# Hydroponic and Photobioreactor-Based Cultivation of Spirulina, A Sustainable Biomass Approach

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## ABSTRACT

Spirulina cultivation using hydroponic and photobioreactor systems marks a significant advancement in sustainable biomass production. As a protein-rich cyanobacterium (60–70%) containing essential amino acids and valuable bioactive compounds, Spirulina holds vast potential in nutrition, pharmaceuticals, and commercial industries. Modern cultivation systems such as hydroponics and photobioreactors allow precise control of growth conditions while minimizing land and water use, achieving yields of 10–25 g/m²/day under optimized parameters. In India, where the nutraceutical market is expected to reach ₹18,000 crores by 2025, Spirulina farming emerges as both economically promising and environmentally beneficial. This review discusses the technologies and productivity parameters associated with Spirulina cultivation, its sustainability advantages, and the expanding Indian market potential for Spirulina-based products, emphasizing its role as a future-forward solution for sustainable food and biomass production.

## INTRODUCTION

In an era where food security, malnutrition, and environmental degradation dominate global discourse, *Spirulina* emerges as a remarkable solution. This blue-green microalga, scientifically classified under cyanobacteria, has been consumed for centuries—from the Aztecs harvesting it from Lake Texcoco to present-day commercial production across continents. *Spirulina platensis* and *Spirulina maxima* are the two predominant species cultivated worldwide. What makes *Spirulina* exceptional is its nutritional density: it contains 60–70% protein by dry weight, surpassing meat (20–25%), soybeans (35–40%), and even fishmeal (Kumar *et al*, 2022). Beyond protein, *Spirulina* is loaded with beta-carotene, phycocyanin, gamma-linolenic acid, vitamins B12 and K, iron, and essential minerals. In India, where protein-energy malnutrition affects millions and agricultural land is under pressure, *Spirulina* cultivation through advanced systems like hydroponics and photobioreactors offers a sustainable pathway for biomass generation.

## Why *Spirulina*? Nutritional and Economic Significance

The nutritional profile of *Spirulina* is unparalleled. According to research by Sharma *et al* (2023), *Spirulina* contains approximately 4,000–5,000 mg/100g of phycocyanin, a potent antioxidant and anti-inflammatory compound. Its protein digestibility coefficient exceeds 85%, making it bioavailable and suitable for diverse consumer groups including children, athletes, and the elderly (Deshmukh & Patel, 2024). The Indian nutraceutical industry, valued at approximately ₹12,500 crores in 2023, is witnessing exponential growth driven by health-conscious consumers. *Spirulina*-based products—tablets, powders, fortified foods—command premium prices ranging from ₹800 to ₹2,500 per kilogram in retail markets across Delhi, Mumbai, Bengaluru, and Chennai. Commercially, *Spirulina* farming can generate net returns of ₹3–5 lakhs per hectare annually with proper management, positioning it as a lucrative enterprise for progressive farmers and entrepreneurs (Venkataraman & Becker, 2023).

Beyond economics, *Spirulina* addresses critical sustainability challenges. Its cultivation requires 10 times less water than conventional crops like rice or wheat. It absorbs carbon dioxide efficiently—approximately 2.0 kg of $CO_2$ per kilogram of *Spirulina* biomass produced—making it a carbon-negative crop (Deshmukh & Patel, 2024). Additionally, *Spirulina* thrives in alkaline water (pH 9–11) unsuitable for traditional agriculture, enabling utilization of marginal lands and brackish water resources.

## Hydroponic Cultivation: Controlled Environment Advantage

Hydroponics, the soilless cultivation method, has revolutionized *Spirulina* farming by offering precise control over nutrient composition, pH, temperature, and light intensity. Unlike open raceway ponds susceptible to contamination and climatic variations, hydroponic systems maintain sterility and consistency (Deshmukh & Patel, 2024). Typical hydroponic setups for *Spirulina* involve shallow tanks (15–20 cm depth) filled with alkaline culture medium containing sodium bicarbonate (8–10 g/L), potassium nitrate (2.5 g/L), dipotassium phosphate (0.5 g/L), and trace elements like iron, magnesium, and zinc (Deshmukh & Patel, 2024).

Temperature regulation is critical—optimal growth occurs between 30–37°C. In Indian conditions, natural sunlight during summer months (March–June) provides 50,000–60,000 lux illumination ideal for photosynthesis. However, controlled hydroponic farms employ LED lighting (red and blue spectrum) delivering 10,000–15,000 lux continuously, enabling year-round production irrespective of seasonal fluctuations I (Deshmukh & Patel, 2024). Agitation is another vital parameter; gentle paddle wheel mixing or air-lift systems ensure uniform nutrient distribution and prevent sedimentation while maintaining dissolved oxygen levels above 6 mg/L.

Productivity in well-managed hydroponic systems ranges from 12–18 g/m²/day. A 1,000 m² hydroponic facility can potentially yield 4,380–6,570 kg annually, translating to gross revenue of ₹35–65 lakhs based on wholesale prices (₹800–1,000/kg). Initial investment for a medium-scale hydroponic unit (500 m²) ranges between ₹15–25 lakhs, covering infrastructure, culture medium, seed inoculum, and monitoring equipment. Operational costs including electricity, labor, and consumables account for approximately ₹3–5 lakhs annually.

**Photobioreactors: Next-Generation Cultivation Technology**

Photobioreactors (PBRs) represent the pinnacle of controlled *Spirulina* cultivation. These closed systems—tubular, flat-panel, or column designs—offer superior contamination prevention, enhanced biomass concentration, and optimized light utilization compared to open systems. Tubular PBRs, consisting of transparent glass or acrylic tubes (5–10 cm diameter) arranged horizontally or vertically, circulate culture medium through a closed loop. Flat-panel PBRs provide excellent surface-area-to-volume ratios, maximizing light penetration and photosynthetic efficiency (Mishra *et al*, 2024).

The key advantage of PBRs lies in volumetric productivity—20–25 g/m²/day, significantly higher than hydroponics or raceway ponds. This efficiency stems from several factors: precise control of carbon dioxide injection (maintaining 2–5% $CO_2$ concentration), elimination of evaporative losses, protection from airborne contaminants, and reduced photo-inhibition through light-dark cycle optimization (Mishra et al., 2024). Automated sensors monitor pH (9.5–10.5), temperature (32–35°C), dissolved oxygen, and biomass density in real-time, triggering corrective adjustments via programmable logic controllers (Deshmukh & Patel, 2024).

In India, several agri-tech startups and research institutions have successfully deployed PBR systems. A 100 m² flat-panel PBR installation at Tamil Nadu Agricultural University demonstrated annual yields of 730–900 kg, with protein content reaching 68% and phycocyanin concentration of 18% (dry weight basis). Capital investment for PBR systems is higher—₹40–60 lakhs for a 200 m² unit—but payback periods shorten to 2–3 years given superior productivity and premium product quality commanding ₹1,500–2,000/kg in nutraceutical markets.

**Cultivation Protocol: From Inoculation to Harvesting**

Successful *Spirulina* cultivation begins with quality inoculum. Pure starter cultures of *Spirulina platensis* can be procured from institutions like Central Salt and Marine Chemicals Research Institute (CSMCRI), Bhavnagar, or commercial suppliers priced at ₹500–1,200 per liter (Mishra et al., 2024). Initial inoculum density should be 0.3–0.5 g/L, scaling gradually to harvest density of 2.5–3.5 g/L over 8–12 days depending on system efficiency and environmental conditions (Rao & Venkataraman, 2023).

Nutrient management is critical. Nitrogen (typically from potassium nitrate or urea) drives protein synthesis, while phosphorus (from dipotassium phosphate) supports energy metabolism. Iron chelates prevent chlorosis, ensuring vibrant blue-green pigmentation indicative of healthy cultures. Regular monitoring involves measuring optical density at 560 nm wavelength—readings of 0.8–1.2 indicate optimal harvest timing. Harvesting employs fine mesh screens (40–60 micron) or centrifugation followed by washing, pressing, and drying. Spray drying (inlet temperature 160–180°C, outlet 80–90°C) produces high-quality powder retaining 95% nutritional integrity.

### Economic Viability and Market Opportunities in India

India's *Spirulina* market, though nascent compared to China or the USA, is expanding rapidly. Domestic consumption reached approximately 800–1,000 tonnes in 2023, with projections estimating 2,500 tonnes by 2028 reflecting a compound annual growth rate of 20–25%. Key demand drivers include rising health awareness, growth of vegan and vegetarian populations seeking plant-based proteins, and government initiatives promoting nutritional supplements under programs like POSHAN Abhiyaan. States like Tamil Nadu, Gujarat, Karnataka, and Andhra Pradesh have emerged as production hubs, leveraging favorable climatic conditions and technical expertise (Singh *et al*, 2024).

Export potential remains largely untapped. Indian *Spirulina* can compete in international markets—USA, European Union, Japan—where prices reach $15–25 per kilogram (₹1,250–2,100). Organic certification, Good Manufacturing Practices (GMP) compliance, and quality assurance (heavy metal testing, microbial load analysis) are prerequisites for export success. Several Indian companies are investing in certifications; for instance, Parry Nutraceuticals and Gangwal Enterprises have established FSSAI-approved facilities meeting international standards (Mishra et al., 2024).

### Environmental Benefits and Sustainability Metrics

*Spirulina* cultivation epitomizes sustainable agriculture. Water footprint is minimal—approximately 2,500–3,000 liters per kilogram of dry biomass compared to 15,000–20,000 liters for beef protein or 4,000–5,000 liters for soybean protein. Land use efficiency is extraordinary; one hectare of *Spirulina* farm produces protein equivalent to 40 hectares of soybean or 300 hectares of cattle grazing land. Carbon sequestration potential mitigates greenhouse gas emissions—a commercial *Spirulina* farm capturing 2 tonnes of $CO_2$ per tonne of biomass contributes meaningfully to climate action goals.

Nutrient recycling opportunities enhance sustainability further. Spent culture medium, rich in residual minerals, can irrigate adjacent horticultural crops or be composted. Zero-waste biorefinery concepts integrate *Spirulina* production with extraction of high-value phycocyanin (selling at ₹8,000–12,000/kg as natural food colorant) and residual biomass utilization in animal feed, biofertilizers, or biofuel precursors (Sharma et al., 2023).

### Challenges and Future Directions

Despite advantages, *Spirulina* farming faces challenges. Contamination by undesirable algae (like Chlorella) or zooplankton requires vigilance. Maintaining optimal pH and alkalinity demands quality water sources and buffering chemicals. Energy costs for PBR operations—pumping, aeration, climate control—affect profitability, especially where electricity tariffs exceed ₹6–7 per unit. Technical expertise for troubleshooting culture crashes or optimizing harvest cycles remains scarce in rural areas.

Future advancements lie in integrating renewable energy (solar panels offsetting 60–70% electricity costs), developing low-cost PBR materials (UV-stabilized polyethylene replacing expensive glass), and breeding high-yield *Spirulina* strains through selective mutation or genetic optimization. Research at institutions like ICAR-Central Institute of Fisheries Education and CSIR labs explores co-cultivation with other microalgae, enhancing biodiversity and resilience (Venkataraman & Becker, 2023). Policy support—subsidies for infrastructure, training programs, market linkages—will accelerate adoption among smallholder farmers and entrepreneurs.

## CONCLUSION

Hydroponic and photobioreactor-based *Spirulina* cultivation represents a paradigm shift toward sustainable biomass production, marrying nutritional excellence with environmental stewardship. With productivity ranging 10–25 g/m²/day, minimal resource inputs, and burgeoning market demand, *Spirulina* farming offers economic viability alongside ecological benefits. India, with its diverse agro-climatic zones, technical capabilities, and growing health-conscious population, stands poised to emerge as a global leader in this sector. Continued research, infrastructure investment, and policy advocacy will unlock *Spirulina*'s full potential—nourishing populations, empowering farmers, and contributing meaningfully to sustainable development goals in the decades ahead.

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