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Spirulina Algae: A Sustainable Solution for Enhancing Global Protein Nutrition

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ABSTRACT

The growing global population further complicates the challenge of achieving food and nutrition security, especially surrounding the demand for sustainable protein sources. Current sources of protein are limited by their relatively high environmental impact. We argue that the cyanobacteria, Arthrospira, or "Spirulina," are an important sustainable alternative to the current protein crisis. Spirulina is unique due to its exceptional nutritional value, high protein content with a complete amino acid profile, superior digestibility, and high levels of bioactive compounds. It can be produced on non-arable land, using saline or wastewater, while sequestering atmospheric CO_2, and offering a framework for a circular bioeconomy. In this article, we will thoroughly examine the biology, nutritional efficacy, sustainable cultivation systems, and unique biotechnological applications of Spirulina. We will also detail product development, the socio-economic implications, and its regulatory situation. In summary, Spirulina represents an agent of change to improve global protein nutrition and support increased environmental sustainability.

INTRODUCTION

The paradox at the beginning of the twenty-first century is staggering: there is enough food produced globally in caloric terms to feed all human beings, but issues such as inequitable distribution, inadequate nutrition, and unsustainable production practices have led us into a state of dual burden malnutrition and environmental collapse (1). At the core of this dilemma is a global protein crisis, a multi-faceted dilemma shaped by demographic forces, a shift to higher intake of animal-sourced foods, and the extreme resource intensity of conventional agricultural production. As a consequence, protein demand is expected to increase by greater than 50% by 2050, while the planetary boundaries to freshwater availability, arable land, and stable climate are now firmly being exceeded (2). The livestock sector is responsible for an estimated 14.5% of all human-caused greenhouse gas emissions while occupying nearly 80% of the world's agricultural land and driving deforestation and biodiversity loss (3). This impending crisis has catalyzed a global search for alternative, sustainable, and resilient protein sources that can decouple food production from environmental harm, moving the world towards a more circular and efficient bioeconomy.

This forthcoming crisis has sparked a worldwide effort to identify alternative, sustainable, and resilient protein options that can disentangle food production from environmental degradation, offering an opportunity for the globe to move toward a more circular and efficient bioeconomy. Within this important context, microalgae have emerged as an exciting frontier, and Spirulina (Arthrospira spp.) is leading the way with its unique history and vast potential (4). Spirulina is not a novelty created in a lab - it has been consumed by ancient civilizations for centuries, including the Aztecs of Lake Texcoco and the Kanembu of Lake Chad. Spirulina's quantitative credentials are compelling; it has a protein content of 60-70% its dry weight, far surpassing the protein content of beef (~20%), soy (~35%), or eggs (~13%) (5). Spirulina also can grow profusely in alkaline and saline conditions that typical agricultural weeds and pests do not, and requires only 2,500-3,000 liters of water to produce one kilogram of protein - this is very low compared to the 100,000+ liters of water required to produce the same amount of protein from beef (6). The fact that Spirulina is produced in non-arable land and uses non-potable water effectively disentangles its production from the limitations and challenges of traditional agricultural production, which changes how we think of food production.

This review sets out to move beyond a simplified view of Spirulina as only a "superfood" supplement and to instead regard it as a substantial, scalable component of a future-oriented food system. We will address the biology and recent ecophysiological studies that enable its resilience, and look into current cultivation techniques and biotechnological advances that are improving its sustainability, productivity, and function (7). We will also investigate its use in modern food product development, establishing challenges with sensory acceptance and consumer acceptance, as well as its considerable development-related socioeconomic potential to alleviate malnutrition and create income opportunities. Finally, we will critically examine important aspects of safety, regulatory systems, and quality control systems to establish public trust and safety in their supply chains (8). The overall approach is to provide a fair and thorough evaluation of how Spirulina can be leveraged to synergistically address human nutritional needs and planetary health while establishing a more secure, just, and resilient food future for all.

Spirulina Biology and Ecophysiology: Unraveling the Secrets of a Robust Cyanobacterium

Taxonomically categorized as part of the genus Arthrospira, spirulina is a filamentous, photosynthetic cyanobacterium. Spirulina is best recognized by its multicellular, helical trichomes (or filaments), which can be anywhere from 50 - 500 micrometers long and have limited, gliding locomotion. The locomotion of the cyanobacterium is facilitated by the excretion of polysaccharide mucilage and it is thought that this may be an adaptation to maximize light and nutrient uptake from the water column (9). The most commercially important species in terms of taxonomy are A. platensis, A. maxima, and A. fusiformis. More recently, the genetic basis of some of the unique features of spirulina has gained attention through genomic studies. For instance, A. platensis has a relatively large genome (estimated at ~ 6.8 Mbp) and a high GC content, which may be beneficial for genomic stability and resistance to stress conditions (10). Genomic comparisons between A. platensis and other profiled strain A. maxima have indicated a high level of genomic plasticity, and possible evidence of horizontal gene transfer, which may have conferred an ability for *Spirulina* to perform a wider range of metabolism that has allowed this organism to adapt to variable, and sometimes extreme environments (11).

A key factor in Spirulina's high productivity is its high photosynthetic efficiency. In contrast to plant species growing in land-based environments, which use a substantial amount of the ecological energy they capture to produce structural units such as lignin and cellulose, Spirulina utilizes a higher proportion of the solar energy it captures for biomass. Spirulina's photosynthetic apparatus is reliably adapted to use very high light intensities. Recent studies have concentrated on optimizing light delivery to increase efficiency. It has been found that certain wavelengths (light-emitting diodes) or LEDs of red (650 nm) or blue (450 nm) increase photosynthetic rates and increase the yield of valuable pigments such as phycocyanin by 30% over the same time period when high-intensity white LED light was provided (12). Spirulina also has a well-defined carbon-concentrating mechanism (CCM) that scavenges inorganic carbon in the form of bicarbonate because it is immersed in a highly alkaline medium. The CCM consists of a variety of specialized transporters and carbonic anhydrases that convert bicarbonate to CO_2, which is used as the substrate by RuBisCO for photosynthesis. This well-developed CCM allows Spirulina to thrive in low dissolved CO_2 conditions, giving it a competitive edge (13).

The toleration of Spirulina as an extremophile that can tolerate high pH (9–11) and salinity (20–30 g/L bicarbonate) is central to its sustainable production since it is naturally resistant to contamination by most microorganisms. Recent ecophysiological research has focused on the molecular-level understanding of this alkaliphily. The identification and characterisation of the distinct Na^+ /H^+ antiporters, as well as the unique composition of their cell membrane and S-layer proteins, is now known to be essential for maintenance of pH homeostasis under high pH conditions to allow pH to remain near neutrality intracellularly (14). This tolerance also applies to variation in temperature. While the optimal temperature for growth is in the range of 35-37°C, certain strains are impressive for their thermotolerance and are known to tolerate temperatures up to 40°C. Proteomic studies of heat-stressed Spirulina have revealed rapid upregulation of specific molecular chaperones, such as the heat shock proteins GroEL and DnaK, that protect essential cellular proteins from denaturation, and may serve as biomarkers for potential selection of more robust industrial strains that can be cultivated under increased climate temperatures (15).

One of the most ecologically significant areas of recent research has been Spirulina's use in bioremediation and participatory governance of a circular economy. Spirulina can uptake, and therefore recover, nitrogen (in the form of nitrates, ammonium, and urea) and phosphorus, which can be from waste streams. New studies have gone beyond simply reestablishing Spirulina in traditional agricultural runoff to also growing it on anaerobic digestate of food waste, aquaculture effluent, and even source-separated human urine (16). For example, one study reported a biomass productivity of 10-12 $g/m^2/day$ using diluted agro-industrial wastewater, with nitrogen and phosphorus removal efficiencies exceeding 90% and 80%, respectively. Research has also expanded to Spirulina's ability to uptake and tolerate heavy metals, such as lead, cadmium, and arsenic, although this would require extremely careful management, as well as lab testing post-harvest to guarantee the final biomass is safe for food purposes. The application of omics technology is important here; transcriptomic profiling of Spirulina when exposed to various types of waste-water will highlight the pathways associated with stress response, as well as detoxification pathways like the upregulation of metallothioneins and phytochelatins to maintain biomass safety and high yield (17). This work solidifies our understanding of Spirulina as more than a crop, but rather as a biological system that could integrate into advanced biorefineries, which closes nutrient loops and valorizes waste, turning pollutants into valuable nutrition.

Nutritional and Functional Profile of Spirulina: A Powerhouse of Bioavailable Nutrients

The protein content of spirulina is its most recognized feature, and can range from 60% to 70% of its dry weight. This protein content is higher than any standard plant source and even higher than some animal protein sources. More importantly, spirulina is a complete protein because it contains all the essential amino acids, meaning the nine amino acids that the human body needs. Spirulina also has high levels of isoleucine, leucine, and valine (BCAAs), which are helpful with muscle protein synthesis. The levels of sulfur-containing amino acids, methionine and cysteine, are lower than found in some animal proteins such as casein, but are greater than most legume proteins. Therefore, spirulina is an excellent nutritional substitute for those diets high in cereals and pulses that are limited in sulfur-containing amino acids (18). The quality of the protein is further substantiated by its high protein digestibility-corrected amino acid score (PDCAAS), which ranges from 0.70 to 0.89, similar to legumes and greater than other plant protein sources in general.

The nutritional value of protein is determined not only by its composition but also by its digestibility and bioavailability. One of the factors providing Spirulina with a high nutritional value is the lack of a rigid cellulose cell wall, as occurs with many other microalgae and plants. The result of this is that in vitro protein digestibility is 85 to 95%. This is similar to casein (a milk protein) and far higher than many plant proteins, such as soybeans, which can contain anti-nutritional factors, such as trypsin inhibitors, which can limit digestibility. This high bioavailability has been confirmed by in vivo studies in human and animal studies, which show nitrogen absorption and retention rates to be supportive of using Spirulina as a protein source with high biological value for supporting growth and maintenance (19).

Spirulina is a veritable gold mine of bioactive compounds that offer substantial functional health benefits, in addition to its macronutrient profile. Phycocyanin, a vivid blue pigment-protein complex that can make up as much as 20% of the dry weight of spirulina, is the most noticeable of these. Strong antioxidant phycocyanin has been shown to scavenge free radicals and prevent lipid peroxidation. Additionally, it has demonstrated neuroprotective effects in a variety of experimental models and demonstrates strong anti-inflammatory qualities by blocking the activity of the nuclear factor kappa B (NF-κB) and cyclooxygenase-2 (COX-2) pathways (20). Vitamins, especially provitamin A (β-carotene) and B vitamins, such as B12 (cobalamin), are abundant in spirulina. Nevertheless, research on the bioactivity of pseudocobalamin, the most common B12 analog in humans, is still ongoing, indicating that it might not be a completely trustworthy method of treating B12 deficiency (21). Gamma-linolenic acid (GLA), a healthy omega-6 fatty acid with anti-inflammatory qualities, makes up a large portion of its lipid content (5-8%), along with other polyunsaturated fatty acids. Crucially, the iron found in spirulina is highly bioavailable and frequently chelated within organic molecules, which makes it a promising dietary intervention for the treatment of iron-deficiency anemia, a condition that affects people all over the world (22).

Studies on humans and animals indicate that consuming spirulina on a regular basis may alter immune function. It has been shown to increase immune system activity by promoting the secretion of cytokines that control immune responses, boosting the growth of immune cells such as T-cells and natural killer (NK) cells, and stimulating the production of antibodies (IgA, IgG) (23). The combined antioxidant capacity, which is mainly ascribed to phycocyanin, β-carotene, and vitamin E, aids in scavenging free radicals and lowering systemic oxidative stress, which is connected to aging and chronic illnesses. Additionally, Spirulina functions as a prebiotic, preventing the growth of harmful bacteria like *Clostridium* and *E. coli* while encouraging the growth of good lactic acid bacteria (*Lactobacillus* and *Bifidobacterium*) in the gut. Beyond its direct nutritional contribution, this alteration of the gut microbiota has a systemic benefit by promoting better gut barrier function, decreased inflammation, and general metabolic health (24).

Spirulina Cultivation and Sustainable Production Systems: Technological Synergy for Scalability

The production of Spirulina has moved to more modern controlled-environment systems, in addition to traditional harvesting methods in ponds or lakes, that allows for growing interest to increase productivity, uniformity, and sustainability. There are primarily two systems: open systems and closed systems, and while the two systems are separated, both systems are advancing the technology with continuous incremental improvements with open systems being the focus in this area. Open Raceway Ponds are the most developed and widely used production system and is usually an oval-shaped channel with paddlewheel mixing. Open raceway ponds tend to be less expensive to build and operate. Generally, the large-scale open raceway ponds are constructed to have depths of about 20-30 cm and an area of 1,000-5,000 m^2. More recently researchers have redesigned the open raceway pond to produce better hydrodynamic performance. Computational fluid dynamics modeling has been extensively used to optimize design components of the paddlewheel and the pond geometry (particularly bend curvature and floor slope) to improve mixing and minimize "dead zones" - areas that the water is not "mixed" - which are not preferred because they will lead to non-uniform light exposure and nutrient distribution in the pond and are wasting energy.

Researchers using computational modeling, have quantified optimization leading to reduction of energy by 20% (25). Alternative composite lining materials and transparent, durable covers continue to be developed to lower evaporation rates, and to stabilize temperature ranges (25-35°) and minimize risks associated with aerial organisms or rain dilution (26). Closed photobioreactors (PBRs) - tubular, flat-panel, and increasingly hybrid designs offer greater control of cultivation parameters that result in greater biomass densities (2-5 g/L; ORPs are 0.5-1.0 g/L) and annual productivity that can be 3-5 times greater. Recent innovations target essential aspects of control – automated, pressurized air-jet systems are realizing for biofilm cleaning and efficient degassing of columns to prevent analyzing oxygen build-up, concentrations greater than 30 mg/L can potentially grow photosynthesis (27). With even larger illuminated area, flat-plate PBRs exhibit an increase in volumetric productivity and are easier to scale-up modularly. Hybrid systems demonstrate additional commercial interest where, an initial, high-density axenic (contamination-free) inoculum is developed in a controlled PBR, 3-5 days, and transferred to a large lower capital ORP, over a period of 10-15 days for bulk production, producing optimization between capital expenditure and operational control (28).

Integrating Spirulina production within circular bioeconomy frameworks greatly bolsters its sustainability, which is an active area of study and development. A primary research objective is to utilize other nutrient sources. Not only are costs lowered, but the use of waste streams greatly enhances the lifecycle environmental performance of the biomass. A recent life-cycle assessment (LCA) found that the environmental footprint of fertilizer applied to grow Spirulina can be reduced over 50% compared to synthetic fertilizers by utilizing nutrients from wastewater (29). Research is also progressing toward the commercial use of industrial flue gas for carbon in Spirulina production. The focus of this research is to have the flue gas rapidly delivered and prepared for the culture system, without excessive cost. For instance, direct bubbling of raw flue gas (10-15% CO_2) into the culture can be limiting; however, if the flue gas is passed through a simple alkaline scrubber, not only are inhibitory SOx removed, but also the bicarbonate concentration of the medium is increased and made available for Spirulina's carbon source. Some strains have also demonstrated the ability to utilize nitrogen oxides (NOx) from flue gas as a nitrogen source, thus being able to convert two pollutants into useful polymeric constituents of the biomass (30).

Cultivation is increasingly being optimized with precision agriculture practices and the application of data science. The traditional approach to controlling variables using occasional manual measurements is being replaced by the use of connected sensor networks that provide real-time data on pH, dissolved oxygen, temperature, turbidity (as a proxy for biomass), and pigment concentration using in-line spectrophotometry. The real novelty is leveraging high-frequency sensor datasets combined with machine learning (ML) and artificial intelligence (AI) algorithms. Recently implemented pilot-scale studies using ML models have proven to predict biomass growth in the next 24-48 hours using historical data and real-time inputs as a basis to predict and adapt controls for nutrient dosing and harvest timing (31). For example, an AI system can learn the specific kinetics of CO_2 uptake by a culture and determine to rationally deliver to the culture when the pH rises above a set point, indicating photosynthesis is occurring and thereby reducing waste and off-gassing CO_2. This energy-efficient strategy can provide a 15-25% reduction in CO_2 consumption, without sacrificing the growth rate.

Overall, Spirulina's sustainability claims are being both vigorously quantified and improved through comprehensive Life Cycle Assessment (LCA), along with ongoing efforts to innovate its technological advancements in downstream processing. Newer LCAs provide more granular data. For instance, although open raceways (ORPs) have a lower energy footprint than photo-bioreactors (PBRs), ORP land use is substantially greater. Studies continually show that the biomass drying stage is the single largest energy sink in Spirulina's overall production process, responsible for 50-70% of total operational energy (32). So there is a significant investment in research around dewatering and drying with low energy demand. Recent innovations like electrocoagulation have demonstrated that this processing method can use reusable electrodes to first concentrate biomass before drying, using electrocoagulation to reduce downstream processing volume by 90% with an extremely modest energy input, moving into solar or advanced dryers with a desiccant systems or heat pump on low heat (40-45°C) to dry for less energy consumption and to preserve the heat sensitive nutrient, like phycocyanin, with potential energy savings of around 60% less energy compared to conventional spray drying. A new systems-level perspective of cultivation that integrates waste streams, utilizes data science, and critically concludes and innovates on environmental impacts, are a way forward in supporting Spirulina to be a truly sustainable and scalable source of nutrition for the global population (33).

Biotechnological Advances for Enhanced Protein Yield and Functionality

Although Spirulina exhibits natural productivity, biotechnological efforts are taking place to advance the protein yield, protein quality, and the accumulation of specific high-value compounds. While both genetic and metabolic engineering represent considerable challenges in cyanobacteria because of intrinsic genetic complexity and restriction systems, they are underway. Engineering strains to elicit the overexpression of critical enzymes involved in nitrogen assimilation (such as glutamine synthetase) is a primary research focus, and similarly with the biosynthesis of rate-limiting amino acids, to increase both protein content and enhance the overall amino acid profile of the biomass, such as increasing methionine (34). An additional strategic opportunity is to manipulate metabolic pathways that take precursors to proteins and reroute them to the accumulation of carbohydrates and/or lipids during stressful conditions. Specifically, the strategy is to redirect carbon from metabolites that would otherwise be allocated to carbohydrate or lipid storage during abiotic stress towards amino acid production.

The emergence of omics technologies has given us a unique, systems-scale perspective on the biology of Spirulina that allows us to improve targeted and efficient strain improvement. Genomic sequencing data of multiple Arthrospira strains have opened up these studies. Transcriptomics (the study of RNA) provides key insights about how gene expression is dynamically regulated in response to environmental cues from nutrient limitation to high light and/or salt stress, regulation by key regulatory genes and promoters. Proteomics (the study of proteins) provides a means to directly quantify the protein complement of the cell - an important functional bridge between genome and cellular phenotype. Metabolomics (the study of metabolites) provides a snapshot of the end-products of cellular processes and the metabolic state of the cell under different conditions. The systematic data integration of omics data through bioinformatics and systems biology approaches may enable the development of predictive models of the Spirulina network. Now armed with a holistic understanding of Spirulina biology, it allows the necessary identification of key genetic bottlenecks and key regulation nodes that may be modified to optimally produce desired traits such as hyper-accumulation of phycocyanin or enhanced stress tolerance (35).

Nanotechnology and bioinformatics are becoming valuable tools in the optimization of Spirulina due to their potential positive effects to aid in the process of crop enhancement. Nanotechnology encompasses the use of engineered nanoparticles (for example, carbon nanotubes or mesoporous silica) as nano-carriers towards nutrient delivery or signaling compounds directly into cells, which has potential impacts on cellular nutrient uptake efficiency (36). Magnetic nanoparticles have been evaluated similarly in Spirulina for biomass recovery by induction of magnetic separation, thus reducing downstream energy-intensive centrifugation steps compared to other technologies. Bioinformatics is an indispensable tool to manage and interpret the large datasets generated from omics technologies to help inform Spirulina optimization. Bioinformatics uses advanced algorithms for genome annotation, comparative genomics and to model metabolic flux, all of which play roles that can accelerate both the discovery of gene function(s) and the rationale design of genetic engineering strategies.

AI and automation are set to transform large scale production of Spirulina from an experience-based management approach to a data-driven, predictive control approach. AI techniques, most notably ML algorithms such as neural networks and support vector machines, can be trained using historical data and real-time sensor data (i.e., pH, DO, temperature, light, and nutrient concentrations) to model the complexities and non-linearities of the cultivation system. These models would enable forecasting of optimal harvest time, predicting the onset of contamination or depletion of nutrient levels, and recommending adjustments to input parameters to optimize total yield and stability. With an integrated automated control system, this capability leads to a closed-loop "smart" photobioreactor which will self-optimize in real time, mitigating variability and ensuring robust and high yield production of Spirulina biomass regardless of the operator's experience. This approach would resolve one of the major barriers to reproducibly and economically producing high yields of high-quality Spirulina biomass on a large scale (37).

Food Innovation and Product Development: Integrating Spirulina into the Mainstream Diet

The incorporation of Spirulina into food products is an expanding area fueled by consumers' desire for inexpensive, nutrient-rich, sustainable ingredients. The most obvious application is in functional and fortified foods, where a portion of the base food is replaced with Spirulina powder or paste in order to improve the nutrient profile of everyday food ingredients. Most successful applications are in the production of pasta, bread, and biscuit products with the nutritional profiles of protein, iron, and antioxidants increased through the partial replacement with Spirulina powder or paste. Textural effects are common for all addition levels, although researchers suggest incorporating Spirulina as a powder at recommended levels between 1–3% is acceptable if the goal is to obtain additional nutrients. More than this level means lowering the protein level, which in turn means raising the total carb volume, whereas lower levels have not been found to significantly affect the sensory aspects of biscuits, bread, or pasta products (38). Its bright green color is also an added benefit as Spirulina can serve as a natural food color substitute for artificial food additives in items like dairy products – ie. yogurt and ice cream, and in many confectionary items.

The nutraceutical and supplement industry represents the most developed market for Spirulina. It is available in a range of forms, including tablets, capsules, and pure powders promoting its richness in protein, vitamins and antioxidant content. Spirulina is also a common feature in "superfood" energy bars, protein powders, and smoothies targeted toward health-conscious consumers. An often cited challenge in these product applications is the distinctive and intense flavor profile of Spirulina, often described as "grassy," "earthy," or "fishy." To address this flavor challenge, companies incorporate flavor-masking agents, combine Spirulina with strong-tasting ingredients, such as chocolate or berries, or utilize processing techniques such as microencapsulation to ensconce the biomass in a neutral-tasting outer layer (39).

A promising and unique use of Spirulina has emerged with the rapidly developing alternative protein market. Its high protein content and umami-like taste make it an exciting and functional natural ingredient and colorant in plant-based meat analogues (e.g., burgers, nuggets, and mince) where it can enhance both nutrition and appearance. More futuristically, Spirulina is being researched as a low-cost, sustainable, and ethically-derived growth medium supplement to help in the development of cultured meat. Spirulina extract has a complex profile of amino acids, vitamins, and growth factors that could replace (or at least reduce reliance on) the costly and ethically questionable fetal bovine serum (FBS) traditionally used to ex vivo culture the cells required to produce cultured meat. Spirulina extract could thus potentially remove a significant cost and sustainability roadblock in this developing industry (40).

The overall acceptance of Spirulina in the mainstream food industry will depend on its sensory properties, consumer perception, and subsequent market introduction. While its strong flavor and intense green color could potentially constrict consumer acceptance beyond the health-food category, research in food science is ongoing to devise effective deodorizing and decolorizing technologies and to develop product formats or applications whereby Spirulina's flavor can be a benefit rather than a deterrent. In general, consumer perception is positive in consumer segments that are concerned with sustainability, naturality, and healthfulness; however, education will be vital for expanding its appeal to a larger demographic. Transparent information about sourcing, production methods, and third-party certification (e.g. organic, non-GMO, etc.) will be difficult, but will be the basis for establishing trust. The global Spirulina market is growing at an impressive rate and is expected to grow, as veganism, clean-label products interest, and consumer awareness of the environmental benefits continue rise in popularity (41).

Socioeconomic and Environmental Impact: Beyond Nutrition

Spirulina has great potential as an effective strategy to fight malnutrition and protein deficiency in developing nations. It is high in protein, vitamin A, and bioavailable iron - all of which can alleviate common micronutrient deficiencies. Spirulina can be farmed in small-scale, low-technology operations in sunny parts of the world that have locally available materials and water sources. These units can be run at the community or household level as a local, reliable source of nutrition for vulnerable populations, including children, pregnant women, HIV/AIDS patients, and others. There are now several NGOs that have initiated such projects in India, Africa, and Latin America, and they have reported improved nutritional status in their study populations (42).

From tiny artisanal farms to massive industrial plants, the development of facilities for the production of spiralina generates a variety of job and revenue-generating opportunities. Jobs in farming, harvesting, processing, quality assurance, packaging, and marketing are all included in this. Spirulina farming can provide a sustainable means of subsistence in rural and peri-urban areas where economic opportunities may be scarce. For women's cooperatives, it can be especially empowering since it gives them a way to make money and help their families eat better. The commercial sale of excess biomass, whether for export or local markets, can bring in a sizable sum of money, promoting regional economic growth and reducing poverty (43).

The advantages of growing spirulina are significant from an environmental standpoint. It has two roles in reducing GHG emissions and capturing carbon. First of all, it actively sequesters CO_2 during growth because it is a photosynthetic organism. It directly absorbs and uses a greenhouse gas that would otherwise be released into the atmosphere when grown with carbon dioxide from industrial flue gases. Second, it indirectly circumvents the significant methane (from ruminants) and nitrous oxide (from manure and fertilizers) emissions linked to livestock production by offering a sustainable substitute for animal-based proteins. Spirulina protein has a global warming potential that is several times lower than that of animal proteins, according to life cycle assessment studies (44). Furthermore, growing it doesn't require the use of pesticides or herbicides, and when combined with wastewater treatment, it helps keep natural water bodies from becoming eutrophic.

To unlock the full potential of Spirulina, it must be included and recognized in global climate and food security policies. National governments and international bodies can have a transformational role in integrating microalgae farming into climate-smart agriculture programs, national dietary guidelines, and pathways to the Sustainable Development Goals (SDGs) of the UN. Spirulina specifically relates to SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (45). Policy incentives could take the form of research funding, a tax incentive for sustainably produced products and/or incorporating Spirulina into a common procurement contract such as school meals or food aid programs, establishing a baseline demand in the private sector that could then stimulate growth in the microalgae industry.

Safety, Regulatory, and Quality Considerations: Ensuring a Trusted Supply

If production is not properly managed, contaminant risks could jeopardize the safety of spirulina for human consumption. Because it is a bio-accumulator, spirulina can take up and concentrate heavy metals from contaminated water or growth media, such as lead, cadmium, mercury, and arsenic. Consequently, it is crucial that the water and nutrients used are of high quality (46). Additionally, even though Arthrospira does not produce hepatotoxic microcystins, if environmental conditions and hygiene are not closely monitored, open-pond cultures may become contaminated with cyanobacteria that produce toxins, such as Microcystis. The necessity of Good Manufacturing Practices (GMP) across the production and processing chain is highlighted by the potential threat posed by bacterial pathogens like *Salmonella* and *E. coli*.

Strong international standards and regulatory frameworks have been put in place to manage these risks. Guidelines for food safety are provided by international organizations such as the Codex Alimentarius, which is jointly administered by the FAO and WHO. Spirulina is regulated as a food or dietary supplement by regional agencies like the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA). For some uses, it is classified as a Novel Food in the EU. These regulatory agencies mandate that products be safe and properly labeled, and they set limits for contaminants (47). As a standard for quality, pharmacopoeias such as the U.S. Pharmacopeia (USP) and others offer comprehensive monographs outlining the identity, purity, and quality tests for ingredients found in spirulina.

Ensuring consistent product safety and quality requires the implementation of industrial-scale quality control and certification procedures. From sourcing to packaging, reputable manufacturers use Hazard Analysis

Critical Control Point (HACCP) systems to detect and manage possible risks at every stage of production. The final biomass is routinely tested for cyanotoxins, heavy metals, and microbial load. Organic (USDA, EU Organic), non-GMO, and responsible sourcing (Friend of the Sea for sustainable aquaculture) certifications are examples of third-party certifications that offer independent verification and aid in identifying premium products in the marketplace (48). In addition to being necessary for compliance, these certifications and open quality control procedures are essential for competing in the global market, particularly for export-focused manufacturers in developing nations.

In the end, public trust, openness, and unambiguous labeling regulations are essential to the long-term viability of the spiralina sector. Customers are becoming more curious about where their food comes from and how it is produced. Stronger customer relationships are developed by businesses that make their third-party testing results available and give clear information about their cultivation methods (such as the use of closed photobioreactors and the source of water and nutrients). Most countries have laws requiring accurate labeling of protein content, allergen information (although Spirulina is not a common allergen), and recommended serving sizes. This is necessary for consumers to make educated decisions. To prevent deceiving customers and undermining confidence in the product category, any health claims on packaging must be supported by scientific data and adhere to local laws (49).

Global Challenges and Future Perspectives

Despite its enormous potential, there are major scalability and financial barriers to Spirulina's widespread use. The current cost of production is the main obstacle preventing it from cost-competitively competing with commodity proteins like soy and whey. There are significant energy inputs required for pumping, mixing, and especially drying the biomass. Even when waste streams partially replace food-grade nutrients, the cost of those nutrients still matters. A significant engineering and logistical challenge that calls for additional innovation and investment in expansive infrastructure is scaling up production while preserving constant quality, high productivity, and low cost (50).

Significant policy gaps also exist, and sustainable food governance that takes into account new food sources is required. Government support and a clear regulatory path for microalgae production are lacking in many nations. Governments and international organizations must create logical policies that assist the sector if they are to realize Spirulina's full potential. Funding for research and development, financial incentives (such as grants or low-interest loans) for the establishment of sustainable algae farms, the inclusion of algae-based proteins in national dietary guidelines, and the use of public procurement to generate initial market demand for example, by incorporating spirulina into food assistance programs are some examples of what this could entail (51)

A major future avenue for workforce development is the integrated approach of Spirulina within climate-smart nutrition efforts. This can take the form of developing integrated systems where Spirulina is cultivated either directly, or indirectly with another sector (example - aquaculture), and as examples of this:

- **Agri-food Integration-** Spilling agricultural runoff or process wastewater and cultivating Spirulina from these sources
- **Carbon capture hubs-** Cultivation facilities are co-located near power plants or industrial swaths to utilize the waste CO_2 and heat generated from a facility
- **Aquaculture Integration-** Using aquaculture effluent as a nutrient source and possibly using Spirulina as a fish feed additive

Encouraging these synergistic systems should be emphasized by international development and environmental institutions as a practical adaptation and mitigation strategy to climate change (52).

Future research directions are multifaceted and exciting. These entail:

- **Hybrid Food Systems:** Creating acceptable, inexpensive, and familiar products that incorporate Spirulina with other plant and alternative proteins.
- **Advanced Strain Engineering:** Harnessing synthetic biology, or CRISPR-based gene editing, to develop strains with improved nutritional quality, and safety characteristics, as well as enhanced growth rates with limited off-flavors.
- **Process intensification:** New environmentally responsible techniques to harvest and dry Spirulina that employ low energy inputs and biorefinery concepts where multiple high-quality products (phycocyanin, lipids, carotenoids) can be extracted from the same biomass.
- **Rugged clinical trials:** More large-scale, longer-term free-range randomized controlled human trials to substantiate health claims, as well as establish evidence-based dietary recommendations for Spirulina consumption (53).

CONCLUSION

Unquestionably, spirulina is much more than just a specialized dietary supplement. It is positioned as a transformative agent and a pillar of future sustainable food systems due to its unmatched combination of superior nutrition, quick growth, and low environmental impact. In terms of land, water, and energy efficiency per unit of protein produced, the data unequivocally demonstrate its superiority over traditional protein sources. Its productivity and economic viability will only increase with ongoing developments in biotechnology and cultivation technology, securing its place in the world's protein portfolio.

Spirulina's real strength is its exceptional capacity to connect human nutrition and environmental health in a complementary way. Through carbon sequestration, wastewater remediation, and the reduction of agricultural land use, its cultivation model provides a practical way to produce vital nutrients while actively regenerating ecosystems. By converting waste streams into high-value nutrition, it exemplifies the ideas of a circular bioeconomy, which benefits both people and the environment.

Spirulina's full potential cannot be realized by a single field or industry. Microbiologists, food technologists, process engineers, economists, nutritionists, sociologists, and policymakers must all work together in a coordinated, multidisciplinary effort. To overcome the remaining obstacles pertaining to cost, scalability, and consumer acceptance, collaborative research, public-private partnerships, and knowledge transfer are crucial. Spirulina can effectively move from a staple in health food stores to a mainstream solution with strategic investment, well-thought-out supportive policies, and a common goal. This would significantly and irrevocably contribute to a more secure, just, and sustainable food future for everybody.

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