may benefit high-training-load athletes by reducing oxidative stress, inflammation, and muscle damage and enhancing recovery. [71]
Spirulina's Impact on Antioxidant, Anti-Inflammatory, and Immunomodulatory Aspects in Exercise and Sports	The review aims to assess *Spirulina's* impact on oxidative stress, immunity, inflammation, and performance in athletes and exercise interventions.	*Spirulina* supplementation may benefit athletes with inadequate antioxidant intake. Additional high-quality research is essential to assess *Spirulina's* impact on performance, the immune system, and recovery in athletes and active individuals.	Antioxidant, Anti-Inflammatory [72]
Cosmetics applications	The study aims to review the antioxidant activity of phenolic compounds, especially in dermatological therapy, emphasizing their mechanisms of action and structure-activity relationships.	The cosmetic potential of phenolic compounds as natural antioxidants is linked to their chemical structure's ability to intervene in various phases of the oxidation process.	The utilization of phenolic extracts presents a sustainable option in cosmetics. Nonetheless, it's vital to assess the toxicity risks of both raw materials and end products [73]
Investigating the Neuroprotective Properties of *Spirulina* platensis	This controlled, blinded study used adult Wistar rats split into treatment (*Spirulina* platensis extract) and control groups. Both groups underwent experimental hemorrhage with different sacrifice times and neurofunctional assessments.	Hemorrhagic events harm the brain, and research aims to protect perilesional tissue using neuroprotective agents like *Spirulina platensis*	The *Spirulina platensis* treated group showed significantly higher viable neurons 24 hours post-hemorrhage, with improved motor performance after 30 days, hinting at potential neuroprotection for acute neurological conditions. [74]

CONCLUSION

It is evident from this comprehensive review that *Spirulina*, known scientifically as *Arthrospira platensis*, stands out as a highly promising natural supplement with minimal side effects, positioning it as a potential "wonder food supplement." *Spirulina* has cemented its reputation as a robust source of nutraceuticals and pharmaceuticals, which is particularly beneficial in regions grappling with social malnutrition, such as developing countries like India. Currently, *Spirulina* production remains somewhat concentrated, primarily in countries like the

United States of America and China. It boasts a favorable financial turnover with relatively low capital investment requirements, simultaneously generating employment opportunities. The advantages of *Spirulina* production are multifaceted. It offers easily digestible high protein content (around 60%) and significant levels of β-carotene, vitamin B12, iron, trace minerals, and the rare essential fatty acid γ-linolenic acid (GLA). Importantly, its consumption holds no apparent cultural or religious concerns. *Spirulina* thrives in saline and alkaline environments typically unsuitable for traditional crops, making it particularly suited to disadvantaged populations vulnerable to natural disasters. Cultivation can range from household "pot culture" to large-scale commercial operations spanning extensive areas.

Spirulina aligns well with the rising demand for sustainable and eco-friendly food sources, particularly in addressing the challenges of climate change and food security. Its resource-efficient cultivation requires less water, land, and energy than traditional agriculture, making it a low-impact alternative that reduces carbon emissions. *Spirulina* can be grown in saline and alkaline water, allowing it to thrive in non-arable lands unsuitable for other crops. This adaptability is especially valuable for regions affected by climate-related disruptions where food production faces increasing challenges. Additionally, *Spirulina's* nutrient density—providing high levels of protein, essential vitamins, and minerals—supports food security by delivering a rich source of nourishment to vulnerable populations. As a sustainable protein source with minimal environmental impact, *Spirulina* holds potential as a vital component of future food systems focused on resilience and ecological responsibility.

This review highlights *Spirulina's* pharmacological and therapeutic potential, primarily attributed to its diverse phytoconstituents and secondary metabolites. Further purification of crude extracts to isolate bioactive compounds is recommended to unlock its full potential. Integrating these active components with synthetic counterparts shows promise for developing innovative medications. *Spirulina* emerges as a valuable natural resource capable of addressing malnutrition challenges, stimulating economies, and advancing therapeutic interventions. Its rich nutritional profile and historical significance underscore its enduring appeal and potential in nutrition and medicine. *Spirulina's* journey from an ancient dietary staple to a modern superfood exemplifies its adaptability and nutritional importance. It continues to captivate researchers and consumers with its health benefits and potential applications in diverse fields.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

As the corresponding author, Monika Bhairam diligently reviewed and refined the study's findings. Akant Verma took the lead in drafting the initial version of the manuscript. Kriti Naurange and Kajal Dewangan offered crucial guidance and carried out meticulous proofreading. Leena Daunday and Kishan Verma provided valuable insights and performed thorough proofreading. All authors have reviewed the manuscript comprehensively and approved the final version for publication.

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