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Review Article

Spirulina (*Arthrospira platensis*): Nutritional Potential, Bioactive Compounds, Cultivation Strategies, Extraction Technologies, and Emerging Applications in Sustainable Biotechnology

Ami Chavda[1]*, Debabrata Sarkar[2] and Ronak Chhaya[2]

[1]*Research and Development, BioAni India Pvt. Ltd., India*

[2]*Research and Development Division, BioAni India Pvt. Ltd., India*

***Corresponding Author:** Ami Chavda, Research and Development, BioAni India Pvt. Ltd., India.

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Abstract

Spirulina, commonly referring to commercially cultivated *Arthrospira* and *Limnospira* taxa, is a filamentous oxygenic cyanobacterium that has been extensively investigated because of its nutritional composition, bioactive compounds, and applications in food, biotechnology, and environmental systems. Although traditionally referred to as a microalgae, spirulina is taxonomically classified within the cyanobacteria and represents one of the most extensively studied microbial biomass resources for food, nutraceutical, pharmaceutical, agricultural, and environmental applications. Its high protein content, balanced amino acid profile, essential fatty acids, vitamins, minerals, pigments, and antioxidant compounds make it a potential alternative source of protein and functional nutrients.

The major bioactive components of spirulina include phycobiliproteins, particularly C-phycocyanin, chlorophyll-a, carotenoids, polysaccharides, polyunsaturated fatty acids, and bioactive peptides. Among these compounds, phycocyanin has attracted significant attention due to its intense natural blue colour, antioxidant capacity, anti-inflammatory activity, and potential pharmaceutical applications. Advances in cultivation technologies, molecular characterization, extraction methods, and downstream processing have further improved the commercial utilization of spirulina-derived products.

This review provides a comprehensive overview of the biological characteristics, taxonomy, morphology, biochemical composition, functional properties, cultivation systems, environmental factors influencing growth, molecular approaches, extraction technologies, and industrial applications of spirulina. Recent advances from 2020 to 2026, including wastewater-based cultivation, integrated biorefinery approaches, and nanotechnology-based applications, are also discussed. Despite its promising potential, challenges related to production cost, strain improvement, pigment stability, large-scale cultivation efficiency, and regulatory standardization remain. Future research integrating molecular biotechnology, process optimization, and sustainable production strategies will be essential for developing advanced spirulina-based bioprocessing systems and maximizing its contribution to the global bioeconomy.

Keywords: *Arthrospira platensis*; Spirulina; Cyanobacteria; Phycocyanin; Bioactive Compounds; Microalgae Biotechnology; Sustainable Protein; Cultivation Systems; Nutraceuticals; Biorefinery

Abbreviations

ALE: Adaptive Laboratory Evolution; BCAA: Branched-Chain Amino Acid; CAT: Catalase; EPS: Extracellular Polysaccharides; GLA: γ-Linolenic Acid; GPx: Glutathione Peroxidase; NF-κB: Nuclear Factor Kappa B; PCB: Phycocyanobilin; ROS: Reactive Oxygen Species; Rubisco: Ribulose-1,5-Bisphosphate Carboxylase/Oxygenase; SOD: Superoxide Dismutase.

Introduction

The increasing global demand for sustainable food resources, renewable biomaterials, and environmentally friendly production systems has stimulated extensive research into microbial biomass as an alternative resource for future applications. Among various photosynthetic microorganisms, spirulina, commercially recognized as *Arthrospira platensis*, has emerged as one of the most promising candidates due to its high nutritional value, rapid growth rate, environmental adaptability, and diverse industrial applications [1,28].

Spirulina biomass has been widely utilized as a functional food, dietary supplement, animal feed ingredient, natural pigment source, and bioactive compound producer. The term "spirulina" is commonly used in commercial and scientific literature; however, the majority of industrially cultivated strains belong to the genus *Arthrospira*, particularly *Arthrospira platensis* and *Arthrospira maxima*. These organisms are filamentous, multicellular cyanobacteria belonging to the phylum Cyanobacteria. Their ability to perform oxygenic photosynthesis enables efficient conversion of carbon dioxide into organic biomass while producing oxygen as a by-product [1,43]. Due to their ancient evolutionary origin and physiological flexibility, cyanobacteria have played a significant role in shaping Earth's atmosphere and continue to represent important biological systems for sustainable biotechnology [43].

Unlike conventional agricultural protein sources, spirulina offers several advantages, including high biomass productivity, efficient nutrient utilization, reduced land requirement, and the ability to grow in saline and alkaline environments unsuitable for many terrestrial crops [1,28]. The protein content of dried spirulina biomass commonly ranges from 55–70%, making it one of the richest microbial protein sources available [28]. Furthermore, spirulina proteins contain essential amino acids, bioactive peptides, and functional proteins that contribute to its nutritional and functional value [28].

In addition to proteins, spirulina contains a wide range of valuable biochemical compounds, including phycobiliproteins, carotenoids, chlorophyll-a, vitamins, minerals, polyunsaturated fatty acids, and polysaccharides [28]. Among these compounds, C-phycocyanin has received considerable attention because of its intense blue colour, antioxidant properties, and potential applications in food, pharmaceutical, and cosmetic industries [2,39]. The increasing consumer preference for natural ingredients has enhanced commercial interest in phycocyanin as an alternative to synthetic food dyes [2].

The biological activities associated with spirulina-derived compounds have expanded its applications beyond nutrition. Numerous studies have reported antioxidant, anti-inflammatory, immunomodulatory, antimicrobial, and metabolic regulatory properties associated with spirulina extracts and purified compounds [2,13]. These functional properties have encouraged research into spirulina-based nutraceuticals and pharmaceutical formulations [28]. From an agricultural perspective, spirulina biomass and extracts have demonstrated potential as biofertilizers, plant growth promoters, and biostimulants due to their rich composition of amino acids, minerals, pigments, and growth-promoting molecules. Similarly, spirulina supplementation in animal and aquaculture feed has been investigated for improving growth performance, immunity, and pigmentation [40].

Despite its significant potential, large-scale commercialization of spirulina faces several challenges, including optimization of cultivation systems, reduction of production costs, maintenance of biomass quality, improvement of pigment stability, and development of efficient downstream processing technologies [1,2,28]. Open pond systems remain the most widely used commercial production method because of their relatively low operational cost; however, limitations such as contamination risk, environmental fluctuations, and limited process control continue to stimulate research into advanced photobioreactor systems [1,4].

Recent developments in molecular biology, omics technologies, and metabolic engineering have provided new opportunities for improving spirulina strains with enhanced productivity and increased accumulation of valuable metabolites. Additionally, integrated biorefinery concepts aim to maximize biomass utilization by recovering multiple products, including proteins, pigments, lipids, carbohydrates, and bioactive compounds from a single cultivation system [16,37,53]. The application of circular economy principles has further expanded the role of spirulina biotechnology. Wastewater-based cultivation, carbon dioxide utilization, and sustainable nutrient recovery approaches are being explored to reduce environmental impacts while generating valuable biomass [8,32]. These strategies position spirulina as a potential contributor to sustainable food production, environmental management, and bio-based industrial development [28,32]. This review summarizes recent advances in spirulina research, covering its taxonomy, morphology, nutritional composition, bioactive compounds, cultivation technologies, environmental factors affecting productivity, molecular characterization approaches, extraction methods, industrial applications, and future perspectives, with particular emphasis on developments reported between 2020 and 2026 to highlight current trends and emerging opportunities in spirulina biotechnology.

Literature search and review methodology

This article presents a narrative review of recent developments in Spirulina biotechnology, with particular emphasis on research published from 2020 to 2026. The review was designed to provide a structured and critical synthesis of published evidence concerning the biology and taxonomy of Spirulina (Arthrospira/Limnospira), nutritional and biochemical composition, bioactive compounds, cultivation systems, environmental factors affecting biomass productivity, molecular characterization, phycocyanin extraction and purification, industrial applications, wastewater-based cultivation, sustainability, and integrated biorefinery approaches.

Literature search strategy

A literature search was conducted using major scientific databases, including PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar. The search focused primarily on peer-reviewed scientific publications published from January 2020 to August 2026, with the final literature search conducted in August 2026. Earlier publications were also included when they provided essential foundational information relating to taxonomy, biochemical composition, established cultivation principles, analytical methods, or extraction technologies.

The literature search used combinations of keywords and Boolean operators. Representative search terms included "Spirulina", "Arthrospira platensis", "Limnospira platensis", "Spirulina cultivation", "cyanobacterial biomass", "Spirulina nutritional composition", "Spirulina bioactive compounds", "phycocyanin extraction", "phycocyanin purification", "Spirulina photobioreactor", "Spirulina wastewater cultivation", "Spirulina nutrient removal", "Spirulina biorefinery", "Spirulina sustainability", "Spirulina life cycle assessment", and "Spirulina biomedical applications". Combinations of these terms were used to identify studies relevant to individual sections of the review.

Inclusion and exclusion criteria

Studies were considered eligible when they addressed one or more of the major themes of this review and provided relevant experimental, analytical, comparative, or review evidence. Priority was given to recent peer-reviewed publications from 2020–2026, particularly for emerging cultivation systems, extraction technologies, wastewater applications, sustainability assessment, and biotechnology applications.

Studies were excluded when they were unrelated to Spirulina/Arthrospira/Limnospira biotechnology, duplicated records, lacked sufficient relevance to the objectives of the review, or did not provide information applicable to the themes discussed. Earlier literature was retained when it represented an important foundational or methodological source.

Screening and evidence selection

The literature-selection process involved an initial screening of retrieved publications based on their titles and abstracts, followed by full-text evaluation of potentially relevant studies. Selected publications were subsequently organized according to the major themes of the review. Where multiple studies addressed similar technologies, processes, or biological properties, the available evidence was critically compared with respect to experimental conditions, biomass productivity, extraction yield, purity, nutrient-removal efficiency, processing requirements, energy demand, scalability, and reported limitations, where such data were available.

For biomedical and therapeutic applications, the evidence was interpreted according to the level of investigation, with clear distinctions made among *in vitro* studies, animal studies, and human clinical investigations. Findings from preclinical studies were considered supportive of biological or mechanistic potential but were not interpreted as evidence of established clinical efficacy in humans.

Evidence synthesis

Because this manuscript is a narrative review rather than a systematic review or meta-analysis, the objective was not to statistically pool all available studies. Instead, findings were critically synthesized to identify areas of agreement, variability, technological advantages and limitations, knowledge gaps, and emerging research directions. Quantitative values were compared where study conditions and reported parameters permitted meaningful interpretation. Differences in strain, cultivation conditions, biomass composition, wastewater characteristics, extraction conditions, analytical methods, and system boundaries were considered when interpreting comparisons.

The review therefore combines narrative synthesis with evidence-based qualitative and quantitative comparison to provide a critical assessment of current Spirulina biotechnology and to identify priorities for future research.

Biology and taxonomy of spirulina (*Arthrospira*)

Taxonomic classification and nomenclature

Spirulina is the widely used commercial and common name for filamentous cyanobacteria that have been extensively cultivated for food, feed, nutraceutical, pigment, and biotechnology applications. Historically, these organisms were assigned to the genus *Spirulina* and subsequently classified mainly within *Arthrospira*. More recent taxonomic revisions based on morphological, molecular, and phylogenetic evidence have recognized the genus *Limnospira* for several commercially relevant taxa. In particular, *Limnospira platensis* is the current taxonomic name corresponding to the organism historically and widely reported as *Arthrospira platensis*, while *Spirulina platensis* is also used as a synonym in the literature [1].

Accordingly, this review uses *Spirulina* as the familiar commercial term and *Limnospira platensis* when referring to the currently accepted taxonomic name, while *Arthrospira platensis* is retained when discussing studies that used this historical nomenclature. This convention maintains consistency with the extensive scientific and industrial literature while acknowledging current taxonomic treatment [1].

The currently recognized classification of *Limnospira platensis* is Domain: Bacteria; Phylum: Cyanobacteriota; Class: Cyanophyceae; Order: Oscillatoriales; Family: Sirenicapillariaceae; Genus: *Limnospira*; Species: *Limnospira platensis*. Taxonomic assignments should be interpreted in conjunction with strain identity because culture collections and historical publications may use the names *Spirulina*, *Arthrospira*, and *Limnospira* for the same or closely related strains [1].

Taxonomic level	Current/revised classification
Domain	Bacteria
Phylum	Cyanobacteriota (Cyanobacteria)
Class	Cyanophyceae
Order	Oscillatoriales
Family	Sirenicapillariaceae*
Genus	*Limnospira*
Species	*Limnospira platensis*
Historical/commercial synonym	*Arthrospira platensis/Spirulina platensis*

Table 1: Taxonomic classification of commercially cultivated spirulina (*Arthrospira*).

The family placement should be referenced consistently with the taxonomic authority selected for this review. Current taxonomic databases may differ from older literature in family-level placement; therefore, nomenclature should be interpreted in conjunction with the selected taxonomic framework [1].

Evolutionary and ecological significance of spirulina

Cyanobacteria represent an ancient and evolutionarily significant group of oxygen-producing microorganisms. Through the development of oxygenic photosynthesis, cyanobacteria played a fundamental role in the transformation of Earth's atmosphere by contributing to the accumulation of atmospheric oxygen. Their evolutionary success is associated with their physiological adaptability and ability to colonize a wide range of ecological niches, including freshwater environments, marine ecosystems, and extreme habitats characterized by high salinity, alkalinity, temperature fluctuations, and intense solar radiation [43].

Among cyanobacteria, *Arthrospira platensis* (commercially known as spirulina) exhibits substantial environmental adaptability and metabolic flexibility. It can tolerate elevated pH, high carbonate and bicarbonate concentrations, strong solar radiation, and relatively high temperatures, conditions that can limit the growth of many competing microorganisms [1,43]. Natural populations of *Arthrospira* are predominantly associated with alkaline and saline lakes containing high concentrations of carbonate and bicarbonate salts. Important natural habitats occur in regions of Africa, Mexico, and Central Asia, where dense populations can develop under highly alkaline conditions [43].

The ecological success of spirulina in these environments is associated with efficient carbon fixation, tolerance to alkaline conditions, effective nutrient utilization, adaptation to high light exposure, and rapid biomass accumulation [1]. The ability of spirulina to grow under alkaline conditions can also reduce competition from some undesirable microorganisms, contributing to its suitability for large-scale open cultivation systems [1]. These physiological characteristics have contributed to the commercial importance of spirulina in food, nutraceutical, pigment, and biotechnology applications [1,28].

Morphology and Cellular Organization of Spirulina

Morphological Characteristics

The distinctive morphology of spirulina is one of its most recognized characteristics and plays an important role in its taxonomic identification and commercial importance. *Arthrospira platensis* is a filamentous cyanobacterium composed of multicellular cylindrical cells arranged in characteristic spiral-shaped filaments known as trichomes. These trichomes consist of individual cylindrical cells connected through transverse septa, forming continuous helical structures that vary in diameter, pitch, and curvature depending on genetic characteristics and environmental conditions [1,43]. Factors such as light intensity, temperature, nutrient availability, pH, and salinity can significantly influence the morphological appearance and structural organization of spirulina filaments [1,33].

Under favourable cultivation conditions, spirulina develops well-defined spiral trichomes with relatively uniform cellular organization. Environmental stress conditions, however, may induce morphological modifications, including filament straightening, trichome fragmentation, changes in filament length, alterations in cellular dimensions, and changes in pigmentation patterns [1,43]. Such morphological variations can provide useful information regarding the physiological status of the culture and are therefore considered during laboratory and industrial cultivation. Spirulina also exhibits gliding and rotational movement along the filament axis, which contributes to cellular positioning within the aquatic environment and may influence exposure to light and nutrients [43].

Cellular structure and functional components

Although spirulina is a prokaryotic microorganism lacking membrane-bound organelles, its cells contain specialized structural and functional components that support photosynthesis, nutrient assimilation, storage, environmental adaptation, and survival under changing conditions [43]. These cellular components operate together to maintain metabolic activity and support biomass formation.

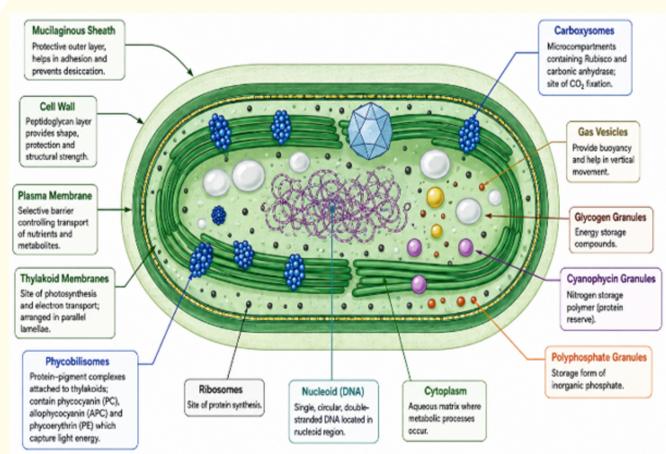

Figure 1: Cellular structure of Spirulina (*Arthrospira platensis*).

Plasma membrane

The plasma membrane forms the boundary of spirulina cells and plays an important role in maintaining cellular integrity, regulating ion transport, nutrient uptake, metabolite exchange, and cellular homeostasis. Transport systems associated with the membrane facilitate the acquisition of nutrients and ions required for cellular growth and metabolism [43].

Thylakoid membranes

Thylakoid membranes are specialized internal membrane structures associated with photosynthetic activity. They contain photosynthetic pigments, including chlorophyll-*a* and phycobiliproteins, which participate in light absorption and energy transfer during photosynthesis (Richmond and Hu, 2013; Usai., *et al.* 2024).

Phycobilisomes

Phycobilisomes are light-harvesting complexes associated with the thylakoid membrane surface. They contain water-soluble phycobiliproteins, including C-phycocyanin, allophycocyanin, and phycoerythrin, which absorb light wavelengths that are less effectively captured by chlorophyll-*a* and transfer excitation energy toward the photosynthetic reaction centres [2,55]. Among these pigments, C-phycocyanin is particularly important commercially because of its intense blue colour and applications as a natural colourant and bioactive ingredient [2,39].

Gas vesicles

Gas vesicles are proteinaceous structures that can contribute to buoyancy regulation and vertical positioning of cyanobacterial cells in aquatic environments. These structures may help optimize light exposure under changing environmental conditions [43].

Carboxysomes

Carboxysomes are specialized protein-based microcompartments associated with carbon-concentrating mechanisms. They contain enzymes involved in carbon dioxide fixation, including ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), and contribute to efficient carbon assimilation under conditions in which inorganic carbon availability may be limiting [43].

Intracellular storage granules

Spirulina contains intracellular storage materials involved in the management of carbon, nitrogen, and phosphorus reserves. Important storage compounds include cyanophycin, polyphosphate, and glycogen, which can support cellular metabolism and survival during periods of nutrient limitation or environmental stress [43].

Importance of morphological and taxonomic characterization

Accurate identification and characterization of spirulina strains are important for research and industrial applications because strain-level differences can influence biomass productivity, biochemical composition, pigment production, stress tolerance, and the accumulation of valuable metabolites [1]. Although morphological characteristics are useful for preliminary identification, they may be insufficient for definitive classification because environmental conditions can alter filament structure, spiral morphology, and pigmentation.

Therefore, modern spirulina characterization can involve an integrated combination of morphological, biochemical, and molecular approaches. Microscopic examination, measurement of filament dimensions, and assessment of spiral morphology can support preliminary identification, whereas biochemical analyses provide information on pigment composition, nutritional characteristics, and metabolic properties. Molecular approaches, including 16S rRNA gene analysis and genome-based characterization, can provide additional information for taxonomic identification and strain differentiation [1,43]. The integration of morphological and molecular characterization can support reliable strain identification and the selection of strains with desirable characteristics for cultivation and biotechnological applications.

Nutritional composition and biochemical profile of spirulina (*Arthrospira*)

Spirulina (*Arthrospira platensis*) has gained worldwide recognition as a highly valuable nutritional microorganism due to its high biochemical composition and the presence of diverse functional compounds. Unlike conventional protein sources obtained from terrestrial crops and animals, spirulina provides a unique combination of high-quality proteins, essential amino acids, polyunsaturated fatty acids, vitamins, minerals, pigments, and bioactive molecules within a single microbial biomass [28].

The nutritional composition of spirulina is influenced by several factors, including species and strain characteristics, cultivation conditions, nutrient availability, environmental stress, harvesting stage, and post-harvest processing methods [1,28]. Generally, dried spirulina biomass contains approximately 50-70% protein, 10-20% carbohydrates, 5-10% lipids, 3-8% minerals, and significant amounts of pigments and antioxidant compounds. although the reported composition varies among strains and cultivation conditions [28].

The high nutritional profile of spirulina has positioned it as a promising sustainable protein source for human nutrition, functional foods, nutraceutical formulations, animal feed, and future alternative food systems [28]. Compared with conventional agricultural protein sources, spirulina cultivation requires significantly less land and water resources while providing higher biomass productivity and efficient carbon fixation through photosynthesis.

Component	Approximate Content (% Dry Weight)	Biological Significance
Protein	55–70%	Provides high-quality protein containing essential amino acids
Carbohydrates	10–20%	Serves as an energy reserve and structural component
Lipids	5–10%	Source of essential fatty acids and bioactive lipids
Minerals	3–8%	Provides essential micronutrients required for metabolism
Pigments	Variable	Responsible for photosynthesis and antioxidant properties
Vitamins	Trace amounts	Participate in metabolic regulation and physiological functions

Table 2: Nutritional Composition of Spirulina Biomass.

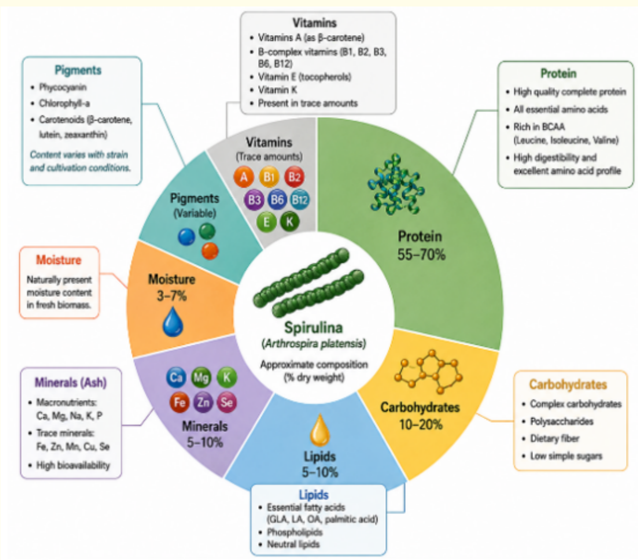

Figure 2: Nutritional composition of *Spirulina (Arthrospira platensis)*.

Protein content and amino acid composition

Protein represents the most abundant and nutritionally significant component of *Spirulina* (*Arthrospira platensis*) biomass. Numerous studies have reported that protein content generally ranges between 55% and 70% of dry biomass, although variations may occur depending on cultivation conditions, nutrient availability, environmental factors, harvesting stage, and processing methods [28]. The high protein concentration of spirulina has contributed to its consideration as an alternative protein resource for food and nutritional applications [28].

The protein fraction of spirulina includes phycobiliproteins and other cellular proteins with nutritional and functional significance [28]. Spirulina protein provides all of the essential amino acids, including leucine, isoleucine, valine, lysine, methionine, threonine, phenylalanine, and tryptophan, although their relative proportions may vary among strains and cultivation conditions [28]. Branched-chain amino acids (BCAAs), particularly leucine, isoleucine, and valine, contribute to the nutritional value of spirulina protein. However, the protein quality of spirulina should be interpreted with consideration of potentially limiting amino acids, particularly sulphur-containing amino acids such as methionine, which may occur at lower relative levels than in some animal proteins. Dietary combination with complementary protein sources may help improve the overall amino-acid balance.

Protein quality and functional properties

In addition to its nutritional value, spirulina protein possesses several functional characteristics relevant to food technology, biotechnology, and nutraceutical applications. Protein solubility, particularly that associated with phycobiliproteins, is an important functional property that supports the incorporation of spirulina proteins into food formulations such as functional beverages, protein supplements, nutritional powders, and fortified food products. Compared with some plant proteins that may require additional processing to improve dispersibility, spirulina proteins can exhibit favourable solubility characteristics.

Spirulina proteins can also serve as substrates for the generation of bioactive peptides through enzymatic hydrolysis. Spirulina-derived peptides have been investigated for antioxidant and other biological activities, including reactive oxygen species scavenging and metal-chelating effects; however, the reported evidence is largely experimental and varies according to peptide preparation and study conditions. These findings have contributed to interest in spirulina-derived peptides for potential applications in functional foods and nutraceutical formulations. Spirulina proteins may also exhibit emulsifying and other functional properties associated with their amphiphilic characteristics, supporting their investigation as functional ingredients in food formulations [1].

Lipid composition and essential fatty acids

Although spirulina is primarily recognized for its high protein content, its lipid fraction contains several nutritionally and biologically relevant molecules. Lipids generally constitute approximately 5–10% of spirulina dry biomass, although the reported lipid content can vary with strain and cultivation conditions. The lipid fraction includes neutral lipids, glycolipids, phospholipids, and other lipid-associated compounds, and its composition can be influenced by environmental factors such as light intensity, temperature, nutrient availability, and growth phase [1].

One of the characteristic fatty acids reported in spirulina is γ-linolenic acid (GLA), an omega-6 polyunsaturated fatty acid that contributes to the nutritional and functional value of the biomass [28]. Spirulina is recognized as a relatively rich microbial source of GLA, supporting its investigation for nutraceutical and functional-food applications [28]. In addition to GLA, spirulina contains other fatty acids, including palmitic acid, oleic acid, and linoleic acid. Environmental stress, particularly nutrient limitation, can alter lipid accumulation and fatty-acid composition; however, excessive stress may reduce biomass productivity and affect overall metabolic performance [1].

Carbohydrate composition

Carbohydrates represent an important fraction of spirulina dry biomass and include glycogen, polysaccharides, and extracellular polysaccharides (EPS), although their relative abundance can vary according to strain and cultivation conditions [28]. Unlike terrestrial plants, spirulina does not possess a cellulose-based rigid cell wall, which contributes to differences in its cellular structure and may facilitate the processing and recovery of intracellular compounds [28].

Glycogen functions as an important carbon-storage compound and can serve as an energy reserve under conditions in which photosynthetic carbon fixation is reduced. Spirulina also produces extracellular polysaccharides that can contribute to cellular protection, environmental adaptation, and interactions with surrounding microorganism. Spirulina-derived polysaccharides have been investigated for immunomodulatory, antioxidant, antiviral, and anti-inflammatory activities, although much of the available evidence remains experimental or preclinical. These findings have supported continued investigation of spirulina polysaccharides for potential applications in functional foods, nutraceuticals, biomaterials, and biotechnology [28].

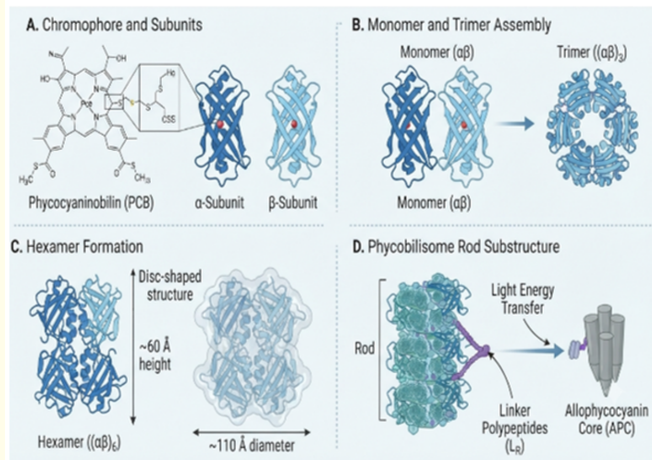

Figure 3: Structural organization and assembly of phycocyanin in *Spirulina (Arthrospira platensis)*.

Vitamin composition of spirulina

Spirulina contains a range of vitamins and vitamin-related compounds that contribute to its nutritional value. The vitamin composition may vary depending on strain, cultivation conditions, environmental factors, and processing methods. Reported vitamins include members of the vitamin B complex, such as thiamine (vitamin B1), riboflavin (vitamin B2), niacin (vitamin B3), pyridoxine (vitamin B6), and folate, which participate in various metabolic and physiological processes [28].

Spirulina also contains vitamin E and carotenoid compounds, including β-carotene, which has provitamin A activity. However, the nutritional contribution of these compounds can vary according to biomass composition and cultivation conditions [28]. Although spirulina contains vitamin B12-like compounds, a considerable proportion may occur as inactive analogues rather than biologically active cobalamin. Therefore, spirulina should not be considered a reliable primary dietary source of vitamin B12 [28].

Mineral composition

Spirulina contains a range of minerals that contribute to its nutritional value, including iron, calcium, magnesium, potassium, zinc, selenium, and phosphorus. The mineral composition of spirulina biomass can vary according to strain, cultivation conditions, nutrient availability, and processing [28].

Iron, calcium, and magnesium are among the nutritionally relevant minerals reported in spirulina. Iron contributes to haemoglobin synthesis and oxygen transport, while calcium and magnesium participate in several physiological and metabolic processes. Magnesium also has an important role in photosynthesis as the central element of chlorophyll. Trace elements such as zinc and selenium participate in enzyme activity and antioxidant defence [28].

Bioactive compound	Reported activity	Evidence level
Phycobiliproteins	Antioxidant, anti-inflammatory, immunomodulatory	Mainly *in vitro*/preclinical
Chlorophyll-a	Antioxidant, detoxification-related effects	Experimental
Carotenoids	Antioxidant, ocular-health-related effects	Nutritional/experimental
Polysaccharides	Immunomodulatory, antimicrobial	Mainly experimental/preclinical
Bioactive peptides	Antioxidant, antihypertensive	Mainly experimental
GLA	Anti-inflammatory, metabolic/cardiovascular potential	Nutritional/clinical evidence varies

Table 3: Major Bioactive Compounds Present in Spirulina.

Bioactive compounds and functional properties of spirulina

Spirulina (*Arthrospira platensis*) is recognized not only as a nutrient-rich microbial biomass but also as an important source of bioactive molecules with significant biological activities.

The functional properties of spirulina are mainly associated with pigments, proteins, peptides, polysaccharides, fatty acids, vitamins, and antioxidant compounds. Increasing scientific interest in spirulina-based functional foods and nutraceutical products are primarily driven by its ability to provide nutritional benefits together with protective physiological effects. *In vitro* studies have reported antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory activities of Spirulina-derived compounds, whereas animal studies have provided preclinical evidence for potential hepatoprotective, neuroprotective, immunomodulatory, and metabolic effects. Evidence from human clinical studies remains comparatively limited and should therefore be considered separately when evaluating the therapeutic relevance of these findings.

Phycobiliproteins

Phycobiliproteins are water-soluble pigment–protein complexes associated with Phycobilisomes, which function as accessory light-harvesting systems in cyanobacteria. These pigments capture wavelengths of light that are not efficiently absorbed by chlorophyll-a and transfer excitation energy toward photosynthetic reaction centres. In spirulina, phycobiliproteins account for approximately 10–20% of total cellular proteins and contribute significantly to both nutritional and commercial value [13,55].

The major phycobiliproteins present in *Spirulina* include C-phycocyanin, allophycocyanin, and phycoerythrin. Among these, C-phycocyanin is the most abundant and commercially valuable phycobiliprotein because of its intense blue color and established applications as a natural food colorant [31,60]. Experimental studies have reported antioxidant and anti-inflammatory activities of phycocyanin, including effects associated with free-radical scavenging, modulation of inflammatory mediators, and regulation of immune signaling pathways. Experimental models have also suggested potential neuroprotective and hepatoprotective effects through enhancement of antioxidant defense mechanisms and protection against oxidative cellular injury [31,60]. However, these findings remain primarily preclinical and should not be interpreted as evidence of established therapeutic efficacy in humans. Further well-designed human clinical studies are required to determine whether these experimentally observed biological activities translate into clinically meaningful therapeutic benefits [13].

Chlorophyll and carotenoids

Spirulina contains several photosynthetic pigments that contribute to light harvesting, energy conversion, photoprotection, and biological activity [17,59]. The major pigments include chlorophyll-*a*, β-carotene, zeaxanthin, lutein, and other carotenoid derivatives [24,49]. Chlorophyll-*a* is the primary photosynthetic pigment responsible for capturing light energy and converting it into chemical energy during photosynthesis [59]. In addition to its photosynthetic role, chlorophyll and its derivatives have attracted scientific interest because of their reported antioxidant and other biological activities, although the extent of these effects depends on the specific chlorophyll derivative and experimental conditions [59]. These properties contribute to the functional value and potential applications of *Spirulina*-based products.

Carotenoids are lipid-soluble pigments that participate in photoprotection and antioxidant defence by quenching reactive oxygen species and dissipating excess excitation energy [24,59]. Important carotenoids identified in *Spirulina* include β-carotene, zeaxanthin, lutein, and other xanthophyll derivatives [18,24]. These compounds can help protect cellular components against photooxidative damage and oxidative stress [24,49]. Zeaxanthin and lutein are also of interest because of their physiological roles in ocular tissues and their association with eye health [49]. β-Carotene is particularly important nutritionally because it functions as a provitamin A carotenoid and can be converted to vitamin A in the human body [24,49].

Antioxidant properties of spirulina

Oxidative stress caused by excessive accumulation of reactive oxygen species (ROS) is associated with cellular damage and the development of various chronic diseases. Spirulina contains multiple antioxidant compounds, including phycocyanin, -carotene, vitamin E, phenolic compounds, and bioactive peptides, which protect cells through different mechanisms [13,60]. Spirulina-derived antioxidants act through free radical scavenging by donating electrons or hydrogen atoms to neutralize reactive molecules. They also exhibit metal-chelating activity by binding transition metals and reducing oxidative reactions. Furthermore, spirulina compounds may enhance endogenous antioxidant defence systems by stimulating enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) [13,60].

Immunomodulatory and therapeutic potential

Bioactive compounds present in spirulina have demonstrated significant potential for regulating immune responses. Phycocyanin, polysaccharides, peptides, and polyunsaturated fatty acids are considered major contributors to these immunomodulatory effects [31,60]. Spirulina-derived polysaccharides and phycocyanin may enhance immune function through activation of immune cells, regulation of cytokine production, and improvement of natural defence mechanisms [31,60].

The anti-inflammatory potential of spirulina is associated with regulation of important inflammatory pathways, including nuclear factor kappa B (NF-B) signaling, cytokine production, and oxidative stress responses [31]. Furthermore, research indicates that spirulina supplementation may influence metabolic health by improving lipid metabolism, supporting blood glucose regulation, and maintaining oxidative balance. These properties highlight spirulina as a promising ingredient for development of functional foods targeted toward improving metabolic health and preventing lifestyle-associated disorders.

Phycocyanin: Structure, properties, extraction, and industrial applications

Phycocyanin is an important bioactive pigment obtained from *Spirulina* (*Arthrospira platensis*) and represents a major proportion of its soluble protein fraction [13,55]. It is responsible for the characteristic blue colour of spirulina biomass and has attracted significant scientific and industrial interest due to its natural colouring properties and diverse biological activities [2,39]. Unlike synthetic dyes, phycocyanin provides both functional pigmentation and health-promoting properties, making it a highly valuable compound for applications in clean label food products, nutraceuticals, pharmaceuticals, cosmetics, and biotechnology. Increasing consumer demand for naturally derived pigments has stimulated extensive research focused on improving spirulina cultivation strategies, extraction efficiency, purification processes, and stabilization technologies to enhance the commercial utilization of phycocyanin [2,39,55].

Molecular structure of phycocyanin

Phycocyanin belongs to the phycobiliprotein family, which includes C-phycocyanin, allophycocyanin, and phycoerythrin. Among these pigments, C-phycocyanin (C-PC) is the predominant phycobiliprotein in *Arthrospira platensis* and is an important commercially utilized natural blue pigment [55,57].

Structurally, phycocyanin consists of two homologous protein subunits, the α-subunit and β-subunit. These subunits are covalently associated with phycocyanobilin (PCB), an open-chain tetrapyrrole chromophore. In C-phycocyanin, the α-subunit generally carries one PCB chromophore, whereas the β-subunit carries two PCB chromophores, which are covalently attached to conserved cysteine residues through thioether linkages [39,50]. The conjugated tetrapyrrole structure of phycocyanobilin is responsible for the characteristic blue colour and major optical properties of C-phycocyanin [55].

The structural organization of C-phycocyanin occurs through a hierarchical assembly process. An α- and β-subunit initially associate to form an αβ heterodimer, which serves as the basic monomeric unit. Three αβ heterodimers subsequently assemble into a disc-shaped trimer, $[(\alpha\beta)_3]$, while two trimers associate face-to-face to form a hexamer, $[(\alpha\beta)_6]$. These higher-order structures contribute to the organization and efficient functioning of Phycobilisomes during photosynthetic light harvesting and energy transfer [30].

C-phycocyanin exhibits characteristic spectral properties, with a principal absorption maximum generally reported near 620 nm, although the exact absorption position may vary depending on the molecular environment and aggregation state. Its fluorescence emission is typically observed in the region of approximately 640–650 nm [55,57]. These distinctive optical properties, together with its intense natural blue colour and fluorescence, make C-phycocyanin valuable as a natural food colourant and as a fluorescent probe in biotechnology, analytical applications, and biomedical research [15,55].

Biological role of phycocyanin

In cyanobacteria, phycocyanin functions as an important accessory photosynthetic pigment that is organized within Phycobilisomes, supramolecular antenna complexes associated with the thylakoid membrane. These complexes absorb light in spectral regions that are less efficiently utilized by chlorophyll *a* and transfer the absorbed excitation energy through phycobiliproteins toward the photosynthetic reaction centres, thereby enhancing the efficiency of light harvesting [19]. Within the Phycobilisomes, excitation energy is transferred sequentially among phycobiliproteins, including phycocyanin, before being transferred to the chlorophyll *a*-containing photosynthetic apparatus [19].

Beyond its primary role in photosynthetic light harvesting, phycocyanin and other phycobiliproteins can serve as important intracellular nitrogen reserves because their degradation provides nitrogen-containing compounds that can be redistributed to essential cellular processes under nutrient-limited conditions [19]. Phycocyanin has also been associated with antioxidant and stress-protective activities, although these functions are influenced by the physiological state of the cyanobacterial cells and the experimental conditions [51]. The cellular production and accumulation of phycocyanin are strongly influenced by environmental and nutritional conditions, including nitrogen availability, light intensity, temperature, nutrient composition, and growth phase [19,51]. Under nitrogen limitation, cyanobacteria can undergo extensive degradation of phycobiliproteins, particularly phycocyanin, through a regulated process associated with Phycobilisomes remodelling and nutrient recycling. This response is commonly linked to the acclimation process known as complementary chromatic adaptation and allows nitrogen released from phycobiliprotein degradation to be redirected toward essential cellular functions and survival under nutrient stress [19].

Extraction technologies for phycocyanin recovery

Efficient extraction technologies are essential for obtaining high-quality phycocyanin suitable for industrial applications. Since phycocyanin is a water-soluble protein pigment, extraction processes are designed to achieve effective cell disruption while maintaining pigment stability and biological activity [15,51]. The general extraction workflow includes biomass preparation, disruption of cellular structures, pigment solubilization, removal of cellular debris, purification, stabilization, and drying [35,57].

Among different extraction approaches, conventional aqueous extraction remains one of the most widely used methods because of its simplicity, low cost, and compatibility with food-grade applications. In this process, spirulina biomass is suspended in water, followed by cell disruption, controlled extraction, centrifugation, and filtration to obtain a phycocyanin-rich extract [35]. The major advantages of aqueous extraction include environmental safety, absence of toxic solvents, and suitability for food applications [15,51]. However, relatively lower extraction efficiency and the presence of impurities remain important limitations [35,57].

Extraction Method	Principle	Reported quantitative result	Advantages	Limitations
Freeze–Thaw	Cell disruption through ice crystal formation	C-PC: 17.03 ± 0.53%*	Simple, economical, food-grade	Time-consuming
Ultrasound-Assisted Extraction	Cavitation-mediated disruption	C-PC: 15.21 ± 0.41%*	Efficient mass transfer	Possible heat generation
Enzyme-Assisted Extraction	Enzymatic disruption	NR	Mild conditions	Enzyme cost
High-Pressure Homogenization	Mechanical disruption	NR	Industrial scalability	Expensive equipment
Microwave-Assisted Extraction	Microwave-induced cell disruption	NR	Rapid extraction	Pigment degradation risk
Pulsed Electric Field	Electroporation	NR	Non-thermal	High equipment cost

Table 4: Extraction Technologies Used for Phycocyanin Recovery.

NR = Not reported in the comparative study.

*Values are specific to the conditions used in (26) and should not be interpreted as universal extraction efficiencies.

Comparative studies indicate that the efficiency of phycocyanin extraction varies considerably among cell-disruption methods. In a comparative study of *Arthrospira maxima*, freeze–thaw extraction produced a C-phycocyanin content of 17.03 ± 0.53%, whereas ultrasound-assisted extraction combined with chitosan–acetic acid flocculation produced 15.21 ± 0.41%. Glass-bead extraction resulted in 10.92 ± 0.74%, while ultrasound-assisted extraction combined with chitosan–lactic acid and chitosan–citric acid flocculation yielded 10.11 ± 0.13% and 8.02 ± 0.58%, respectively. These findings demonstrate that extraction performance depends strongly on the disruption and downstream-processing strategy and that higher pigment recovery does not necessarily correspond to higher extract purity [26].

Freeze–thaw extraction

Freeze–thaw extraction is a simple physical method commonly used for phycocyanin recovery from *Arthrospira platensis*. The technique relies on repeated freezing and thawing cycles to promote disruption of cellular structures and enhance the release of intracellular phycocyanin into the extraction medium [51,57]. During freezing, the formation and growth of ice crystals can cause mechanical stress and structural damage to cellular membranes, whereas subsequent thawing facilitates the release and diffusion of soluble intracellular components into the surrounding extraction medium [36,51].

The general process involves preparation of a *Spirulina* biomass suspension, freezing at a controlled low temperature, thawing, repetition of the freeze–thaw cycle when required, followed by centrifugation and filtration to obtain a phycocyanin-rich extract [36,57]. The method offers several advantages, including operational simplicity, limited use of chemical reagents, and compatibility with aqueous extraction systems [51]. However, prolonged processing time, energy requirements associated with freezing and thawing, and the need for repeated cycles to improve pigment release may limit its practical application at larger scales [57]. Freeze–thaw treatment can also be combined with other cell-disruption approaches, such as ultrasound-assisted extraction or enzymatic treatment, to improve phycocyanin recovery by enhancing cellular disruption [51,57]. In a comparative study, freeze–thaw extraction achieved a C-phycocyanin content of 17.03 ± 0.53%; however, extraction performance was dependent on the specific operating conditions employed [26].

Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE) has emerged as an efficient technique for improving phycocyanin recovery from *Arthrospira platensis*. The method uses high-frequency sound waves to generate acoustic cavitation within the extraction medium. The formation, growth, and collapse of microscopic bubbles generate mechanical shear forces, localized pressure and temperature changes, and turbulence, which can disrupt cellular structures and enhance mass transfer, thereby promoting the release of intracellular phycocyanin [9,51,57].

The major advantages of ultrasound-assisted extraction include improved extraction efficiency, reduced processing time, enhanced mass transfer, and the potential to reduce the quantity of extraction solvent required compared with some conventional extraction approaches [9]. However, excessive ultrasound intensity or prolonged treatment can generate localized heating, free radicals, and mechanical stress that may promote protein denaturation and degradation of sensitive pigments such as phycocyanin [9,57]. Therefore, optimization of parameters such as ultrasound power or intensity, treatment duration, temperature, frequency, and biomass concentration is necessary to maximize phycocyanin recovery while maintaining pigment stability and quality [51,57].

In the same comparative study, ultrasound-assisted extraction combined with chitosan–acetic acid flocculation produced a C-phycocyanin content of 15.21 ± 0.41%, demonstrating substantial pigment recovery but a slightly lower C-phycocyanin content than the freeze–thaw treatment under the reported experimental conditions [26].

Enzyme-assisted extraction

Enzyme-assisted extraction involves the use of specific enzymes to facilitate phycocyanin release by weakening or degrading cellular and extracellular structural components surrounding the intracellular pigment [51,57]. Although *Arthrospira platensis* does not possess a typical cellulose-based cell wall characteristic of higher plants, its cells are surrounded by a complex envelope containing peptidoglycan and other structural components that can limit the accessibility of intracellular compounds [21]. Enzymatic pretreatment can therefore improve cellular permeability and facilitate the release of water-soluble phycocyanin into the extraction medium. Enzymes such as lysozyme, proteases, cellulases, and pectinases have been investigated individually or in combination for the disruption of microbial or algal biomass, although their effectiveness depends strongly on the composition of the target biomass and the selected operating conditions [51,57].

The main advantages of enzyme-assisted extraction include relatively mild processing conditions, reduced dependence on intensive mechanical disruption, and the potential to improve pigment recovery while minimizing thermal damage to protein-based pigments [9,51]. However, important limitations include the relatively high cost of commercial enzymes, the requirement for controlled pH and temperature conditions, enzyme-specific reaction times, and the possible need for subsequent clarification or purification steps [9,57]. Because enzymatic extraction can be performed under relatively mild conditions and may help preserve the structural and functional characteristics of phycocyanin, it represents a promising approach for producing higher-quality pigment extracts for nutraceutical, pharmaceutical, and other value-added applications [51,57].

High-pressure and emerging extraction technologies

High-pressure homogenization is an advanced mechanical extraction technique that can be used to enhance phycocyanin recovery from *Arthrospira platensis*. In this method, a biomass suspension is forced through a narrow valve or homogenization chamber under high pressure. The resulting pressure drops; shear forces, turbulence, and cavitation promote disruption of cellular structures and facilitate the release of intracellular phycocyanin into the extraction medium. Because high-pressure homogenization can be operated continuously, it has potential for large-scale processing and industrial applications. However, excessive pressure or repeated processing cycles may generate heat and mechanical stress, which can affect the stability of sensitive protein pigments such as phycocyanin. Therefore, optimization of pressure, number of homogenization passes, temperature, and biomass concentration is necessary to achieve effective cell disruption while minimizing pigment degradation [15,51,57].

Several emerging technologies have also been investigated for the extraction of valuable compounds from microalgal and cyanobacterial biomass. Microwave-assisted extraction uses electromagnetic energy to promote rapid heating and cellular disruption, potentially reducing extraction time. However, excessive microwave exposure may cause thermal degradation of phycocyanin and other heat-sensitive compounds. Pulsed electric field (PEF) technology is another non-thermal approach in which short, high-voltage electrical pulses induce temporary or permanent pores in cellular membranes through electroporation. This process can improve the release of intracellular compounds while potentially reducing thermal damage. Despite these advantages, the application of PEF may be limited by equipment cost and optimization requirements at industrial scale [9,15,51,57].

Other emerging approaches include combinations of physical, enzymatic, and membrane-based processing technologies. Hybrid extraction strategies may improve overall phycocyanin recovery by combining effective cell disruption with mild downstream processing conditions. However, comparison among extraction technologies remains difficult because reported recovery and purity values are strongly influenced by biomass characteristics, cultivation conditions, extraction solvent, temperature, processing time, purification procedures, and the analytical methods used. Consequently, the selection of an extraction technology should consider not only pigment recovery but also phycocyanin purity, stability, energy requirements, processing cost, food-grade compatibility, and scalability [15,51,57].

Purification and quality evaluation of phycocyanin

Following extraction, purification is required to remove unwanted cellular components, including cellular debris, other proteins, nucleic acids, pigments, and low-molecular-weight compounds. The degree of purification determines the commercial value and application suitability of phycocyanin.

Spectrophotometric analysis is commonly used for evaluating phycocyanin quality through the purity ratio calculated as:

Purity ratio=A620/A280

where A_{620} represents the absorbance of C-phycocyanin at 620 nm and A_{280} represents total protein absorbance at 280 nm. A higher A_{620}/A_{280} ratio indicates a preparation with lower levels of contaminating proteins and therefore greater phycocyanin purity [44,51]. A purity ratio of approximately 0.7 or higher is commonly considered food-grade, values around 3.9 have been reported for reactive-grade preparations, and values of ≥4.0 are generally associated with analytical-grade C-phycocyanin [44,51].

Several purification techniques are employed, including ammonium sulphate precipitation, dialysis, ion-exchange chromatography, gel-filtration chromatography, and membrane filtration (Eriksen, 2008; Sonani., *et al*. 2016). Ammonium sulphate precipitation is commonly used as an initial concentration step because of its simplicity and effectiveness in protein recovery. Dialysis removes salts and low-molecular-weight impurities while retaining proteins. Ion-exchange chromatography provides selective purification based on protein charge differences, whereas gel-filtration chromatography separates molecules according to size. Membrane filtration technologies are particularly attractive for industrial applications because they can support continuous processing, reduced chemical usage, and scalability [15,57].

Purification Technique	Principle	Purity Level	Application
Ammonium Sulphate Precipitation	Protein precipitation based on solubility differences	Low–Medium	Initial purification
Dialysis	Removal of salts and small molecules	Medium	Desalting process
Ion-Exchange Chromatography	Separation based on protein charge	High	Pharmaceutical-grade purification
Gel-Filtration Chromatography	Separation according to molecular size	High	Laboratory purification
Ultrafiltration	Membrane-based protein concentration	Medium–High	Industrial production

Table 5: Purification Techniques for Phycocyanin.

Stability challenges and stabilization technologies of phycocyanin

Although phycocyanin exhibits valuable functional and optical properties, its commercial utilization can be limited by its relatively high sensitivity to environmental and processing conditions compared with many synthetic pigments [15,51]. Factors such as temperature, pH, light exposure, oxygen, and storage conditions can significantly influence the stability of the pigment–protein complex [35]. Elevated temperatures can promote protein unfolding, alteration of the phycocyanobilin chromophore environment, and subsequent loss of colour intensity and fluorescence. Consequently, phycocyanin-containing products are generally processed and stored under controlled temperature conditions to minimize thermal degradation [15,35].

pH also strongly influences phycocyanin stability. C-phycocyanin is generally more stable within a moderately neutral pH range, whereas exposure to strongly acidic or highly alkaline conditions can promote structural changes, protein aggregation or denaturation, and loss of pigment colour [35]. Continuous exposure to light can induce photochemical degradation and decrease pigment intensity, while oxidative conditions may also contribute to deterioration of the chromophore and associated functional properties. Therefore, protection from excessive light and oxygen is important during processing, formulation, and storage.

To overcome these stability limitations, several stabilization strategies have been investigated. Encapsulation is a promising approach in which phycocyanin is incorporated into protective matrices such as polysaccharides, proteins, or other food-compatible carrier materials. Encapsulation can provide a physical barrier against environmental stressors and improve the storage stability of the pigment [46,57]. Spray drying can convert phycocyanin-containing extracts into a more convenient powder form, facilitating handling, transportation, and storage; however, appropriate control of inlet and outlet temperatures is necessary because excessive thermal exposure may reduce pigment stability [51,57]. Freeze-drying is generally performed at low temperatures and can provide effective preservation of protein structure, pigment characteristics, and bioactivity compared with more intensive thermal drying processes, although its relatively high energy and equipment costs can limit large-scale application [15,51].

Industrial applications of phycocyanin

The unique colour characteristics and diverse biological activities of phycocyanin have expanded its potential applications across food, pharmaceutical, nutraceutical, cosmetic, and other biotechnology-related industries [15,51,38].

Food Industry: Phycocyanin is considered a promising natural alternative to synthetic blue colourants because of its natural origin, intense blue colour, and potential additional functional properties [15,51]. It has been investigated and utilized as a natural colouring ingredient in beverages, dairy products, ice creams, confectionery products, functional foods, and dietary supplements, although its application is influenced by its sensitivity to temperature, pH, light, and other processing conditions [35,38].

Pharmaceutical Applications: Phycocyanin has attracted considerable research interest because of its reported antioxidant and anti-inflammatory activities, as well as its potential anticancer, hepatoprotective, and neuroprotective effects [38,51]. Experimental studies have suggested that phycocyanin and its derived components may modulate oxidative-stress and inflammatory pathways and may influence cellular mechanisms associated with apoptosis and cell proliferation [31,51]. However, evidence for many of these biomedical activities is predominantly derived from *in vitro* and animal studies. These findings therefore represent promising preclinical evidence rather than established therapeutic efficacy in humans. Further well-designed clinical studies are required to determine the clinical relevance, effective dosage, safety, bioavailability, pharmacokinetics, and therapeutic potential of phycocyanin [38,51].

Cosmetic Industry: The cosmetic industry has also shown increasing interest in phycocyanin because of its natural pigmentation characteristics, antioxidant properties, and potential protective effects against oxidative stress. Potential applications include natural colour cosmetics, skincare formulations, and products designed to provide antioxidant or anti-ageing benefits. However, further formulation and stability studies are required to optimize the incorporation of phycocyanin into cosmetic products and maintain its colour and bioactivity during storage [38].

Photosynthetic Pigments of Spirulina

Chlorophyll-a

Chlorophyll-*a* is a major photosynthetic pigment present in *Arthrospira platensis* (spirulina) and plays a fundamental role in the conversion of solar energy into chemical energy during photosynthesis [38,43]. Unlike higher plants, cyanobacteria possess internal thylakoid membrane systems that contain chlorophyll-*a* associated with photosynthetic protein complexes responsible for light harvesting, electron transport, and energy conversion [43]. Chlorophyll-*a* performs several essential functions, including absorption of light energy, excitation and transfer of electrons, photosynthetic energy conversion, and contribution to the regulation of carbon assimilation [43]. During photosynthesis, chlorophyll-*a* absorbs light predominantly in the blue and red regions of the visible spectrum, and the resulting excitation energy is directed toward the photosynthetic reaction centres through associated antenna systems. The overall process involves light absorption, excitation of photosynthetic pigments, electron transfer through photosynthetic complexes, generation of ATP and NADPH, and subsequent incorporation of inorganic carbon into organic molecules through carbon-fixation pathways [43].

In addition to its photosynthetic function, chlorophyll and its derivatives have been investigated for several biological activities. Chlorophyll-derived compounds can exhibit antioxidant properties and may participate in the modulation of oxidative processes under appropriate experimental conditions [27]. Chlorophyll derivatives, particularly chlorophyllin, have also been investigated for potential chemoprotective and detoxification-related effects, including interactions with certain chemical compounds and reduction of their biological activity [27]. Furthermore, some chlorophyll derivatives have demonstrated antimicrobial activity against selected microorganisms, although their effectiveness depends on the specific derivative and experimental conditions [27]. These reported functional properties have contributed to increasing interest in chlorophyll-containing *Arthrospira* extracts for potential applications in nutraceuticals, functional foods, and other health-related products [38].

Carotenoids

Carotenoids are lipid-soluble pigments that contribute to the yellow-orange coloration of *Arthrospira platensis* (spirulina) and play important roles in photoprotection [38,49]. The major carotenoids reported in *A. platensis* include β-carotene, zeaxanthin, and lutein, although their relative abundance can vary depending on strain, cultivation conditions, and environmental factors [3,49]. These pigments perform two major biological functions: they contribute to light harvesting by absorbing wavelengths of light that are not efficiently absorbed by chlorophyll-*a*, and they protect the photosynthetic apparatus against photooxidative stress by dissipating excess excitation energy and participating in antioxidant mechanisms [49]. Thus, carotenoids are important components of the photosynthetic pigment system of *Arthrospira* and contribute to both efficient light utilization and protection against excessive light-induced oxidative damage.

-Carotene

β-Carotene is one of the major carotenoids reported in *Arthrospira platensis* and serves as an important provitamin A carotenoid because it can be enzymatically converted to vitamin A in animals and humans [3,49]. It also contributes to photoprotection by quenching reactive oxygen species, including singlet oxygen, thereby helping to protect photosynthetic membranes and other cellular components from photooxidative damage [49].

Zeaxanthin and Lutein

Zeaxanthin and lutein are xanthophyll carotenoids that contribute to photoprotection by dissipating excess excitation energy and quenching reactive oxygen species, thereby helping to limit photooxidative damage to cellular membranes [49]. In humans, lutein and zeaxanthin are the principal carotenoids of the macular pigment, where they are selectively accumulated in the retina and contribute to protection against photooxidative stress. Their presence in the macula has therefore been associated with the maintenance of normal visual and retinal function [49].

Cultivation Systems for Spirulina Production

Large-scale spirulina production requires optimized cultivation systems capable of achieving high biomass productivity, nutritional quality, economic feasibility, and process sustainability [20,58]. Commercial cultivation strategies are designed to maximize biomass yield, protein production, pigment accumulation, product quality, and environmental efficiency [42]. Based on operational design and cultivation control, spirulina production systems are broadly classified into open cultivation systems, closed photobioreactor systems, and hybrid cultivation systems [42,43]. The selection of cultivation technology depends on production objectives, environmental conditions, investment capacity, and the intended application of spirulina biomass [20,43].

Cultivation System	Advantages	Limitations	Commercial Suitability
Open Ponds	Low investment and easy operation	Contamination risk	High
Raceway Ponds	Large-scale production and simple management	Climate dependent	Very High
Tubular Photobioreactors	High productivity and controlled conditions	High operational cost	High-value products
Flat-Panel Photobioreactors	Efficient light utilization	Expensive construction	Pigment production
Column Photobioreactors	Good mixing and controlled growth	Limited scale	Laboratory studies
Hybrid Systems	Improved productivity and flexibility	Complex operation	Emerging technology

Table 6: Cultivation Systems Used for Spirulina Production.

Open pond cultivation systems

Open pond cultivation is one of the most widely used approaches for commercial *Spirulina* production because of its comparatively low construction and operational costs and its suitability for large-scale biomass production [20,42]. Common open cultivation configurations include raceway ponds, circular ponds, and other shallow pond designs that utilize sunlight as the primary energy source and atmospheric or supplemented carbon dioxide as a carbon source for biomass production [42,43]. Raceway ponds are particularly common because their paddle-wheel-driven circulation facilitates mixing and helps maintain relatively uniform exposure of the culture to light and nutrients [42].

The major advantages of open pond systems include relatively low capital investment, straightforward operation, large-scale production potential, and lower energy requirements compared with highly controlled closed photobioreactor systems [20,42]. *Arthrospira* is particularly suitable for open cultivation because it can grow efficiently under alkaline conditions, which can provide a selective ecological advantage and suppress the growth of many competing microorganisms [20,58]. However, this selectivity does not completely eliminate the risk of biological contamination, and unwanted microorganisms, grazers, or other contaminants may still affect culture productivity and biomass quality [43].

Open pond systems also have several important limitations. Environmental variability, including fluctuations in temperature, rainfall, solar radiation, and light intensity, can substantially influence biomass productivity and culture stability [42,43]. High evaporation rates may increase the concentration of salts and dissolved nutrients and consequently alter the physicochemical conditions of the culture medium [20]. In comparison with closed cultivation systems, open ponds also provide more limited control over gas exchange, temperature, light exposure, nutrient distribution, and contamination, which can result in greater batch-to-batch variability and reduced process consistency [42,43].

Raceway pond systems

Raceway ponds represent one of the most widely adopted open cultivation configurations for commercial *Spirulina* (*Arthrospira*) biomass production because of their relatively simple design, scalability, and comparatively low operating costs [42,43]. These systems generally consist of shallow, elongated or oval-shaped channels equipped with paddle wheels that continuously circulate the culture medium. Continuous circulation promotes relatively uniform distribution of nutrients and cells, improves exposure of the culture to available light, facilitates gas exchange, and reduces cell sedimentation and the development of localized concentration gradients [43].

Successful operation of raceway systems requires appropriate control of important cultivation parameters, including pH, light availability, mixing rate, temperature, and nutrient concentration [20,43]. Maintaining alkaline conditions is particularly important for *Arthrospira* cultivation because this organism is well adapted to alkaline media, which can provide a selective advantage against some competing microorganisms [20,58]. Adequate light availability and penetration are essential for photosynthetic productivity, while appropriate circulation helps minimize cell settling and nutrient gradients within the pond [42]. Balanced nutrient availability supports biomass formation and can influence the accumulation of proteins and photosynthetic pigments, including phycocyanin [20,58].

Raceway systems offer several advantages for industrial *Spirulina* production, including relatively low construction and operating costs, simple operational design, scalability, and lower energy requirements than many closed photobioreactor systems [42,43]. However, productivity and culture stability remain strongly dependent on climatic conditions, including solar radiation and temperature. In addition, open raceway systems provide less control over contamination and environmental fluctuations than closed cultivation systems, which may affect biomass productivity, consistency, and product quality [43].

Closed photobioreactor systems

Closed photobioreactor systems provide greater control over cultivation parameters and can achieve higher biomass productivity than open cultivation systems under appropriately optimized conditions [42,43]. These systems reduce the exposure of cultures to external contaminants and allow more precise regulation of environmental factors such as light availability, temperature, carbon dioxide supply, pH, and nutrient concentration [42]. Common photobioreactor configurations include tubular, flat-panel, and column reactors, each offering different advantages in terms of light utilization, gas transfer, mixing, scalability, and process control [42,43].

Quantitative comparisons further demonstrate the potential productivity advantage of closed systems under specific operating conditions. In a recent comparative study of *Arthrospira platensis*, a closed tubular photobioreactor achieved a maximum biomass concentration of 3.50 g L^{-1} and an average biomass productivity of 0.457 g L^{-1} day^{-1}, compared with 1.32 g L^{-1} and 0.073 g L^{-1} day^{-1}, respectively, in an open cultivation system [14]. Based on the reported average productivity values, the closed system achieved approximately 6.26-fold higher biomass productivity than the open system under the experimental conditions evaluated. However, these values are system- and condition-specific and should not be interpreted as universally representative of all closed and open cultivation systems.

Despite the productivity and environmental-control advantages of closed photobioreactors, their higher capital, operational, and maintenance requirements can limit their economic feasibility for bulk biomass production [42]. In contrast, open and raceway pond systems remain attractive for large-scale *Spirulina* production because of their relatively simple design, lower investment requirements, and established scalability [20,43]. Therefore, cultivation-system selection involves a trade-off between productivity and process control on one hand and economic and operational simplicity on the other [42,43].

Tubular photobioreactors

Tubular photobioreactors consist of transparent tubes through which the *Spirulina* culture circulates. Their large illuminated surface area can enhance light utilization and photosynthetic productivity, while controlled gas transfer can improve carbon dioxide utilization and reduce direct exposure to external contaminants compared with open systems [42,43]. However, important limitations include oxygen accumulation, biofilm formation on illuminated surfaces, pressure and pumping requirements, and increased cleaning and maintenance demands [42].

Flat-panel photobioreactors

Flat-panel photobioreactors provide a high surface-area-to-volume ratio and efficient light penetration because of their relatively short optical path length. These characteristics can support high biomass productivity and make such systems attractive for the production of high-value compounds, including pigments and other bioactive metabolites [42,43]. Additional advantages include relatively efficient gas transfer and improved control of cultivation conditions. However, large-scale implementation can be constrained by panel construction costs, sealing requirements, culture circulation, and difficulties associated with maintaining uniform environmental conditions across large panels.

Column photobioreactors

Column photobioreactors generally consist of vertically oriented vessels in which mixing and gas transfer are achieved through controlled aeration. They can provide effective gas–liquid mass transfer, relatively uniform mixing, reduced contamination compared with open systems, and convenient operation at laboratory and pilot scales [42,43]. However, scale-up to very large industrial volumes can be challenging because of limitations related to light penetration, reactor geometry, gas distribution, and maintaining uniform cultivation conditions throughout the vessel.

Hybrid cultivation systems

Hybrid cultivation systems combine features of open and closed cultivation approaches to integrate the economic advantages and scalability of open systems with the greater environmental control offered by closed photobioreactors [42,43]. A typical strategy involves biomass production in relatively low-cost open ponds, followed by controlled cultivation or processing stages designed to enhance the accumulation or recovery of specific high-value compounds, such as pigments and other bioactive metabolites [42,43]. Such systems may provide a practical compromise between the lower production costs and scalability of open systems and the improved control of environmental and cultivation parameters achievable in closed photobioreactors [42,43].

However, the overall performance of a hybrid system depends strongly on its process configuration, operating conditions, target product, and the additional costs associated with biomass transfer, intermediate processing, and system integration. Therefore, hybrid approaches should be evaluated using parameters such as biomass productivity, target-product yield, process complexity, energy consumption, resource utilization, and overall economic feasibility rather than being assumed to be inherently more efficient than single-system approaches [42]. Hybrid cultivation strategies are also relevant to integrated microalgal biorefinery concepts, in which a single biomass feedstock is fractionated or processed to recover multiple valuable products, thereby potentially improving overall resource utilization and process economics [11,42].

Future trends in spirulina cultivation

Recent advances in *Spirulina* (*Arthrospira*) cultivation increasingly focus on developing sustainable, resource-efficient, and economically viable production systems. Emerging approaches include the use of appropriately treated wastewater or nutrient-rich waste streams as cultivation inputs, carbon dioxide supplementation or utilization of industrial CO_2 sources, automated monitoring and control systems, artificial intelligence (AI)- and data-driven process optimization, and integrated biorefinery strategies [11,12,43]. Wastewater-based cultivation can potentially reduce freshwater and inorganic nutrient requirements while simultaneously contributing to nutrient recovery; however, feedstock composition, contaminant removal, biosafety, and regulatory requirements must be carefully evaluated before biomass is considered suitable for food or nutraceutical applications [12]. Similarly, CO_2 supplementation can enhance carbon availability and potentially improve biomass productivity when appropriately matched with light, pH, and gas-transfer conditions [43]. Automated sensing and process-control technologies can facilitate real-time monitoring of parameters such as pH, temperature, dissolved oxygen, light, and biomass concentration, thereby improve process consistency and reduce manual intervention [42]. More recently, artificial intelligence, machine learning, and digitalization have emerged as potential tools for predicting biomass productivity, optimizing cultivation parameters, detecting process deviations, and supporting data-driven operation of microalgal cultivation systems [11,48]. Integrated biorefinery approaches further aim to improve resource utilization and economic feasibility by recovering multiple value-added products, including proteins, pigments, lipids, carbohydrates, and bioactive compounds, from a single *Spirulina* biomass stream [11,42]. Collectively, these strategies have the potential to improve productivity, reduce resource consumption and environmental impacts, and support more sustainable large-scale *Spirulina* production, although their commercial implementation remains dependent on process economics, technological maturity, product quality requirements, and regulatory considerations.

Environmental and nutritional factors affecting spirulina growth and biomass productivity

The growth, biochemical composition, and productivity of *Arthrospira platensis* are strongly influenced by environmental and nutritional conditions. As a photoautotrophic cyanobacterium, *A. platensis* depends on the interaction among light availability, temperature, pH, inorganic carbon supply, nutrient composition, and other cultivation parameters for efficient biomass production [20,58]. These factors regulate photosynthetic activity, cellular metabolism, pigment biosynthesis, protein accumulation, and the production of other bioactive compounds [33,42].Optimization of environmental and nutritional conditions is therefore essential for achieving high biomass productivity while maintaining the desired biochemical composition and quality of *Spirulina*-derived products [20,42].

In commercial cultivation systems, maintaining an appropriate balance between growth-promoting conditions and metabolic stimulation is important because changes in environmental conditions can substantially alter the biochemical profile of *Arthrospira* [33,58]. Under favourable growth conditions, *Arthrospira* can accumulate substantial amounts of protein-rich biomass, whereas appropriately controlled stress or nutrient-modification strategies may alter the accumulation of specific metabolites, including carotenoids, phycobiliproteins, lipids, and antioxidant-related compounds [3,33]. Therefore, cultivation strategies should be designed according to the intended application of the biomass, such as nutritional supplements, natural pigment production, nutraceutical or pharmaceutical research, and agricultural biostimulants applications [20,42].

(Table 7)

Influence of light intensity and photoperiod

Light is one of the most critical environmental factors controlling *Arthrospira platensis* growth because it provides the energy required for photosynthesis and influences cellular metabolism and pigment synthesis [42,58]. Both light intensity and photoperiod affect biomass productivity and biochemical composition. Excessive light can cause photoinhibition and photooxidative stress, potentially reducing photosynthetic efficiency and damaging cellular components, whereas insufficient light limits photosynthetic activity and can decrease biomass productivity [33,58]. Therefore, optimization of light intensity and light–dark cycles are important for maintaining efficient photosynthetic activity and achieving the desired biomass and pigment productivity.

Carbon source and utilization

The major inorganic carbon sources available to *Arthrospira* include dissolved carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}), with their relative availability being strongly influenced by the pH and chemical composition of the cultivation medium [20,42]. In commercial cultivation systems, sodium bicarbonate is widely used as a carbon source because it provides inorganic carbon while contributing to the buffering capacity and alkaline conditions favourable for *Arthrospira* growth [20,58].

CO_2 supplementation has also received considerable attention as a strategy for increasing inorganic carbon availability and potentially improving photosynthetic productivity and biomass accumulation when appropriately matched with cultivation conditions [42,43]. Additional CO_2 supply can enhance carbon availability and support higher growth rates under optimized conditions; however, the response depends on factors such as CO_2 concentration, gas-transfer efficiency, pH, light availability, temperature, and nutrient status [43]. Therefore, excessive CO_2 supplementation should be avoided because rapid acidification of the culture medium can adversely affect *Arthrospira* growth.

Integration of *Arthrospira* cultivation with industrial CO_2 sources represents an emerging strategy for coupling carbon utilization with biomass production. However, the suitability of industrial CO_2 streams depends on gas composition, contaminant levels, pretreatment requirements, and regulatory considerations, particularly when biomass is intended for food or nutraceutical applications [11,42]. Efficient carbon utilization is therefore an important consideration in the development of sustainable *Arthrospira* production systems. Integration of carbon recycling with nutrient recovery from appropriately treated wastewater and biomass production may further contribute to circular bioeconomy models by reducing resource consumption and recovering valuable nutrients and carbon [11,12].

Nitrogen availability and its influence on biomass composition

Nitrogen is one of the most important nutrients regulating the growth, biomass productivity, and biochemical composition of *Arthrospira platensis*. It is required for the synthesis of proteins, nucleic acids, enzymes, chlorophyll-*a*, and phycobiliproteins [42,58]. Because protein constitutes a major fraction of *Arthrospira* biomass, nitrogen availability can substantially influence biomass quality and nutritional value [3,20]. Different nitrogen sources, including nitrate salts, ammonium salts, and urea, have been investigated or used in *Arthrospira* cultivation media, with their suitability depending on concentration, pH, strain, and cultivation conditions [42,33].

Under nitrogen-sufficient conditions, adequate nitrogen availability supports protein biosynthesis, biomass formation, and the production of nitrogen-containing photosynthetic pigments, including phycobiliproteins such as phycocyanin [33,58].

Phycobiliproteins are particularly responsive to cellular nitrogen status because they contain substantial amounts of nitrogen and can function as intracellular nitrogen reserves in cyanobacteria [19]. When nitrogen becomes limiting, cyanobacteria can undergo degradation of phycobiliproteins through a process known as bleaching or Phycobilisomes degradation, resulting in reduced phycobiliprotein and pigment content. Nitrogen limitation can also reduce protein accumulation and redirect cellular carbon toward storage compounds, including carbohydrates, depending on the severity and duration of the stress and the physiological state of the organism [33].

These responses represent adaptive mechanisms that allow *Arthrospira* and other cyanobacteria to redistribute cellular resources under nutrient-deficient conditions [19]. Although nitrogen limitation generally reduces protein and phycocyanin productivity, controlled nitrogen stress can be investigated as a cultivation strategy for modifying biomass composition and increasing the relative accumulation of selected storage or stress-associated metabolites [33]. Therefore, precise nitrogen management is important for directing *Arthrospira* metabolism toward specific production objectives, including high-protein biomass, pigment production, or the accumulation of selected value-added metabolites.

Phosphorus and mineral requirements

Phosphorus is an essential macronutrient required for energy metabolism, nucleic acid synthesis, membrane formation, and several cellular regulatory processes. Adequate phosphorus availability supports ATP metabolism, nucleic acid biosynthesis, membrane development, and active cell division, thereby contributing to efficient biomass formation in *Arthrospira platensis* [33,42]. In addition to nitrogen and phosphorus, *Arthrospira* requires a range of macronutrients, minerals, and trace elements to maintain normal physiological and metabolic functions. Elements such as magnesium, iron, calcium, potassium, sodium, sulphur, and zinc participate in enzymatic reactions, ion balance, photosynthesis, electron transport, and other cellular processes [20,58].

Magnesium plays a central role in photosynthesis because it forms the central metal ion of the chlorophyll-*a* molecule and is also involved in several enzyme-catalysed reactions [43]. Iron is essential for photosynthetic and respiratory electron-transfer processes and is required for the activity of several iron-containing proteins and enzymes involved in cellular metabolism and pigment biosynthesis [42,43]. Other mineral nutrients and trace elements function as enzyme cofactors, contribute to osmotic and ionic regulation, and influence cellular growth and biochemical composition [20,42].

The mineral composition and availability of nutrients in the cultivation medium can influence both the physiological performance and nutritional composition of *Arthrospira* biomass [3,20]. Therefore, appropriate optimization of phosphorus, mineral, and trace-element supplementation is important for maintaining productive cultivation and obtaining biomass with the desired nutritional and biochemical characteristics. However, nutrient supplementation should be balanced because excessive concentrations of individual minerals may disturb ionic balance or negatively affect cell growth. Nutrient management should consequently be optimized according to the strain, cultivation system, medium composition, and intended commercial application.

Molecular approaches and strain improvement

Strain improvement strategies

Adaptive laboratory evolution (ALE) is a non-genetic strain-improvement approach in which microbial populations are subjected to defined selective environmental conditions over successive generations, allowing naturally occurring genetic variation and selection to enrich phenotypes with desirable characteristics [7]. In *Arthrospira*, ALE and related adaptive approaches have potential for improving tolerance to environmental stresses such as elevated temperature, salinity, and nutrient fluctuations, as well as for improving biomass productivity and resource-use efficiency. Genetic engineering, in contrast, aims to modify specific genes or metabolic pathways to redirect cellular metabolism toward desired products or phenotypes. Potential engineering targets in cyanobacteria include pathways associated with photosynthetic carbon fixation, pigment biosynthesis, stress responses, and carbon metabolism, which could theoretically be manipulated to enhance biomass productivity, phycocyanin or carotenoid accumulation, and environmental tolerance [16,51].

Despite these opportunities, genetic engineering of *Arthrospira* remains technically challenging compared with established genetic model organisms. Important limitations include transformation efficiency, genetic stability, availability of suitable promoters and selectable markers, limited genome-editing toolkits, and difficulties in achieving predictable expression of heterologous or modified pathways [51,52]. In addition, regulatory requirements, biosafety considerations, intellectual-property issues, and public acceptance may influence the commercial development of genetically modified *Arthrospira* strains. Consequently, further development of reliable genetic tools and comprehensive evaluation of strain stability and safety will be necessary before engineered strains can be widely adopted for commercial production.

Molecular approaches for quality control and future perspectives

Molecular techniques are increasingly valuable for the authentication, traceability, and quality assessment of commercial *Spirulina* products. DNA-based approaches, including PCR, DNA barcoding, sequencing, and metagenomic analysis, can support species or strain identification, detection of unwanted microbial contaminants, verification of production strains, and characterization of microbial communities associated with cultivation systems [43,52]. These approaches are particularly relevant because commercial *Spirulina* products may differ in strain identity, nutritional composition, pigment concentration, and microbiological quality depending on cultivation conditions, processing methods, and product formulation.

Future molecular research is expected to increasingly integrate genome sequencing, comparative genomics, transcriptomics, metabolomics, and genome-assisted strain selection to identify genetic determinants associated with high biomass productivity, pigment accumulation, stress tolerance, and improved resource utilization [52]. Artificial intelligence and machine-learning approaches may further support the prediction of strain performance and optimization of cultivation conditions when combined with sufficiently large and reliable datasets. Synthetic biology and metabolic-engineering approaches may also provide opportunities to improve pigment biosynthesis, carbon fixation, stress tolerance, and production of other value-added compounds. The integration of molecular biotechnology with controlled cultivation, digital monitoring, and downstream processing could therefore contribute to the development of more productive, climate-resilient, and sustainable *Spirulina*-based biorefineries, although technical, economic, biosafety, and regulatory barriers must still be addressed.

Industrial applications of spirulina

Spirulina (*Arthrospira*) has been investigated and commercially utilized across several industrial sectors because of its high protein content, bioactive compounds, natural pigments, and adaptability to diverse cultivation systems [3,20]. Its nutritional composition includes proteins, essential amino acids, vitamins, minerals, pigments, polyunsaturated fatty acids, and other biologically active compounds, supporting applications in food, nutraceuticals, pharmaceuticals, animal nutrition, cosmetics, agriculture, and other biotechnology-related sectors [3,20,48]. The development of improved cultivation systems, extraction technologies, purification processes, and downstream processing methods has further increased interest in *Spirulina* as a multifunctional microbial biomass resource [11,43].

Increasing demand for alternative protein sources and naturally derived bioactive ingredients has contributed to continued research and commercial interest in *Spirulina* biomass [3,7]. Unlike conventional terrestrial agricultural systems, *Spirulina* can be cultivated in aquatic production systems and therefore has the potential to reduce dependence on arable land; however, the magnitude of this advantage depends strongly on cultivation technology, geographical conditions, nutrient inputs, water-management practices, harvesting efficiency, drying requirements, and downstream processing [7,11]. Consequently, claims regarding lower land, freshwater, energy, or greenhouse-gas requirements should be evaluated using system-specific life-cycle and techno-economic assessments rather than being considered universal characteristics of *Spirulina* production.

The ability of *Arthrospira* to grow efficiently under alkaline conditions and, depending on the strain and cultivation medium, relatively elevated salinity provides opportunities for production in environments that may be unsuitable for some conventional crops [20,58]. Furthermore, *Spirulina*-based production systems may contribute to circular bioeconomy strategies through carbon dioxide utilization, nutrient recovery from appropriately treated waste streams, and integrated valorization of biomass into multiple value-added products [11,12]. However, the environmental and economic benefits of these approaches remain dependent on appropriate process integration, resource efficiency, product safety, and overall system performance.

Quantitative Sustainability Evidence

Recent life-cycle assessment studies provide quantitative evidence that the environmental performance of *Spirulina* can be favourable under appropriately designed production systems, although substantial variation occurs among cultivation configurations. In a large-scale geothermal-integrated *Spirulina* production system in Iceland, production of 1 kg of wet edible biomass required approximately 0.0378 m^2 of non-arable land, 8.36 m^3 of freshwater, and 54.48 kWh of electricity under the assessed system boundary. The cultivation stage accounted for 77.36% of land use, 63.63% of freshwater use, and 87% of electricity consumption, demonstrating that cultivation efficiency and energy management are critical determinants of overall environmental performance [54].

A more recent cradle-to-consumer comparative life-cycle assessment evaluated industrial, geothermal, artisanal, and Perma cultural *Spirulina* systems using 1 kg of protein as the functional unit. The best-performing *Spirulina* configuration reported a global-warming impact of 4.56 kg CO_2-equivalent per kg protein, compared with 187.17 kg CO_2-equivalent per kg protein for beef, corresponding to up to approximately 98% lower greenhouse-gas emissions. Land use was reported as 0.25 m^2·year crop-equivalent per kg protein compared with 116.95 m^2·year crop-equivalent per kg protein for beef, representing more than 99% lower land use. Importantly, the study also demonstrated substantial differences among *Spirulina* production systems: relative to the industrial baseline, global-warming impacts were reduced by approximately 56–82% and land use by 26–73%, depending on the production configuration. These findings demonstrate both the potential sustainability advantage of *Spirulina* and the importance of production-system design when interpreting environmental performance [56].

These results indicate that *Spirulina* should not simply be described as an inherently low-impact protein source. Instead, sustainability should be evaluated using defined functional units and quantitative indicators, including land use (m^2 kg^{-1} biomass or protein), freshwater consumption (L or m^3 kg^{-1} biomass), electricity or total energy demand (kWh kg^{-1} biomass), greenhouse-gas emissions (kg CO_2-equivalent kg^{-1} biomass or protein), and nutrient-recovery efficiency. Such indicators allow comparisons among production systems and help identify the stages responsible for the largest environmental burdens [54,56].

Sustainability indicator	Unit	Reported quantitative evidence	Sustainability significance
Land requirement	m^2 kg^{-1} wet biomass	0.0378 in geothermal-integrated production	Indicates potential for production on non-arable land
Freshwater requirement	m^3 kg^{-1} wet biomass	8.36 in the assessed geothermal system	Demonstrates that water demand should be explicitly quantified
Electricity demand	kWh kg^{-1} wet biomass	54.48 in the assessed geothermal system	Identifies energy demand as an important process parameter
GHG emissions	kg CO_2-eq kg^{-1} protein	4.56 in the best-performing *Spirulina* configuration	Provides a standardized climate-impact indicator
Beef comparison—GHG emissions	% reduction	Up to ~98% lower	Indicates potential climate advantage under the assessed LCA conditions
Land use	m^2·year crop-eq kg^{-1} protein	0.25 in the assessed best-performing *Spirulina* system	Indicates low land occupation per unit of protein
Beef comparison—land use	% reduction	>99% lower	Indicates potential land-use advantage under the assessed conditions
Global-warming impact vs. industrial *Spirulina* baseline	% reduction	56–82% depending on production system	Demonstrates strong configuration-dependent differences

Phosphate removal from aquaculture bio floc effluent	%	Approximately 90% after 20 days	Demonstrates nutrient-recovery potential
Biomass concentration in bio floc effluent	$g\ L^{-1}$	0.50 ± 0.59	Demonstrates simultaneous biomass generation
Ammonium removal from agro-industrial digestate	%	Up to 97%	Demonstrates nitrogen recovery from waste-derived nutrients
Phosphate removal from agro-industrial digestate	%	Up to 100%	Demonstrates phosphorus recovery potential

Table 8: Quantitative sustainability indicators reported for *Spirulina* production and environmental applications.

The numerical values in Table 8 are derived from individual studies and therefore should not be interpreted as universal performance values. Differences in system boundaries, functional units, climate, cultivation configuration, nutrient sources, water-reuse strategies, and downstream processing can substantially alter environmental performance. The use of standardized functional units is therefore essential for reliable comparison among *Spirulina* production systems [54,56].

Food and nutraceutical applications

Spirulina is widely recognized as a nutrient-dense functional food ingredient because of its high protein content and diverse biochemical composition. The protein content of *Spirulina* biomass generally ranges from 55–70% of dry weight, although the exact value varies according to strain, cultivation conditions, harvesting stage, and processing method [3,20]. In addition to protein, *Spirulina* contains essential amino acids, γ-linolenic acid, vitamins, minerals, carotenoids, phycocyanin, and other bioactive compounds that contribute to its nutritional and functional properties [27,48]. The incorporation of *Spirulina* into food products has attracted increasing interest in the context of alternative proteins, naturally derived ingredients, and functional-food development [7,27].

Spirulina biomass is commercially available in forms including powders, tablets, capsules, extracts, and fortified food products. It has been incorporated or investigated as an ingredient in protein supplements, energy bars, beverages, bakery products, dairy and dairy-alternative products, and other functional foods [7,27]. The presence of bioactive constituents further contributes to the nutraceutical potential of *Spirulina*. Phycocyanin, carotenoids, phenolic compounds, polysaccharides, and peptides have demonstrated antioxidant and other biological activities in experimental studies [48,60]. *Spirulina*-derived peptides generated through enzymatic hydrolysis have also demonstrated antioxidant, antihypertensive, and anti-inflammatory activities, although the strength of evidence varies among individual peptides and experimental models [48]. Therefore, these activities should not automatically be interpreted as established therapeutic effects in humans.

The demand for natural food colourants has also increased the commercial value of *Spirulina*-derived C-phycocyanin. Unlike synthetic dyes, phycocyanin provides natural blue pigmentation together with potential functional properties, making it attractive for applications in naturally coloured and clean-label food formulations [38]. It has been investigated for use in beverages, confectionery products, dairy products, frozen desserts, and nutritional products. However, sensory acceptance, pigment stability, regulatory requirements, production cost, and consumer acceptance remain important challenges for broader application [38]. Consequently, current research continues to focus on improved extraction, purification, stabilization, encapsulation, formulation, and sensory optimization technologies to improve the practical utilization of *Spirulina*-derived pigments.

Pharmaceutical and biomedical applications

The bioactive molecules present in *Spirulina* have attracted considerable attention in pharmaceutical and biomedical research because of their reported antioxidant, anti-inflammatory, antimicrobial, immunomodulatory, and cytoprotective activities. However, the strength of evidence varies substantially among individual compounds and biological effects. *In vitro* studies have demonstrated biological activities associated with C-phycocyanin, polysaccharides, carotenoids, peptides, and other *Spirulina*-derived constituents, while animal studies have suggested potential immunomodulatory, hepatoprotective, neuroprotective, metabolic, and anti-inflammatory effects [48,60]. These findings provide important preclinical evidence but cannot by themselves establish therapeutic efficacy in humans.

Phycocyanin is one of the most extensively studied *Spirulina*-derived compounds because of its reported pharmacological activities. Experimental studies have demonstrated antioxidant and anti-inflammatory effects that have been associated with modulation of oxidative-stress pathways and inflammatory mediators [51,60]. However, much of the available evidence remains based on *in vitro* and preclinical models, and the extent to which these mechanisms translate into clinically meaningful effects in humans remains uncertain. Therefore, phycocyanin should currently be regarded as a bioactive compound under investigation rather than an established therapeutic agent.

Spirulina-derived compounds have also been investigated for potential anticancer effects. Cellular and animal studies have suggested that phycocyanin may influence apoptosis-related pathways, abnormal cell proliferation, oxidative stress, and other cellular processes [51,60]. Nevertheless, these observations require appropriate clinical validation before therapeutic conclusions can be drawn. Similarly, reported neuroprotective, metabolic, and immunomodulatory effects remain predominantly supported by experimental evidence [48].

Preclinical versus Clinical Evidence

The biological and therapeutic potential of *Spirulina* (*Arthrospira platensis*) should therefore be interpreted according to the level and quality of available evidence. Preclinical evidence includes *in vitro* cellular experiments and animal studies, whereas clinical evidence is derived from controlled investigations involving human participants. *In vitro* and animal studies provide mechanistic evidence for antioxidant, anti-inflammatory, antimicrobial, immunomodulatory, cytoprotective, hepatoprotective, neuroprotective, and metabolic effects, but such findings do not establish therapeutic efficacy in humans [48,60].

In contrast, clinical evidence for therapeutic applications of *Spirulina* remains comparatively limited and heterogeneous. Human studies have investigated *Spirulina* mainly as a nutritional supplement and have reported effects on selected metabolic, antioxidant, immune, and nutritional parameters; however, differences in study design, participant characteristics, intervention duration, dosage, and *Spirulina* preparation limit direct comparison among studies [48]. Consequently, human findings are more appropriately interpreted as evidence of nutritional effects, supplementation-related outcomes, tolerability, or preliminary physiological benefits, rather than definitive evidence for treatment of specific diseases.

Claims regarding the biomedical potential of *Spirulina* should therefore clearly identify the corresponding evidence level, and therapeutic claims should be expressed cautiously where robust human clinical evidence is insufficient. Well-designed randomized controlled trials using standardized preparations, clearly defined doses, appropriate control groups, clinically relevant endpoints, adequate sample sizes, and sufficient follow-up are required to establish clinical efficacy, safety, bioavailability, and long-term therapeutic outcomes.

Agricultural applications

The application of *Spirulina* in agriculture has emerged as an important research area because of its nutrient-rich composition and potential to support plant growth and stress tolerance. *Spirulina* biomass and extracts contain amino acids, peptides, minerals, vitamins, pigments, polysaccharides, and other bioactive compounds that have been investigated as biofertilizers and plant biostimulants [41,48]. *Spirulina*-based preparations have demonstrated potential to improve seed germination, root development, nutrient uptake, and plant growth under specific experimental conditions [41]. However, the magnitude of these effects depends on the *Spirulina* strain, formulation, application rate, crop species, and environmental conditions. The integration of *Spirulina* production with agricultural wastewater treatment also represents an emerging strategy for nutrient recycling and biomass generation, although application rates, long-term soil effects, contaminant risks, and product standardization require further validation.

Animal feed and aquaculture applications

Spirulina has been investigated as a protein-rich feed supplement for livestock, poultry, and aquaculture species. Its high protein content, essential amino acids, pigments, vitamins, minerals, and bioactive compounds make it a potentially valuable alternative or complementary feed ingredient [20,23]. In aquaculture, *Spirulina* supplementation has been investigated for its effects on growth performance, feed utilization, immune response, disease resistance, antioxidant status, and pigmentation [23,43]. Carotenoids, particularly β-carotene and zeaxanthin, may contribute to pigmentation in fish and crustaceans and are therefore of interest in aquaculture feed formulations [23].

In poultry and livestock production, *Spirulina* supplementation has also been investigated in relation to growth performance, antioxidant status, immune function, meat or egg quality, and overall animal health [20,23]. Nevertheless, the relatively high production cost of *Spirulina* compared with conventional feed ingredients remains an important constraint for large-scale adoption, particularly where *Spirulina* is used at high inclusion levels [20]. Improvements in cultivation productivity, nutrient recycling, strain selection, biomass processing, and incorporation into optimized feed formulations may improve its economic feasibility.

Cosmetic and personal care applications

The cosmetic and personal-care industries have shown increasing interest in *Spirulina* because of its natural pigments, antioxidant compounds, vitamins, proteins, and other bioactive molecules. *Spirulina* extracts and isolated compounds have been investigated for applications involving antioxidant protection and skin-care formulations [34]. Phycocyanin, carotenoids, chlorophyll derivatives, and other *Spirulina*-derived compounds contribute to the functional value of these ingredients because of their pigmentation and reported biological activities.

Spirulina-derived ingredients have been investigated for incorporation into formulations such as creams, masks, serums, and natural colour cosmetics [34]. However, pigment stability remains an important limitation, particularly for phycocyanin, which is sensitive to temperature, light, and pH [38]. Encapsulation, formulation optimization, and other stabilization technologies are therefore being investigated to improve pigment stability and extend the shelf life of *Spirulina*-derived cosmetic ingredients.

Environmental and biotechnological applications

Beyond nutritional and commercial applications, *Spirulina* has potential applications in environmental biotechnology because of its photosynthetic capacity, carbon assimilation, and ability to utilize inorganic nutrients. *Spirulina* cultivation can contribute to inorganic carbon utilization, wastewater nutrient recovery, and simultaneous biomass generation. Quantitative evidence is particularly relevant for wastewater-based cultivation because treatment performance depends strongly on wastewater composition and operating conditions.

In aquaculture bio floc effluent, *A. platensis* achieved approximately 90% phosphate removal after 20 days, with reported biomass concentrations of 0.50 ± 0.59 g L^{-1} in the untreated bio floc treatment and 0.18 ± 0.14 g L^{-1} in the decanted treatment [22]. Similarly, cultivation of *A. platensis* using agro-industrial anaerobic digestate resulted in reported ammonium removal of up to 97% and phosphate removal of up to 100% under the respective experimental conditions [29]. These findings demonstrate the potential of *Arthrospira* to combine nutrient recovery with biomass production; however, the reported removal efficiencies are system-specific and should not be interpreted as universal treatment capacities [22,29].

The integration of *Spirulina* cultivation with industrial processes also provides opportunities for sustainable biorefineries. Such systems aim to recover multiple products, including proteins, pigments, biofertilizers, lipids, carbohydrates, and other bioactive compounds from a single biomass source. Integrated biomass valorization may improve resource efficiency and potentially increase the economic value of the production process by reducing waste and diversifying product streams [11,27]. However, the sustainability of such integrated systems should be assessed using quantitative indicators covering nutrient recovery, biomass productivity, energy demand, water consumption, greenhouse-gas emissions, and downstream-processing requirements rather than relying solely on the number of products recovered.

Overall, the industrial applications of *Spirulina* continue to expand because of its nutritional value, functional properties, and potential contribution to circular and resource-efficient biotechnological systems. Available quantitative evidence supports substantial sustainability potential under selected cultivation configurations, particularly with respect to land use, greenhouse-gas emissions, nutrient recovery, and biomass valorization [54,56]. However, environmental performance varies considerably among production systems. Future industrial development should therefore prioritize standardized life-cycle assessment, resource-efficient cultivation, wastewater and nutrient recycling, renewable-energy integration, contaminant control, and complete biomass valorization.

Recent advances in spirulina research (2020–2026)

In recent years, research on *Spirulina* (*Arthrospira platensis*) has expanded beyond its traditional use as a nutritional supplement toward advanced biotechnology, sustainable cultivation, and integrated biorefinery approaches. During the period from 2020 to 2026, research has increasingly focused on improving cultivation efficiency, reducing environmental impacts, enhancing the recovery of valuable bioactive compounds, and developing applications in food technology, agriculture, biomedical research, and environmental biotechnology [11,27,48]. These developments have been supported by growing interest in alternative protein sources, natural bioactive ingredients, resource-efficient production, carbon utilization, and circular-bioeconomy approaches [7,54].

Modern *Spirulina* biotechnology increasingly focuses on maximizing biomass and product productivity while reducing production costs and environmental burdens. Conventional cultivation systems, particularly open and raceway ponds, remain important for large-scale production because of their relatively low capital and operating requirements; however, contamination, climatic variability, limited process control, and fluctuations in productivity remain important challenges [20,54]. Consequently, recent research has emphasized strain selection and improvement, optimization of cultivation parameters, controlled photobioreactor systems, automation, digital monitoring, and process integration to improve production reliability and product quality [27,54]. The integration of cultivation with wastewater nutrient recovery, carbon utilization, and downstream biomass valorization is also being investigated as a strategy for improving resource efficiency and supporting more sustainable *Spirulina*-based production systems [11,48].

Advantages	Challenges
High protein content	High production cost
Rapid biomass production	Contamination problems in open systems
Natural pigment production	Pigment instability
CO_2 fixation capability	Scale-up limitations
Sustainable cultivation	Regulatory challenges
Wastewater-based cultivation	High harvesting cost

Table 9: Advantages and Challenges of Spirulina Biotechnology.

Wastewater-Based Cultivation and Nutrient Recovery

Wastewater-based cultivation of *Spirulina* (*Arthrospira*) has emerged as a promising approach for integrating nutrient recovery, wastewater treatment, and biomass production, while potentially reducing the requirement for conventional freshwater and externally supplied nutrients. However, the magnitude of these potential benefits depends strongly on wastewater composition, pretreatment requirements, cultivation conditions, water-reuse practices, and downstream processing [32]. Reported treatment and biomass-production performance can vary considerably according to wastewater composition, nutrient availability, pretreatment, cultivation conditions, and reactor configuration. Therefore, quantitative performance should be evaluated on a study-specific basis rather than assuming a universal nutrient-removal efficiency.

Conventional *Spirulina* cultivation requires substantial nutrient inputs, particularly nitrogen and phosphorus, and the use of nutrient-rich wastewater has therefore been investigated as an alternative nutrient source while simultaneously supporting wastewater remediation and biomass production [32]. In this context, wastewater-based cultivation can contribute to circular-resource strategies by coupling nutrient recovery with biomass generation.

Recent studies have demonstrated substantial but variable nutrient-removal performance during *Arthrospira platensis* cultivation in different waste-derived media. In an aquaculture bio floc effluent, *A. platensis* achieved approximately 90% phosphate removal after 20 days, while final biomass concentrations were reported as 0.50 ± 0.59 g L^{-1} in the untreated bio floc treatment and 0.18 ± 0.14 g L^{-1} in the decanted treatment [22]. These findings demonstrate the potential of *A. platensis* to simultaneously produce biomass and reduce nutrient loads, while also showing that pretreatment of the effluent can influence biomass production.

Further evidence of nutrient recovery was reported for *A. platensis* cultivated using agro-industrial liquid anaerobic digestates. Under the reported experimental conditions, removal reached up to 97% for ammonium nitrogen and 100% for phosphate, with potassium removal of up to 66% [29]. These results demonstrate the potential of anaerobic digestate as an alternative nutrient source for *Arthrospira* cultivation; however, these removal efficiencies were obtained under specific wastewater characteristics and cultivation conditions and should therefore not be interpreted as universal treatment efficiencies.

The variation in reported biomass production and nutrient-removal efficiency indicates that wastewater composition, nutrient concentration, pretreatment, cultivation duration, light availability, and operating conditions can substantially influence process performance. Consequently, quantitative comparisons among studies should be interpreted in relation to their specific experimental conditions rather than as direct measures of the inherent treatment capacity of *Arthrospira*. For a comprehensive assessment of sustainability, nutrient-removal efficiency should be considered together with biomass productivity, nutrient recovery per unit biomass, water consumption, energy requirements, and greenhouse-gas emissions [32]. In particular, reporting nutrient removal only as a percentage does not account for differences in initial nutrient concentrations or cultivation duration among studies. Future studies should therefore report standardized indicators such as g N or P L^{-1} wastewater, g biomass L^{-1} day^{-1}, freshwater consumption per kg biomass, energy consumption per kg biomass, and kg CO_2-equivalent kg^{-1} biomass.

However, wastewater-based cultivation requires careful management because wastewater may contain heavy metals, pharmaceutical residues, pesticides, pathogenic microorganisms, and other emerging contaminants that could potentially accumulate in the harvested biomass. Consequently, high nutrient-removal efficiency alone is insufficient to establish the suitability of wastewater-grown *Arthrospira* biomass for food or nutraceutical applications [32]. Particular attention should be given to microbiological hazards and chemical contaminants, including lead, cadmium, mercury, arsenic, and other wastewater-derived toxic substances. The potential accumulation of contaminants is particularly important because *Spirulina* has demonstrated capacity for interacting with and accumulating heavy metals under contaminated conditions [5].

The safety assessment should therefore extend beyond the cultivation medium to the final harvested biomass, because removal of a contaminant from wastewater does not necessarily indicate its degradation; contaminants may instead be transferred to or associated with the biomass. Wastewater characterization and final-biomass testing should consequently be incorporated into the cultivation process. Depending on the wastewater source and intended application, microbiological quality assessment, heavy-metal analysis, and source-specific chemical-contaminant monitoring should be performed. Previous reviews have also emphasized that wastewater-based *Spirulina* systems require consideration of both wastewater treatment and biomass safety rather than evaluating nutrient removal alone [32].

The intended application is particularly important when assessing the suitability of wastewater-derived *Arthrospira*. Biomass intended for human food, dietary supplements, or nutraceutical applications requires substantially greater attention to microbiological and chemical safety than biomass intended for non-food applications. Wastewater-derived biomass should therefore not automatically be considered equivalent to conventionally cultivated food-grade *Arthrospira*. Recent research continues to identify contamination and heavy-metal accumulation as important considerations for the safety assessment of wastewater-grown *Spirulina* biomass. For non-food applications, wastewater-grown biomass may provide greater flexibility in wastewater selection, provided that the wastewater is appropriately characterized and the biomass satisfies the safety requirements applicable to its intended use.

Regulatory compliance and traceability should also be incorporated into wastewater-based *Arthrospira* production. Regulatory requirements may differ according to the intended application and jurisdiction and may include requirements concerning wastewater source and treatment, contaminant concentrations, microbiological quality, processing conditions, and the permitted end use of the biomass. A traceability system linking the wastewater source, pretreatment conditions, cultivation batch, analytical results, harvesting, and final product would strengthen quality assurance and facilitate regulatory assessment. Accordingly, appropriate microbiological and chemical quality-control testing, contaminant monitoring, documentation, and traceability should be established before wastewater-derived *Arthrospira* biomass is considered for food, feed, or nutraceutical use.

Overall, wastewater-based cultivation should be regarded not only as a nutrient-recovery and biomass-production strategy, but also as a process requiring integrated environmental, microbiological, chemical, and regulatory risk management.

Its sustainability potential is therefore best evaluated using a combination of nutrient-removal efficiency, biomass productivity, resource consumption, contaminant fate, product safety, and life-cycle environmental indicators rather than nutrient-removal percentages alone.

Hazard category	Examples	Main concern	Recommended control
Microbial	Pathogenic bacteria, viruses, protozoa	Foodborne/infectious risk	Pretreatment + microbiological testing
Heavy metals	Pb, Cd, Hg, As, Cr	Bioaccumulation/toxicity	Source control + biomass testing
Pesticides	Agricultural pesticide residues	Toxicity/residue accumulation	Wastewater characterization + residue analysis
Pharmaceuticals	Antibiotics, hormones, other residues	Persistence/accumulation	Source characterization + targeted analysis
Emerging contaminants	Industrial/organic contaminants	Unknown chronic effects	Source-specific monitoring
Biological contaminants	Undesirable cyanobacteria/microbial contaminants	Toxin or quality risk	Culture purity + appropriate screening
Processing contamination	Post-harvest microorganisms	Product spoilage/safety	Hygienic harvesting, drying and storage
Regulatory	Application-specific requirements	Market/legal non-compliance	Traceability + jurisdiction-specific compliance

Table 10: Major Food-Safety Hazards and Quality-Control Measures for Wastewater-Grown *Arthrospira*.

Integrated spirulina biorefinery approaches

The traditional *Spirulina* industry has primarily focused on producing dried biomass for nutritional applications. However, recent research has shifted toward integrated biorefinery concepts that aim to utilize the complete biomass and recover multiple high-value products from a single cultivation process. A *Spirulina*-based biorefinery approach involves sequential extraction and utilization of different cellular components, including proteins, pigments, lipids, carbohydrates, polysaccharides, and bioactive compounds. This strategy can improve economic feasibility by increasing product diversity and reducing biomass waste [24,56].

Protein recovery represents one of the major targets of *Spirulina* biorefineries because of its high abundance and nutritional value. Extracted proteins can be used in functional foods, dietary supplements, and alternative protein formulations. In addition, protein hydrolysates generated through enzymatic treatment can produce bioactive peptides with antioxidant, antihypertensive, and antimicrobial properties, although the biological effects depend on the peptide composition and experimental model [6,28]. Pigment extraction, particularly phycocyanin recovery, represents another important component of *Spirulina* biorefineries. The increasing demand for natural colorants has stimulated research into efficient extraction, purification, stabilization, and formulation technologies for producing high-quality phycocyanin [20,38]. The lipid fraction of *Spirulina*, although relatively low compared with some other microalgae, contains valuable fatty acids and other bioactive molecules that can contribute to the overall valorization of the biomass [20,24].

Limitations, research gaps, and future directions

Limitations of current evidence

Several limitations should be considered when interpreting the current evidence on *Spirulina* (*Limnospira*) biotechnology. First, substantial variation exists among strains, cultivation systems, wastewater compositions, environmental conditions, harvesting procedures, extraction methods, and analytical protocols. Consequently, biomass productivity, biochemical composition, pigment recovery, nutrient-removal efficiency, and environmental performance reported in individual studies cannot always be directly compared [24,38,56].

Second, much of the evidence supporting the biomedical activities of *Spirulina* and phycocyanin remains derived from *in vitro* and animal studies. Although these studies provide mechanistic and preclinical evidence, they do not establish therapeutic efficacy in humans. Human clinical evidence remains comparatively limited, and standardized preparations, doses, clinical endpoints, and sufficiently powered randomized trials are required to establish clinical relevance [20,45,60].

Third, sustainability claims remain sensitive to system boundaries and production configuration. Land use, freshwater demand, energy consumption, carbon emissions, nutrient inputs, harvesting, drying, and downstream processing can vary substantially among open ponds, raceway systems, closed photobioreactors, and integrated wastewater-based systems. Therefore, the environmental advantages of *Spirulina* should be evaluated using standardized life-cycle assessment methodologies and clearly defined functional units [24,56].

Wastewater-based cultivation introduces additional limitations related to feedstock variability, contaminant accumulation, microbiological safety, pretreatment requirements, and regulatory compliance. High nutrient-removal efficiency does not necessarily indicate that the resulting biomass is suitable for human food or nutraceutical applications. Source-specific chemical and microbiological monitoring is therefore essential [22,29].

Finally, large-scale commercialization continues to be constrained by production cost, contamination control, harvesting and dewatering requirements, pigment stability, extraction efficiency, product standardization, and regulatory differences among markets. These limitations indicate that laboratory-scale performance should not automatically be interpreted as evidence of industrial or commercial feasibility [24,38].

Research gaps

Important research gaps remain in the development of robust *Spirulina* bioprocesses. Harmonized cultivation and analytical protocols are needed to enable reliable comparison of biomass productivity, biochemical composition, pigment concentration, nutrient recovery, and environmental performance among studies. Greater emphasis should also be placed on strain-resolved characterization because taxonomic identity, genotype, and physiological characteristics can strongly influence productivity and metabolite accumulation [24,52].

For wastewater-based cultivation, future studies should quantify nutrient recovery using mass-based indicators such as g N or P recovered per litre of wastewater and per unit biomass, while simultaneously evaluating contaminant accumulation, water reuse, energy consumption, and greenhouse-gas emissions. Long-term pilot- and demonstration-scale studies are needed to determine whether laboratory-scale nutrient-removal results remain stable under seasonal and operational variability [22,29].

In biomedical research, future work should prioritize standardized *Spirulina* and phycocyanin preparations, dose-response studies, bioavailability assessments, well-powered randomized controlled trials, and clinically relevant endpoints. This would help distinguish nutritional effects from established therapeutic effects [45,60].

For industrial development, research should focus on improving harvesting, dewatering, drying, pigment stabilization, extraction selectivity, process integration, and economic feasibility. Integrated biorefineries should be evaluated using combined techno-economic and life-cycle assessments rather than considering product recovery alone [24,38,56].

Future Directions

Future research should prioritize strain-specific improvement, precision cultivation, digital monitoring, and data-driven process optimization. Adaptive laboratory evolution, genomics, transcriptomics, metabolomics, and carefully controlled metabolic engineering may provide opportunities to improve biomass productivity, stress tolerance, pigment accumulation, and nutrient-use efficiency. However, technological improvements should be evaluated alongside regulatory, economic, and biosafety considerations [52].

Integrated production systems combining wastewater nutrient recovery, carbon utilization, renewable energy, water recycling, and multiproduct biomass valorization represent an important research direction [24,29]. The development of standardized sustainability metrics, harmonized nomenclature, reproducible analytical methods, and validated scale-up strategies will be necessary to determine the actual contribution of *Spirulina* biotechnology to sustainable food, environmental, and bio-based production systems [24,56].

Conclusion

Spirulina, including commercially important *Limnospira* taxa historically reported as *Arthrospira*, is a nutritionally valuable cyanobacterial biomass with established applications in food, feed, pigments, nutraceutical products, agriculture, cosmetics, and environmental biotechnology. Its high protein content and production of commercially relevant compounds such as C-phycocyanin provide a strong basis for continued technological development. However, the magnitude of these benefits varies according to strain, cultivation conditions, biomass processing, extraction technology, and intended application.

The available evidence supports the feasibility of using *Spirulina* for biomass production, pigment recovery, and nutrient removal from selected wastewater streams. Quantitative studies demonstrate substantial phosphate and ammonium removal under specific experimental conditions, while life-cycle assessments indicate that some *Spirulina* production configurations can achieve favourable land-use and greenhouse-gas performance relative to conventional protein production. Nevertheless, these advantages are not universal. Water consumption, energy demand, harvesting, drying, nutrient inputs, pretreatment, downstream processing, and system boundaries can substantially influence overall environmental performance.

Evidence for biomedical applications should also be interpreted according to study type. Many reported antioxidant, anti-inflammatory, immunomodulatory, hepatoprotective, neuroprotective, and anticancer effects remain primarily supported by *in vitro* and animal studies. The available human evidence is more limited and is insufficient to support broad therapeutic claims for specific diseases. Consequently, *Spirulina* and phycocyanin are better characterized at present as nutritionally and biologically active ingredients with therapeutic research potential rather than established therapeutic agents.

Wastewater-based cultivation represents an important research direction because it may combine nutrient recovery with biomass production; however, contaminant accumulation, microbiological safety, wastewater variability, pretreatment, regulatory requirements, and final-biomass quality must be considered simultaneously. Similarly, integrated biorefinery approaches may improve resource utilization and economic feasibility, but their environmental and economic benefits require validation through standardized techno-economic and life-cycle assessments.

Future research should therefore focus on standardized nomenclature and analytical methods, strain-specific characterization, reproducible scale-up studies, improved harvesting and downstream processing, contaminant and safety assessment of wastewater-derived biomass, rigorous clinical evaluation of biomedical claims, and integrated environmental and economic assessments. Overall, current evidence supports *Spirulina* as a versatile and technically promising biomass platform, but further standardized, long-term, and scale-relevant studies are required to establish the extent to which its proposed nutritional, environmental, and industrial advantages can be translated into robust and commercially sustainable applications.

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