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A Review of Biotechnological Approaches for Optimising Spirulina platensis Cultivation and Enhancing its Antibacterial Activity and Commercial Potential

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Abstract

Spirulina platensis is a filamentous, alkaliphilic cyanobacterium of considerable nutritional, pharmaceutical, and industrial value, and biotechnological interest in its cultivation has intensified in response to growing demand for natural, sustainably produced antimicrobial and functional ingredients. Optimizing the cultivation of S. platensis, enhancing its antibacterial activity, and realizing its commercial potential. The physicochemical determinants of growth, principally initial medium pH, light intensity, incubation temperature, and nutrient composition, are examined, together with the use of alternative substrates such as wastewater for cost-effective, sustainable biomass production. The extraction and characterization of antibacterial bioactive constituents, including phycocyanin, phenolic compounds, flavonoids, and antimicrobial peptides, are reviewed in relation to solvent polarity and the differential susceptibility of Gram-positive and Gram-negative bacteria. The commercial applications of optimized S. platensis biomass across the pharmaceutical, nutraceutical, cosmetic, food-preservation, and animal-feed sectors are also considered. The review methodology, comprising a structured search of major scientific databases, is described, and the synthesized findings are consolidated into five comparative tables. The review concludes that the rational manipulation of readily controllable cultivation parameters constitutes a scalable, evidence-based strategy for enhancing both the yield and the functional bioactivity of S. platensis biomass, and it identifies priority directions for future research, including factorial optimization designs, strain improvement, and pilot-scale validation.

Keywords: Spirulina platensis; cultivation optimization; antibacterial activity; biotechnology; commercial application; review

1. Introduction

1.1 Taxonomy, Morphology, and Natural Habitat of Spirulina platensis

Spirulina platensis, taxonomically situated within the genus Arthrospira and more recently reclassified under Limnospira, is a multicellular, filamentous cyanobacterium characterized by a helically coiled trichome morphology and a distinctive blue-green pigmentation (Sinetova et al., 2024). The organism occurs naturally in alkaline, saline lakes across tropical and subtropical regions, where it has adapted physiologically to high pH, high irradiance, and elevated temperature, a set of environmental adaptations that has direct bearing on the

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cultivation conditions required for its efficient large-scale production (Spínola et al., 2024). Its long history of natural occurrence in such extreme alkaline environments, together with an equally long history of traditional human consumption, underlies its present-day recognition as a safe and well-characterized biotechnological organism.

The taxonomic revisions affecting the organism, whereby the names Spirulina, Arthrospira, and Limnospira have variously been applied to what is now recognized as a single biological entity, reflect an evolving understanding of cyanobacterial systematics rather than any change in the organism's underlying biology or industrial relevance (Sinetova et al., 2024). For consistency with the majority of the applied biotechnological literature reviewed here, and in keeping with the terminology most widely used in the antibacterial and cultivation-optimization studies discussed in subsequent sections, the name Spirulina platensis is retained throughout this review.

1.2 Nutritional and Industrial Importance of Spirulina platensis

S. platensis biomass is distinguished by an exceptionally high protein content, frequently exceeding sixty percent of dry weight, together with a rich complement of vitamins, essential fatty acids, and pigments, including the phycobiliprotein phycocyanin, chlorophyll a, and carotenoids (Grosshagauer et al., 2020). These attributes have established Spirulina as one of the most commercially significant microalgae worldwide, marketed extensively as a dietary supplement and functional food ingredient (Lafarga et al., 2020). The expanding global market for natural, minimally processed nutritional and functional ingredients has, in turn, created strong commercial incentives for research directed at improving both the yield and the bioactive quality of cultivated biomass.

The scalability of Spirulina cultivation, achievable in open raceway ponds as well as in closed photobioreactor systems, further distinguishes the organism from many other microalgae of comparable nutritional interest, since it permits production to be matched to a wide range of climatic and economic contexts (Soni et al., 2017). This operational flexibility, combined with a comparatively short doubling time under favourable conditions, has supported the establishment of commercial Spirulina production facilities across multiple continents, providing the industrial foundation upon which the biotechnological optimization strategies reviewed in this article are ultimately intended to be applied.

1.3 Cyanobacterial Secondary Metabolites and Antibacterial Potential

Beyond its established nutritional value, S. platensis synthesizes a diverse array of secondary metabolites with demonstrated antibacterial activity, including phenolic acids, flavonoids, polysaccharides, and bioactive peptides (Ilieva et al., 2024). The mounting global concern surrounding antibiotic resistance has intensified scientific and commercial interest in natural, multi-target antimicrobial agents of this kind, since their combined mode of action across several molecular targets is considered less liable to elicit the emergence of resistant bacterial strains than single-target synthetic antibiotics (Gheda & Ismail, 2020). This has positioned Spirulina-derived extracts as promising candidates for pharmaceutical, food-preservation, and cosmetic antimicrobial applications.

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The antibacterial potential of cyanobacterial secondary metabolites is further reinforced by the ecological role that many of these compounds are believed to play in the natural environment, where they may confer a competitive advantage against co-occurring bacterial populations.

1.4 Biotechnological Strategies for Cultivation Enhancement

A substantial body of biotechnological research has sought to enhance the productivity and functional quality of S. platensis biomass through the systematic manipulation of cultivation conditions, including medium composition, pH, light regime, and temperature, as well as through the use of alternative, cost-effective substrates such as agro-industrial or municipal wastewater (Zhai et al., 2017). These strategies exploit the organism's well-defined physiological optima to achieve simultaneous improvements in biomass yield and bioactive constituent content, offering a practical alternative to genetic modification or costly synthetic medium supplementation (Molazadeh et al., 2019).

Complementary strategies reviewed in this article include the selection and screening of robust production strains, the optimization of downstream extraction procedures to maximize the recovery of antibacterial constituents, and the coupling of cultivation with wastewater bioremediation or carbon dioxide biofixation to improve overall process sustainability. Considered together, these approaches illustrate the breadth of the biotechnological toolkit currently available for enhancing the commercial value of S. platensis biomass, extending well beyond the manipulation of cultivation parameters alone.

1.5 Scope and Structure of the Review

The biotechnological optimization of S. platensis cultivation, the mechanisms and characterization of its antibacterial activity, and the commercial applications of the resulting biomass. The review is organized into four thematic sections addressing, respectively, the optimization of physicochemical cultivation parameters, the use of alternative nutrient media and substrates, the extraction and characterization of antibacterial bioactive compounds, and the commercial and industrial applications of Spirulina biomass. A structured review methodology is subsequently described, followed by a synthesis of conclusions and a discussion of priority directions for future research.

In adopting this four-part thematic structure, the review is intended to trace a coherent narrative arc from the fundamental biology and cultivation requirements of S. platensis, through the mechanistic basis of its antibacterial activity, to the applied commercial contexts in which that activity, together with the organism's broader nutritional profile, may ultimately be exploited. This structure is designed to be of practical value both to researchers seeking to identify gaps in the existing cultivation-optimization literature and to industry stakeholders evaluating the commercial feasibility of Spirulina-based antimicrobial products.

2. Literature Review

2.1 Optimization of Physicochemical Cultivation Parameters

The influence of physicochemical cultivation parameters on the growth of S. platensis has been extensively documented. Zhai et al. (2017) applied response surface methodology to synthetic municipal wastewater and identified optimum conditions of pH 8.8–8.9, light intensity of

3300–3400 lux, and a temperature of 25 °C, under which biomass and protein yield were maximized. Working with seawater-based medium, comparable investigations have reported optimum pH values close to 9.0 and optimum temperatures in the range of 32–35 °C, findings broadly consistent with the alkaliphilic, mesophilic physiology of the organism (Gurbuz, 2020). Light intensity has similarly been shown to exhibit a well-defined optimum, beyond which photoinhibition suppresses growth; reported optimal values vary with cultivation vessel and irradiance measurement method but generally fall within the range of approximately 1500 to 4500 lux under laboratory and pilot-scale conditions (Singh et al., 2017).

A recurring finding across this literature is that each of pH, light, and temperature exerts an independent and statistically significant effect on biomass yield, and that the combination of parameters at their individual optima typically produces an enhancement in biomass exceeding that attributable to any single parameter, indicating a synergistic or additive relationship among these variables (Singh et al., 2017). Table 1 summarizes the optimum cultivation conditions and associated biomass outcomes reported across a representative selection of studies published within the review period.

The predominant experimental design employed across the reviewed cultivation-optimization studies remains the one-factor-at-a-time approach, in which a single parameter is varied while others are held constant; while this approach offers clarity in isolating individual parameter effects, it inherently limits the extent to which interaction effects among parameters can be quantified. A smaller number of studies have employed response surface methodology or central composite designs, exemplified by the work of Zhai et al. (2017), and these more sophisticated designs have generally yielded tighter confidence intervals around the identified optima, suggesting that the wider adoption of such methods, discussed further in Section 5, could meaningfully improve the precision of future cultivation-optimization research.

Table 1. Comparative summary of optimum physicochemical cultivation parameters for Spirulina platensis reported in selected studies (2015–2024)

Study	Optimum pH	Optimum light intensity	Optimum temperature (°C)	Reported outcome
Zhai et al. (2017)	8.8–8.9	3300–3400 lux	25	Biomass 262.5 mg L^{-1}; protein 46.0%
Gurbuz (2020)	9.0	5 Klux	35	Enhanced biomass, lipid and chlorophyll-a
Singh et al. (2017)	7.0–9.0	1500–2500 lux	28–32	Enhanced polyphenolic content
Pereira et al. (2019)	9.0–9.5	Natural/mixotrophic	28–30	Increased biomass and antioxidant capacity
Molazadeh et al. (2019)	8.5–9.5	Moderate–high	26–30	Improved CO_2 biofixation and biomass

2.2 Nutrient Media and Alternative Cultivation Substrates

While modified Zarrouk's medium remains the standard cultivation medium for S. platensis owing to its high alkalinity and balanced macronutrient composition, the substantial cost of synthetic media components has motivated research into alternative, low-cost substrates. Wastewater-based cultivation has attracted particular attention, since it offers the dual benefit of biomass production and nutrient bioremediation. Pereira et al. (2019) demonstrated that mixotrophic cultivation of S. platensis in dairy wastewater enhanced biomass yield, altered biochemical composition, and increased antioxidant capacity relative to autotrophic controls, while Zinicovscaia et al. (2018) reported that S. platensis biomass retained substantial productive capacity when cultivated in metal-contaminated wastewater, simultaneously achieving appreciable zinc removal.

Molazadeh et al. (2019) further reviewed the coupling of microalgal cultivation with wastewater treatment and carbon dioxide biofixation, concluding that Spirulina and related cyanobacteria are particularly well suited to such dual-purpose applications owing to their tolerance of alkaline, nutrient-rich effluents. Collectively, this literature indicates that alternative substrates can substantially reduce the input costs associated with commercial-scale cultivation without compromising, and in some cases enhancing, biomass productivity, thereby improving the overall economic and environmental sustainability of the production process (Table 2).

Notwithstanding these advantages, the use of wastewater-based substrates introduces additional considerations not applicable to cultivation in synthetic media, including the variability of influent composition, the risk of microbial or chemical contamination, and, where the resulting biomass is intended for food, feed, or pharmaceutical application, the need for rigorous compositional and safety verification. These considerations suggest that wastewater-based cultivation may currently be best suited to applications in which the biomass is directed towards non-ingestible commercial products, such as biofertilizers or industrial biopreservatives, pending further validation of its safety for higher-value nutraceutical and pharmaceutical uses.

Table 2. Effect of alternative cultivation substrates on Spirulina platensis biomass production and nutrient recovery

Substrate/medium	Study	Cultivation mode	Key reported effect
Synthetic municipal wastewater	Zhai et al. (2017)	Autotrophic/mixotrophic	Biomass yield 262.5 mg L^{-1}; nutrient uptake optimized
Dairy wastewater	Pereira et al. (2019)	Mixotrophic	Increased biomass, altered biochemical profile, higher antioxidant capacity
Metal-contaminated wastewater	Zinicovscaia et al. (2018)	Autotrophic	Zinc removal 71–99%; sustained biomass productivity
CO_2-enriched effluent	Molazadeh et al. (2019)	Autotrophic	Enhanced CO_2 biofixation coupled with biomass gain

Modified Zarrouk's medium (standard)	Multiple studies	Autotrophic	Reference biomass and bioactivity benchmark

2.3 Extraction and Characterization of Antibacterial Bioactive Compounds

The antibacterial activity of S. platensis has been attributed to a range of bioactive constituents extractable using solvents of differing polarity. Usharani et al. (2015) reported that methanolic extracts consistently produced the largest zones of inhibition among the solvents tested against pathogenic bacteria and fungi, a finding echoed by Al-ghanayem (2017), who observed pronounced activity of methanolic and related organic extracts against both Gram-positive and Gram-negative isolates. Sun et al. (2016) isolated a discrete antibacterial peptide from protein hydrolysates of S. platensis, providing direct molecular evidence for a proteinaceous contribution to its antimicrobial action, while Gheda and Ismail (2020) attributed much of the antibacterial potency of methanolic extracts to their elevated total phenolic content. Ilieva et al. (2024) subsequently reviewed the recognized antimicrobial bioactive compounds of Arthrospira and related microalgae, concluding that phenolics, phycobiliproteins, polysaccharides, and fatty acid derivatives act synergistically to produce broad-spectrum, predominantly bactericidal activity.

A consistent pattern across this literature is the greater susceptibility of Gram-positive relative to Gram-negative bacteria, generally attributed to the additional lipopolysaccharide-rich outer membrane possessed by Gram-negative organisms, which restricts the penetration of many natural antibacterial constituents (Usharani et al., 2016). Nevertheless, several studies report appreciable activity even against resistant Gram-negative organisms such as Pseudomonas aeruginosa and Klebsiella pneumoniae, indicating that at least some antibacterial constituents of S. platensis are capable of overcoming this permeability barrier (Al-ghanayem, 2017). Reported zone-of-inhibition and minimum inhibitory concentration values vary considerably between studies, reflecting differences in strain, extraction solvent, and bacterial isolate, as summarized in Table 3, while the principal constituent classes implicated in this activity, together with their proposed mechanisms, are summarized in Table 4.

The extraction methodology employed also emerges as an important determinant of reported antibacterial potency; studies that combined mechanical cell disruption with solvent extraction, or that employed sequential multi-solvent extraction protocols, generally reported higher yields of bioactive constituents and correspondingly stronger antibacterial activity than studies relying on single-solvent maceration alone. This observation suggests that standardization of extraction protocols across future studies would materially improve the comparability of reported antibacterial outcomes and facilitate more rigorous cross-study synthesis than is currently possible.

Table 3. Antibacterial activity (zone of inhibition and minimum inhibitory concentration) of Spirulina platensis extracts reported in selected studies

Study	Extract/solvent	Representative organism	ZOI (mm)	MIC ($\mu g\ mL^{-1}$)

Usharani et al. (2015)	Methanol	Staphylococcus aureus	Highest among solvents tested	Not reported
Al-ghanayem (2017)	Aqueous/organic	Escherichia coli	15.0–24.0	Not reported
Sun et al. (2016)	Protein hydrolysate/peptide	Multiple bacteria	Not reported	Peptide-specific, low range
Gheda & Ismail (2020)	Methanol	Multiple pathogens	Moderate–strong	Not reported
Ilieva et al. (2024)	Multiple (review)	Gram-positive & Gram-negative panel	Broad-spectrum, variable	Variable, compound-dependent

Table 4. Principal antibacterial bioactive constituents of Spirulina platensis and their proposed mechanisms of action

Constituent class	Representative source	Proposed antibacterial mechanism
Phycocyanin (phycobiliprotein)	Citi et al. (2024)	Membrane interaction; antioxidant-mediated disruption of oxidative balance
Phenolic compounds	Gheda & Ismail (2020)	Disruption of bacterial membrane integrity; enzyme inhibition
Flavonoids	Ilieva et al. (2024)	Chelation of metal cofactors; interference with nucleic acid synthesis
Antibacterial peptides	Sun et al. (2016)	Direct membrane permeabilization; pore formation
Polysaccharides and fatty acid derivatives	Ilieva et al. (2024)	Synergistic potentiation of co-extracted antibacterial constituents

2.4 Commercial and Industrial Applications of Spirulina Biomass

The commercial exploitation of S. platensis biomass spans several major industrial sectors, underpinned principally by its protein content, its antioxidant and antimicrobial pigments, and its established safety profile as a food-grade organism. Citi et al. (2024) reviewed the nutraceutical properties of C-phycocyanin, highlighting its antioxidant, anti-inflammatory, and immunomodulatory actions and its widespread use as a natural food colourant, while Spínola et al. (2024) documented the expanding application of Spirulina across the food, feed, and medicinal sectors. Lafarga et al. (2020) further observed that consumer preference for natural, minimally processed functional ingredients has been a principal driver of market growth for Spirulina-derived products, and AlFadhly et al. (2022) reviewed emerging technological advances in the incorporation of Spirulina into functional food formulations.

Beyond the food and nutraceutical sectors, Özogul et al. (2021) demonstrated a practical food-preservation application, whereby S. platensis extracts extended the microbiological shelf-life of chilled fish fillets, illustrating the translational relevance of the antibacterial properties reviewed in the preceding section. The convergence of these findings indicates that optimized S. platensis biomass possesses substantial and diversified commercial value, summarized by application sector in Table 5.

A notable feature of the commercial literature reviewed is the recurrence of phycocyanin as a common bioactive thread linking multiple, seemingly disparate application sectors, from its use as a natural blue food colourant in the nutraceutical sector to its antioxidant role in cosmetic formulations and its contribution to antibacterial activity in pharmaceutical and food-preservation contexts (Citi et al., 2024). This convergence suggests that biotechnological strategies aimed specifically at enhancing phycocyanin yield and stability during cultivation and downstream processing may offer disproportionate commercial returns relative to strategies targeting other individual bioactive constituents in isolation.

Table 5. Commercial and industrial application sectors of Spirulina platensis biomass and associated bioactive constituents

Application sector	Principal bioactive basis	Representative source
Pharmaceutical	Broad-spectrum antibacterial peptides and phenolics	Sun et al. (2016); Ilieva et al. (2024)
Nutraceutical / functional food	High protein and phycocyanin content	Citi et al. (2024); Lafarga et al. (2020)
Cosmetic	Antioxidant and antimicrobial pigments	Citi et al. (2024)
Food preservation	Bactericidal extract activity	Özogul et al. (2021)
Animal feed	Protein, pigment and immunomodulatory compounds	Spínola et al. (2024)

3. Research Methodology

This review was conducted as a structured narrative synthesis of the peer-reviewed scientific literature concerning the biotechnological cultivation, antibacterial activity, and commercial application of Spirulina platensis. The review methodology was designed to ensure a systematic, transparent, and reproducible approach to literature identification, screening, and synthesis, comparable in rigour to established narrative and scoping review practice.

Relevant literature was identified through structured searches of major scientific databases and indexing services, including ScienceDirect, PubMed, Scopus, Google Scholar, MDPI, and Springer Link. Search terms combined the keywords "Spirulina platensis" or "Arthrospira platensis" with terms relating to the three thematic pillars of the review, namely "cultivation optimization", "pH", "light intensity", "temperature", "wastewater cultivation", "antibacterial activity", "antimicrobial", "bioactive compounds", "phycocyanin", and "commercial application". Boolean operators were used to combine these terms, and searches were restricted to publications appearing between January 2015 and December 2024 in order to ensure the currency and relevance of the evidence base.

Records retrieved from the initial search were screened by title and abstract to exclude studies unrelated to S. platensis cultivation, antibacterial activity, or commercial application, as well

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as non-peer-reviewed sources, conference abstracts lacking sufficient methodological detail, and studies published outside the specified date range. The full texts of the remaining records were then assessed for eligibility, with priority given to primary research articles reporting quantitative cultivation, antibacterial, or compositional data, alongside authoritative review articles providing broader contextual synthesis. Studies were included if they reported original data or synthesis relevant to at least one of the four thematic areas addressed in the literature review, namely physicochemical cultivation optimization, alternative cultivation substrates, antibacterial bioactive compound characterization, or commercial application.

Data extracted from the included studies encompassed, where reported, the cultivation parameters examined and their optimum values, the biomass or productivity outcomes achieved, the extraction solvents and antibacterial assay methods employed, the zone-of-inhibition and minimum inhibitory concentration values obtained, the bioactive constituents identified, and the commercial application sectors discussed. These data were synthesized thematically rather than statistically pooled, in keeping with the heterogeneity of experimental designs, strains, and reporting conventions across the reviewed literature, and were consolidated into the five comparative tables presented in Section 2. Twenty studies meeting the eligibility criteria were retained for detailed synthesis and are cited throughout this review; this number was considered sufficient to provide balanced coverage of each thematic area while remaining consistent with the scope of a focused narrative review.

A degree of methodological heterogeneity among the reviewed studies should be acknowledged as an inherent limitation of the synthesis presented here. Differences in Spirulina strain, cultivation vessel geometry, light-measurement methodology, and antibacterial assay protocol limit the extent to which quantitative values can be directly compared across studies, and the comparative tables presented in this review should accordingly be interpreted as indicative summaries of reported trends rather than as strictly equivalent, pooled datasets.

4. Conclusion

This review has synthesized the peer-reviewed literature published between 2015 and 2024 concerning the biotechnological optimization of Spirulina platensis cultivation and the enhancement of its antibacterial activity and commercial potential. The evidence reviewed consistently indicates that the systematic manipulation of readily controllable physicochemical parameters, principally initial medium pH, light intensity, and incubation temperature, produces substantial and reproducible enhancements in biomass yield, with reported optimum values converging within relatively narrow ranges across independent studies. Alternative, low-cost cultivation substrates, particularly wastewater streams, have been shown to support comparable or enhanced biomass productivity while simultaneously achieving nutrient bioremediation, offering a commercially and environmentally attractive complement to conventional synthetic media.

The antibacterial activity of S. platensis extracts, most consistently and potently expressed in methanolic extracts, has been attributed to a range of bioactive constituents including phycocyanin, phenolic compounds, flavonoids, and antibacterial peptides, which appear to act synergistically to produce broad-spectrum, predominantly bactericidal activity against both Gram-positive and Gram-negative bacteria. This bioactivity, together with the organism's established nutritional value and favourable safety profile, underpins a diverse and expanding range of commercial applications across the pharmaceutical, nutraceutical, cosmetic, food-preservation, and animal-feed sectors. Taken together, the reviewed literature supports the conclusion that biotechnological cultivation optimization represents a scientifically well-substantiated and commercially viable strategy for enhancing the value of S. platensis biomass, warranting continued investment in both fundamental and applied research.

5. Future Work

Several priority directions emerge from the synthesis presented in this review. First, the majority of cultivation-optimization studies reviewed employed one-factor-at-a-time experimental designs; future research would benefit from the wider adoption of factorial and response-surface methodologies capable of quantifying interaction effects among pH, light intensity, temperature, and nutrient composition, thereby enabling more precise and potentially more efficient optimization strategies. Second, comparatively few studies have directly examined how the cultivation regime under which biomass is produced influences the potency and spectrum of the resulting antibacterial activity; controlled studies linking specific cultivation conditions to quantified antibacterial outcomes would strengthen the mechanistic basis for cultivation-driven bioactivity enhancement.

Third, the isolation, purification, and structural characterization of the specific antibacterial constituents responsible for the activity reported across the reviewed studies remains incomplete, and further phytochemical and analytical work, including chromatographic and mass-spectrometric profiling, is needed to identify the active molecules with precision and to elucidate their mechanisms of action at the molecular level. Fourth, the translation of laboratory-scale optimization findings to pilot- and industrial-scale cultivation systems, whether open raceway ponds or closed photobioreactors, requires further validation, together with techno-economic analysis to confirm the commercial viability of optimized cultivation regimes under production conditions. Finally, strain-improvement approaches, including the screening and selection of naturally robust isolates or the application of adaptive laboratory evolution, represent a complementary avenue by which the biomass productivity and bioactive potential of S. platensis might be further enhanced, and the integration of such approaches with the cultivation-optimization strategies reviewed here constitutes a promising direction for future biotechnological development.

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