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An analytical review of spirulina: Cultivation techniques and biological properties

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Abstract
Cyanobacteria, commonly referred to as blue-green algae, represent some of the earliest life forms to emerge on our planet. Specifically, spirulina thrives naturally in warm, alkaline aquatic environments. The use of microalgae as both human and animal sustenance has deep historical roots, dating back centuries. These organisms are highly versatile, offering a variety of food and industrial applications, and are favoured for their ability to withstand harsh environments regardless of the season. Spirulina, in particular, is highly prized for its exceptional nutritional profile and safety record, making it a viable dietary supplement. Given its dense concentration of essential nutrients and bioactive compounds, along with its lack of toxicity, spirulina serves as a potent tool to combat global malnutrition and address various dietary deficiencies in the future.

Keywords: Cynobacteria, superfood, nutritious, photosynthesis, culture

Introduction

Widely celebrated as a premier "superfood," Spirulina stands out as one of the most concentrated and adaptable nutritional sources available. Its significant health potential and impressive nutrient density have been well-documented in scientific literature (Miranda *et al*., 1998; Desai and Sivakami, 2004) [8, 16]. Taxonomically, Spirulina is a member of the *Oscillatoria* family and represents a lineage of cyanobacteria that pioneered photosynthesis. These organisms are effectively the evolutionary precursors to modern higher plants (Khan *et al*., 2005; Singh *et al*., 2013) [13, 24]. Named for its characteristic helical, spiral-like filaments, this blue-green microalga is famous for its resilience in extreme habitats where few other life forms can survive (Zhang *et al*., 2011; Sabart *et al*., 2010) [18, 31]. Spirulina is natively found in highly alkaline environments, including specific regions across the Pacific—such as Hawaii and Japan as well as freshwater lakes spanning Africa, Mexico, and both North and South America. The variants *Spirulina platensis* and *Spirulina maxima* are the most prevalent species harvested for human consumption, prized for their abundance of proteins, essential minerals, vitamins, and other bioactive ingredients (Kazmierczak *et al*., 2009) [11].

Although colloquially grouped with algae, Spirulina is fundamentally a prokaryote, sharing more biological traits with eubacteria. Its physical architecture is diverse, manifesting as single cells or complex filamentous colonies that adapt to their surroundings. Mechanisms such as heterocyst-mediated nitrogen fixation allow the organism to thrive in resource-scarce environments, playing a vital role in nitrogen cycling, most notably within rice cultivation (Sigler *et al*., 2003; Al-Thukair and Golubic, 1991) [4, 23]. *Arthrospira platensis* is of special scientific interest, favored for its distinctive coiled structure and its ability to flourish in high-pH waters. Recent breakthroughs in molecular biology and genetic mapping have clarified the taxonomy and survival mechanisms of these organisms, paving the way for more efficient, industrial-scale production (Keerti *et al*., 2025) [17].

The historical origins of spirulina as a human food source are well-documented, tracing back to both ancient civilizations and colonial-era scientific observations. In 1940, French researcher Pierre Dangeard formally recorded the Kanembu people's traditional practice of harvesting cyanobacteria from the shores of Lake Chad using clay vessels. His report detailed the consumption of these algae locally known as *dihé* and noted their presence in the East African Rift Valley, where they also served as a staple for local flamingo populations (Metcalf *et al*., 2012). Further botanical investigations by Jean Léonard in 1964 and 1965 identified that the green, edible cakes sold in the markets of Fort-Lamy (modern-day N'Djamena) were derived from algal blooms occurring near Lake Chad. Beyond the African continent, historical accounts from Spanish explorers such as Hernando Cortez indicate that the Aztecs were harvesting a blue-hued substance known as *tecuitlatl* from Lake Texcoco, a practice later validated by scholars like Sasson (1997) and Vonshak (1997) [21, 27]. Spirulina thrives naturally in the alkaline lake environments of Africa and Mexico (Belay *et al*., 1996; Shimamatsu, 2004[6, 22]; Metcalf *et al*., 2012). Collectively, these historical records underscore the enduring value of spirulina as a nutrient-rich resource, providing the foundational context for this manuscript's exploration of its modern potential in sustainable development.

Classification of Spirulina

The historical identification and classification of the distinct microalgae known as *Spirulina* have undergone significant evolution since the early 19th century. P.J. Turpin is credited with the initial isolation of the organism from freshwater environments in 1827 (Ciferri, 1983) [7]. By 1844, researchers Wittrock and Nordstedt characterized a spiral-shaped, septate blue-green alga discovered in the vicinity of Montevideo, labeling it *Spirulina jenneri F. platensis*. A few years afterward, in 1852, Stizenberger proposed the taxonomic designation *Arthrospira*, emphasizing the presence of septa and a coiled structure a classification later substantiated by Gomont in 1892. This taxonomy was simplified in 1932 by Geitler, who grouped both *Arthrospira* and *Spirulina* under the latter name based solely on their helical appearance, effectively ignoring the physiological distinction of the septa (Vonshak, 1997) [27].

Scientifically, this organism belongs to the kingdom Monera, division Cyanophyta, order Oscillatoriales, and family Phormidiaceae, a group comprising 15 distinct species across the two genera. The modern consensus, based on a 1989 reclassification, once again treats *Spirulina* and *Arthrospira* as separate entities (Tomaselli *et al*., 1996) [26]. Despite this, there is persistent taxonomic ambiguity, and the term "spirulina" is frequently used as a commercial label for *Arthrospira* products (Sanchez *et al*., 2003) [20].

Defined as a multicellular, filamentous, edible cyanobacterium, these organisms exhibit a blue-green pigmentation (Becker, 2007) [5]. The most prominent varieties include *Arthrospira maxima* and *Arthrospira platensis*, which are distinguished by specific morphological characteristics, such as the regularity of their capsules, vacuole presence, and filament arrangement (Tomaselli, 1997) [27]. Advanced identification often relies on 16S rRNA biochemical analysis alongside traditional microscopic examination (Spiller *et al*., 2000). While roughly 87 species have been historically attributed to the *Spirulina* genus, only 47 are currently recognized taxonomically, including examples such as *Spirulina labyrinthiformis* and *Spirulina subsalsa* (Guiry and Guiry, 2011) [9].

Morphological features of spirulina

Arthrospira, commonly known as Spirulina, is a filamentous, multicellular blue-green microalga that maintains a symbiotic relationship with nitrogen-fixing bacteria. This autotrophic organism generates energy through photosynthesis, utilizing a pigment profile that includes chlorophyll a, carotenoids, phycocyanin, and occasionally phycoerythrin. It propagates through the process of binary fission (AlFadhly *et al*., 2022; Ola *et al*., 2025) [17]. Historical research from the 1970s demonstrated that it is possible to extract protoplasts from these cyanobacteria through enzymatic degradation (Abo-Shady *et al*., 1992) [1], and the organism's smooth cellular structure renders it highly bioavailable and easy to digest (Larrosa *et al*., 2018) [14].

The physical structure of *Arthrospira* is notably plastic, shifting in response to its surroundings. Under a microscope, one can observe helical trichomes featuring distinct transverse walls; these spirals can range from densely wound coils to nearly linear strands. Measuring roughly 3 to 4µm in width and between 50 and 500µm in length, these trichomes are kept buoyant by internal gas vacuoles (Tomaselli, 1997) [27]. The cell walls are structurally similar to those of Gram-negative bacteria, reinforced with peptidoglycan, which provides essential protection against osmotic pressure (Habib *et al*., 2008; Zafilaza *et al*., 2015) [10, 30]. A defining trait of *Arthrospira platensis* is the presence of cylindrical, multicellular trichomes that grow in a characteristic open, left-handed helical pattern (Ali *et al*., 2012) [3].

The Health Benefits and Cultivation of Spirulina

Spirulina is a powerhouse of nutrition, recognized for its potent anti-inflammatory and antioxidant properties. Research indicates it supports cardiovascular health by effectively reducing levels of triglycerides and LDL cholesterol. Beyond heart health, it is utilized in managing oral cancer and alleviating the discomfort associated with allergic rhinitis. Furthermore, spirulina strengthens the immune system—which is particularly advantageous for those living with HIV and promotes cognitive vitality by enhancing ribonucleic acid synthesis. Studies on animal models have also demonstrated its efficacy in regulating blood glucose, improving digestive immunity, and providing both anti-aging and anti-anemic benefits (Yadav *et al*., 2021) [29]. A single tablespoon of spirulina offers a robust nutritional profile, including 4 grams of protein, essential vitamins (B1, B2/Riboflavin at 15% RDA, B3), minerals (iron, copper, manganese, potassium, and magnesium), and 1 gram of combined omega-3 and omega-6 fatty acids (Yadav *et al*., 2021) [29].

Factors Influencing Spirulina Cultivation

Successful spirulina production depends on a variety of environmental variables, including light exposure, temperature, wind, water standards, and potential contamination. Maintaining a temperature range of 30–35°C is essential for optimizing both biomass growth and protein synthesis. Light intensity also serves as a critical driver for development, impacting growth rates, pigment concentration, and protein levels; an intensity of 20,000–30,000 lux is considered optimal. Regarding water quality, mass cultivation requires a balanced saline solution with a pH level maintained between 8 and 10. Consistent water quality is vital for the algae to efficiently conduct photosynthesis. Additionally, growers must be vigilant regarding purity, as the presence of chlorine in the water supply is toxic and can prove fatal to spirulina cultures (Yadav *et al*., 2021) [29].

Batch culture

To maintain an adequate supply of microalgae for larval and zooplankton sustenance, a method known as progressive batch culture is employed. This technique involves scaling up algal production by transferring concentrated inoculums into progressively larger containers filled with nutrient-enriched, treated water. The process begins with axenic stock cultures housed in test tubes, which are then systematically transferred through a series of larger vessels. This cascading expansion continues until the desired cell density for feeding is achieved (Sachin and Amit, 2021).

For indoor operations, airlift batch cultivation is commonly conducted using 20-liter aspirator bottles. A variety of growth media are commercially available, including Zarrouk's medium, Modified Zarrouk's medium, the Nallayam Research Center (NRC) medium, and various NRC derivatives. When utilizing modified media, common adjustments include substituting urea and phosphoric acid with sodium nitrate and anhydrous di-potassium hydrogen phosphate, as well as lowering the ferrous sulphate heptahydrate concentration.

Proper maintenance of these cultures relies on aeration via an injection device, with airflow carefully calibrated to ensure uniform mixing through the upward circulation of air bubbles. While urea can serve as a substitute for sodium nitrate, it must be strictly regulated; concentrations should remain between 300 and 500 mg/L, as exceeding this range can negatively impact or entirely stunt the development of *Spirulina* (Sachin and Amit, 2021) [19].

Cultivation and Nutritional Optimization of *Spirulina*

Outdoor Cultivation Methods

The secondary cultivation of *Spirulina* is initiated in earthen pots, which necessitate consistent and powerful aeration.

These sub-cultures serve as the inoculum source, periodically transferred into large-scale rectangular earthen pits. To prevent leakage, these pits are lined with polyethylene. It is essential that the water supply is sourced from uncontaminated groundwater. Proper nutrient distribution is maintained via daily manual agitation, though the use of mechanized wheel aerators can enhance efficiency.

To boost yield, Zarrouk's medium enriched with 0.75g of molasses can achieve production rates as high as 2.94g per liter daily. Furthermore, a specialized Fertilizer Media (FM) has been formulated by Sachin and Amit (2021), featuring a blend of sodium bicarbonate (8g/l), sodium nitrite (2.5g/l), sodium chloride (0.5g/l), magnesium sulphate (0.15g/l), calcium chloride di-hydride (0.04g/l), single super phosphate (1.25g/l), and potassium chloride (0.98g/l) in boiled water.

Utilization of Waste as Nutrient Sources

Animal waste is an effective, nutrient-dense amendment for *Spirulina* mass production, particularly due to its high nitrogen and phosphorus content. This process involves anaerobic digestion of the waste followed by a 90–95% dilution. After the solids settle in the digester, the nutrient-rich liquid effluent is drained into cultivation ponds, where it is supplemented with sodium nitrite and sodium bicarbonate. To minimize expenditures, sugar may replace sodium bicarbonate. Additionally, urea serves as an economical nitrogen alternative, provided its concentration remains beneath 1.5g/L and the pH is maintained at 8.4 (Sachin and Amit, 2021).

Environmental Growth Parameters

Spirulina productivity is heavily dictated by light and thermal conditions. The algae flourish at light intensities ranging from 20,000 to 30,000 lux and are highly heat-tolerant; while they thrive between 32°C and 45°C, they can endure temperatures up to 60°C. For peak growth, a minimum temperature of 18°C is required. *Spirulina* is versatile, capable of growth in both seawater and freshwater, provided it can navigate a pH range of 8.3 to 11.0 and a salinity level of 5 to 15 ppt. notably, in commercial setups, sodium bicarbonate often accounting for over 60% of total nutrient costs remains the primary carbon source.

Harvesting, drying and storage of Spirulina

Following a five-day growth period after inoculation, Spirulina reaches the stage where it can be harvested through filtration. The process utilizes inclined screens (380–500 mesh) with a surface area spanning 2–4 m^2 per unit, allowing for the extraction of 10–18 m^3 of culture per hour. Once filtered, the biomass must be rinsed thoroughly with distilled water to eliminate any residual culture medium, salts, or impurities. Finally, the material is pressed to extract excess moisture, preparing it for the dehydration stage (Sachin and Amit, 2021).

Because fresh Spirulina is at its nutritional peak but prone to spoilage within 48 hours, drying is essential for long-term preservation. A common manual method involves placing the biomass into a kitchen press to create thin strands, which are then spread across clean cloths to dry in direct sunlight. To accelerate this process, one may utilize solar or electric dehydrators. Alternatively, an oven can be used, set at 60°C for four hours or at 40°C for 15 to 16 hours. Once fully dehydrated, the algae is processed through a grinder to produce a fine powder, which is subsequently packaged and sealed for commercial distribution (Sachin and Amit, 2021).

Conclusion

Beyond its reputation as a "superfood," Spirulina is now being recognized as a cornerstone for future energy and environmental restoration. As a fundamental element of the planet's ecosystem, algae offer a blueprint for sustainable development, from greening deserts to cleaning our waters. By harnessing Spirulina's unique properties, we can revolutionize industries through bio-packaging and carbon-neutral biofuels. By replacing harmful petroleum-based chemicals with natural biopolymers, Spirulina acts as a versatile tool for both economic efficiency and ecological renewal, signalling a shift toward a healthier, more sustainable global future.

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