



# Biotechnological Applications, Nutritional Significance, and Pharmacological Properties of *Spirulina platensis* Isolated from Soda Lake Ecosystems: A Review

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## Abstract

*Spirulina platensis* (*Arthrospira platensis*) is a filamentous cyanobacterium widely acknowledged for its high nutritional composition and diverse range of biologically active compounds. The growing worldwide interest in sustainable protein alternatives, natural medicinal products, and environmentally friendly biotechnological resources has significantly increased research attention toward microalgae with industrial and therapeutic importance. In this context, soda lakes provide distinctive ecological habitats characterized by strong alkalinity, high salinity, and carbonate-rich conditions that support the growth of alkaliphilic cyanobacteria, particularly *S. platensis*.

Recent ecological and biochemical studies have revealed that isolated soda lakes serve as rich natural sources of uniquely adapted *Spirulina* strains possessing improved nutritional, biochemical, and pharmacological characteristics. These strains are known to contain substantial amounts of proteins, essential amino acids, vitamins, minerals, pigments, antioxidants, and other valuable metabolites with potential applications in food, pharmaceutical, cosmetic, and environmental industries. Furthermore, bioactive compounds derived from *S. platensis* exhibit several therapeutic properties, including antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, and anticancer activities.

This review highlights the biotechnological relevance, nutritional importance, and pharmacological potential of *Spirulina platensis* isolated from soda lake environments, emphasizing its promising role in sustainable health, industrial biotechnology, and future therapeutic developments

## Objective

This review comprehensively evaluates existing scientific knowledge concerning the ecological adaptation, cultivation feasibility, biochemical characteristics, nutritional importance, biotechnological utility, and pharmacological relevance of *Spirulina platensis* obtained from soda lake habitats.

## Key Findings

The highly alkaline nature (pH > 9) and increased carbonate/bicarbonate content of soda lakes trigger adaptive metabolic responses in *S. platensis*, leading to greater synthesis of commercially valuable metabolites such as C-phycocyanin, carotenoids, essential amino acids, gamma-linolenic acid (GLA), vitamins, and antioxidant molecules. These biochemical enhancements substantially increase its applicability in nutraceutical,



pharmaceutical, cosmetic, agricultural, and industrial fields. In addition, experimental investigations have reported remarkable antioxidant, anti-inflammatory, antimicrobial, immunoregulatory, anticancer, and neuroprotective effects associated with strains isolated from soda lake ecosystems.

## Conclusion

Soda lake ecosystems represent naturally enriched and sustainable reservoirs of high-value *Spirulina platensis*. The incorporation of advanced cultivation technologies, omics-based strain analysis, and integrated biorefinery systems may significantly improve industrial utilization and therapeutic applications. Future efforts should emphasize clinical verification and development of scalable downstream processing methods to fully realize the bioeconomic importance of this extremophilic cyanobacterium.

## Keywords

*Spirulina platensis*; *Arthrospira platensis*; Soda lakes; Extremophilic cyanobacteria; Phycocyanin; Nutraceutical applications; Pharmacological activities; Biorefinery technology; Microalgae biotechnology

## 1. Introduction

Rapid population growth and increasing stress on conventional agricultural resources have intensified the need for sustainable nutritional sources and naturally derived therapeutic compounds. Among various biological resources, microalgae have emerged as highly promising due to their rapid biomass productivity, efficient photosynthetic capacity, low land requirements, and extensive biochemical diversity. Within this group, *Spirulina platensis* (*Arthrospira platensis*) has attracted considerable scientific and industrial interest because of its rich nutritional profile and broad range of applications in biotechnology, medicine, environmental sustainability, and food industries.

For centuries, *Spirulina* has been consumed as a nutrient-rich dietary supplement owing to its elevated protein content, balanced amino acid composition, essential fatty acids, vitamins, minerals, and antioxidant pigments. The organism has been categorized as Generally Recognized As Safe (GRAS) and recommended by several international organizations as a valuable nutritional supplement for addressing malnutrition and micronutrient deficiencies. Additionally, numerous studies have demonstrated its antioxidant, antimicrobial, anti-inflammatory, anticancer, neuroprotective, and immunomodulatory activities.

Soda lakes are among the most extreme aquatic ecosystems globally, characterized by strong alkalinity, high concentrations of sodium carbonate and bicarbonate, intense solar exposure, and fluctuating salinity conditions. These harsh environmental parameters create selective pressure favoring alkaliphilic and haloalkaliphilic microorganisms, especially cyanobacteria such as *S. platensis*. Moreover, such extreme conditions minimize contamination by competing microorganisms, allowing the formation of near-monoculture cyanobacterial populations.

Recent scientific findings indicate that soda lake-derived strains possess enhanced physiological and biochemical characteristics compared with conventional freshwater strains. Environmental stress conditions stimulate osmoadaptive mechanisms and promote synthesis of protective metabolites including phycobiliproteins and carotenoids. Despite growing attention toward extremophilic microalgae, comprehensive reviews specifically focused on soda lake-derived *S. platensis* remain limited.

Therefore, this review critically discusses the ecological characteristics, cultivation opportunities, biochemical composition, nutritional advantages, biotechnological applications, and pharmacological importance of *Spirulina platensis* isolated from soda lake environments. Furthermore, current limitations and future research perspectives for industrial and therapeutic exploitation are highlighted.



## 2. Ecological Dynamics and Cultivation Prospects

### 2.1 Physicochemical Characteristics of Soda Lakes

Soda lakes are alkaline saline ecosystems enriched with sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and sodium bicarbonate ( $\text{NaHCO}_3$ ), generally exhibiting pH values between 9.0 and 11.0. These aquatic environments commonly contain high dissolved inorganic carbon and elevated salinity levels, creating extreme conditions unsuitable for most aquatic life forms.

Important physicochemical factors influencing the growth of *S. platensis* include:

- Strong alkalinity (pH 9.5–10.5)
- High carbonate and bicarbonate concentrations
- Relatively stable temperatures
- Intense sunlight exposure
- Reduced microbial contamination
- Elevated dissolved  $\text{CO}_2$  availability

These conditions provide a competitive advantage to alkaliphilic cyanobacteria by restricting the proliferation of contaminating fungi, bacteria, protozoa, and other algae. Consequently, soda lakes frequently support extensive *Spirulina* blooms with dense biomass accumulation.

### 2.2 Natural Abundance and Bloom Dynamics

Bloom development of *S. platensis* in soda lakes is regulated by seasonal variations in temperature, nutrient availability, solar intensity, and hydrological conditions. Under favorable environmental conditions, thick cyanobacterial mats are formed, resulting in high biomass productivity.

Research indicates that elevated temperatures, increased solar irradiation, and abundant bicarbonate concentrations stimulate photosynthetic efficiency and rapid cellular growth. Conversely, excessive rainfall and nutrient dilution may reduce bloom intensity.

The remarkable ecological tolerance of *Spirulina* enables continuous biomass production even under stressful environmental conditions. This resilience is mainly associated with efficient osmoadaptation strategies and carbon-concentrating mechanisms.

### 2.3 Ex-situ Cultivation Mimicking Soda Lake Conditions

Industrial cultivation of *S. platensis* commonly utilizes open raceway ponds and closed photobioreactor systems (PBRs). Replicating soda lake environmental conditions within cultivation systems has shown substantial advantages for biomass production.

High-alkaline cultivation media provide several operational and economic benefits, including:

- Lower contamination susceptibility
- Reduced sterilization requirements
- Decreased protozoan grazing
- Higher biomass quality
- Enhanced pigment biosynthesis

Open pond systems are economically suitable for large-scale production, whereas photobioreactors offer better environmental regulation and metabolite consistency.

Optimization strategies include:

- Controlled bicarbonate enrichment
- Regulation of light intensity
- Temperature optimization
- Nutrient balance management
- Salinity adjustment

Studies reveal that soda lake-origin strains frequently exhibit faster growth and greater productivity under alkaline culture conditions compared with freshwater-derived strains.



### 3. Biochemical Profiling and Nutritional Superiority

#### 3.1 Macronutrient Composition

*Spirulina platensis* is regarded as one of the richest natural protein sources, containing approximately 60–70% protein on a dry-weight basis. Its protein fraction includes all essential amino acids, making it an important dietary supplement.

##### Proteins

- Rich source of essential amino acids
- Easily digestible protein fraction
- Higher protein quality than many plant-derived proteins

##### Lipids

Although total lipid content is moderate, *S. platensis* contains beneficial polyunsaturated fatty acids (PUFAs), particularly gamma-linolenic acid (GLA), known for anti-inflammatory and cardioprotective effects.

##### Carbohydrates

The cyanobacterium contains bioactive polysaccharides exhibiting antioxidant and immunomodulatory functions.

#### 3.2 Vitamins and Minerals

Soda lake-derived *S. platensis* is abundant in several vitamins and minerals, including:

- Vitamin B complex
- Vitamin E
- Iron
- Magnesium
- Calcium
- Potassium
- Selenium
- Zinc

Its highly bioavailable iron content makes it particularly beneficial in combating nutritional anemia and mineral deficiencies.

#### 3.3 Stress-Induced Secondary Metabolites

Extreme environmental stress within soda lakes stimulates adaptive physiological responses that increase secondary metabolite synthesis.

##### Phycobiliproteins

C-phycocyanin (C-PC) represents the principal blue pigment of *Spirulina* and exhibits:

- Strong antioxidant activity
- Anti-inflammatory properties
- Fluorescent applications in biotechnology
- Natural food-coloring potential

Additional phycobiliproteins such as allophycocyanin and phycoerythrin contribute to antioxidant defense and photosynthetic performance.

##### Carotenoids

Major carotenoids include:

- Beta-carotene
- Zeaxanthin
- Myxoxanthophyll

These compounds protect cells against photooxidative stress while also providing important health benefits.



**Suggested Table 1. Comparative Biochemical Composition of Soda Lake and Freshwater *S. platensis***

| Parameter             | Soda Lake Str | Freshwater Str |
|-----------------------|---------------|----------------|
| Protein (%)           | 65–70         | 55–60          |
| C-Phycocyanin         | High          | Moderate       |
| Carotenoids           | High          | Moderate       |
| GLA Content           | Elevated      | Moderate       |
| Antioxidant Activity  | Superior      | Standard       |
| Contamination Resista | Excellent     | Moderate       |

#### 4. Biotechnological Applications

##### 4.1 Natural Colorants and Cosmeceuticals

Growing consumer demand for naturally sourced additives has increased the industrial importance of microalgal pigments. C-phycoyanin extracted from *S. platensis* is widely utilized as a natural blue pigment and fluorescent biomarker.

Applications include:

- Functional beverages
- Dairy products
- Confectionery products
- Cosmetic formulations
- Anti-aging products
- Sunscreen preparations

The antioxidant and anti-inflammatory characteristics of phycocyanin contribute to skin protection against oxidative and UV-induced damage.

##### 4.2 Nutraceuticals and Functional Foods

*Spirulina* biomass is commonly incorporated into:

- Protein supplements
- Nutritional capsules and tablets
- Functional drinks
- Protein bars
- Dairy substitutes
- Sports nutrition formulations

Its dense nutrient composition and antioxidant potential make it useful for improving nutritional health and immune function.

##### 4.3 Agricultural Biostimulants

Extracts derived from *S. platensis* act as environmentally friendly agricultural biostimulants.

Reported advantages include:

- Enhanced seed germination
- Improved drought tolerance
- Greater salinity resistance
- Better nutrient absorption
- Increased crop yield

These effects are associated with the presence of phytohormones, amino acids, and antioxidant compounds.



#### 4.4 Green Biotechnology and Biorefinery

Residual biomass remaining after pigment extraction still possesses considerable industrial importance.

Potential applications include:

##### **Bioplastics**

Cyanobacterial biomass can be utilized for production of biodegradable polyhydroxyalkanoates (PHAs).

##### **Biofuels**

Lipid fractions may be converted into biodiesel through transesterification.

##### **Biofertilizers**

Protein-rich residual biomass can serve as organic fertilizers and soil conditioners.

The cascade biorefinery concept enhances sustainability through complete biomass utilization and reduced waste generation.

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