ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(8): 202-209
www.agriculturaljournals.com
Received: 14-06-2026
Accepted: 17-07-2026

Prachi A Patil
M.Tech. Research Scholar, Department of Food Microbiology and Safety, College of Food Technology, VNMKV, Parbhani, Maharashtra, India

Dr. SK Sadawarte
HOD & Associate Professor, Department of Food Microbiology and Safety, College of Food Technology, VNMKV Parbhani, Maharashtra, India

Dr. AA Joshi
Assistant Professor, Department of Food Processes Technology, College of Food Technology, VNMKV Parbhani, Maharashtra, India

Dr. GM Machewad
HOD & Associate Professor, Department of Food Business Manegment, College of Food Technology, VNMKV Parbhani, Maharashtra, India

HW Deshpande
Emeritus Professor, Department of Food Microbiology and Safety, College of Food Technology, VNMKV, Parbhani, Maharashtra, India

Corresponding Author:
Prachi A Patil
M.Tech. Research Scholar, Department of Food Microbiology and Safety, College of Food Technology, VNMKV, Parbhani, Maharashtra, India

Phycocyanin from *Arthrospira platensis*: Recent advances in production, extraction, purification, stability enhancement, and industrial applications

Prachi A Patil, SK Sadawarte, AA Joshi, GM Machewad and HW Deshpande

DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i8c.1772

Abstract
Arthrospira platensis (Spirulina) is a nutrient-rich cyanobacterium widely recognized for its high protein content and valuable bioactive compounds, particularly C-phycocyanin. This review summarizes recent advances in Spirulina cultivation, nutritional composition, phycocyanin extraction and purification techniques, factors affecting pigment stability, and its applications in the food, nutraceutical, pharmaceutical, cosmetic, and biomedical industries. Conventional and emerging extraction technologies, along with purification strategies, are discussed to highlight their influence on pigment yield and quality. The review also outlines current challenges and future prospects for improving the large-scale production and commercial utilization of phycocyanin as a sustainable natural blue pigment and functional ingredient.

Keywords: Arthrospira platensis, spirulina, c-phycocyanin, natural blue pigment, functional foods

Introduction
The continuously increasing global population poses a significant challenge to food security by intensifying the demand for safe, nutritious, and sustainable food resources. According to the United Nations, the global population is projected to reach approximately 9.8 billion by 2050, thereby exerting substantial pressure on existing agricultural systems and food production capacity (United Nations, 2017). Conventional agricultural practices alone may not be sufficient to satisfy future nutritional requirements; therefore, the exploration of alternative and sustainable biological resources has become an important research priority.

Among the various alternative food resources, microalgae have emerged as one of the most promising candidates due to their rapid growth rate, high photosynthetic efficiency, minimal land requirement, and exceptional nutritional composition. Microalgae are rich sources of high-quality proteins, essential amino acids, polyunsaturated fatty acids, vitamins, minerals, carbohydrates, pigments, and numerous bioactive compounds. These valuable metabolites have attracted considerable attention for their potential applications in the food, nutraceutical, pharmaceutical, cosmetic, and biotechnology sectors (Lafarga, 2020; Lim *et al.*, 2021) [1, 2].

In addition to their nutritional benefits, microalgae contribute significantly to environmental sustainability. They efficiently convert solar energy and atmospheric carbon dioxide into valuable biomass through photosynthesis and can be cultivated using non-arable land, saline water, or wastewater, thereby reducing competition with conventional agricultural production. Their ability to support carbon sequestration and facilitate resource recycling further strengthens their role in the development of a sustainable circular bioeconomy (Lim *et al.*, 2021; AlFadhly *et al.*, 2022) [2, 3]. Consequently, the commercial demand for algal biomass and algae-derived products has increased substantially, with the global algae products market expected to exhibit steady growth in the coming years.

Among commercially cultivated microalgae, *Arthrospira platensis* (commonly known as *Spirulina*) is one of the most extensively investigated cyanobacteria because of its outstanding nutritional profile, ease of cultivation, rapid biomass productivity, and economic feasibility. *Spirulina* thrives under highly alkaline conditions, which naturally reduce microbial contamination and facilitate large-scale cultivation. Its dry biomass typically contains 55-70% protein, along with essential fatty acids, vitamins, minerals, polysaccharides, and several

biologically active pigments, making it an important functional food and dietary supplement (Paniagua-Michel, 2015; Sorrenti *et al.*, 2021) [4, 5].

Among the various bioactive compounds present in *Spirulina*, C-phycocyanin has attracted considerable scientific and industrial interest. C-phycocyanin is a water-soluble blue phycobiliprotein that functions as an accessory photosynthetic pigment by absorbing light energy and transferring it to chlorophyll during photosynthesis. Owing to its intense natural blue colour, non-toxic nature, excellent biocompatibility, and biodegradability, phycocyanin has emerged as a promising natural alternative to synthetic food colourants and is increasingly utilized in the food, pharmaceutical, cosmetic, and biomedical industries (de Morais *et al.*, 2018) [6].

Beyond its colouring properties, C-phycocyanin exhibits a broad spectrum of biological activities, including antioxidant, anti-inflammatory, antimicrobial, immunomodulatory, hepatoprotective, neuroprotective, antidiabetic, anticancer, and wound-healing effects. These multifunctional biological properties have significantly expanded its applications as a functional ingredient, nutraceutical, and potential therapeutic agent for the prevention and management of various chronic diseases (Yuan *et al.*, 2022) [7].

Despite its enormous commercial potential, the large-scale utilization of phycocyanin remains challenging due to its intracellular localization and its susceptibility to degradation during processing and storage. Efficient recovery of phycocyanin requires effective cell disruption and extraction techniques, while its stability is strongly influenced by environmental factors such as temperature, pH, light intensity, oxygen exposure, solvent composition, and storage conditions. These factors can adversely affect pigment yield, purity, colour stability, and biological activity, thereby limiting its industrial applications. Consequently, considerable research has focused on optimizing cultivation practices, extraction methods, purification techniques, stabilization strategies, and downstream processing to improve the recovery efficiency and functional stability of phycocyanin (Jaeschke *et al.*, 2021; de Morais *et al.*, 2018) [8, 6].

In recent years, increasing consumer preference for natural colourants and clean-label food products has accelerated research on phycocyanin as a sustainable natural blue pigment. Advances in extraction technologies, purification processes, encapsulation methods, and stabilization approaches have further enhanced its commercial prospects across multiple industries. Nevertheless, additional research is required to develop cost-effective, scalable, and environmentally sustainable production technologies that can facilitate its wider industrial application.

Therefore, this review comprehensively discusses the current advances in the production, extraction, purification, stabilization, and industrial applications of C-phycocyanin obtained from *Arthrospira platensis*. Furthermore, the review summarizes the critical factors influencing extraction efficiency and pigment stability, highlights recent technological developments, and outlines future research directions aimed at improving the commercial exploitation of this valuable natural blue pigment.

Structure of Phycocyanin

C-phycocyanin is a water-soluble blue phycobiliprotein predominantly present in cyanobacteria, particularly *Arthrospira platensis* (*Spirulina*), and certain species of red algae. It is an integral component of the phycobilisome, a supramolecular light-harvesting complex attached to the thylakoid membrane, where it functions as an accessory photosynthetic pigment. The primary role of C-phycocyanin is to absorb light energy within the orange-red region of the visible spectrum (approximately 615-620 nm) and efficiently transfer the absorbed energy to chlorophyll a, thereby enhancing photosynthetic efficiency under low-light conditions. This unique light-harvesting capability contributes significantly to the high photosynthetic productivity of cyanobacteria. (Glazer, 1994; Eriksen, 2008) [9, 10]

Structurally, C-phycocyanin is composed of two homologous protein subunits, designated as α (alpha) and β (beta), which assemble to form an $\alpha\beta$ heterodimer. The α-subunit possesses a molecular weight of approximately 17-18 kDa, whereas the β-subunit ranges between 18 and 20 kDa. Three heterodimers further associate through non-covalent interactions to form a trimer $((a\beta)_3)$, and two trimers subsequently assemble into a hexameric complex $((\alpha\beta)_6)$, representing the biologically active form of the pigment. The quaternary structure provides structural stability and facilitates efficient transfer of excitation energy during photosynthesis. (Glazer, 1994) [9]

The characteristic blue colour of C-phycocyanin originates from phycocyanobilin, a linear tetrapyrrole chromophore that is covalently attached to conserved cysteine residues of the protein through thioether linkages. Typically, one chromophore is attached to the α-subunit and two chromophores are attached to the β-subunit, enabling efficient absorption and fluorescence emission. The pigment exhibits a maximum absorption wavelength of 620 nm and fluorescence emission at approximately 640-650 nm. Owing to its high fluorescence quantum yield, excellent photophysical properties, and low toxicity, C-phycocyanin is extensively employed as a fluorescent probe in biomedical diagnostics, immunoassays, flow cytometry, and fluorescence microscopy. (Sekar & Chandramohan, 2008) [11]

Extraction Techniques of Phycocyanin

Efficient extraction of phycocyanin is a critical step in maximizing its yield, purity, and functional properties. Because phycocyanin is an intracellular, water-soluble phycobiliprotein located within the thylakoid membranes of *Arthrospira platensis* (*Spirulina*), effective disruption of the rigid cell wall is essential for its release. The efficiency of extraction depends on several factors, including the cell disruption method, biomass condition (fresh or dried), extraction solvent, pH, temperature, biomass-to-solvent ratio, and processing time. Various physical, mechanical, chemical, and emerging non-thermal techniques have been developed to improve phycocyanin recovery while preserving its structural integrity and biological activity (Jaeschke *et al.*, 2021; de Morais *et al.*, 2018) [8, 6].

Freeze-Thaw Extraction

The freeze-thaw technique is one of the most widely employed laboratory-scale methods for extracting phycocyanin due to its simplicity and minimal equipment requirements. This method involves repeated cycles of freezing and thawing, during which intracellular ice crystal formation mechanically disrupts the cell membrane, facilitating the release of phycocyanin into the extraction medium. Sodium phosphate buffer (pH 6.8-7.0) is commonly used as the extraction solvent because it enhances pigment stability and improves extraction efficiency. Several

studies have reported that three to four freeze-thaw cycles provide the optimum balance between extraction yield and purity, whereas excessive cycles may increase the release of contaminating proteins and reduce pigment quality. Although the method provides high-quality extracts, it is time-consuming, energy-intensive, and therefore more suitable for laboratory-scale applications than industrial production (Silveira *et al.*, 2007; Tavanandi *et al.*, 2018; Chentir *et al.*, 2018) [12, 13, 14].

Homogenization

Homogenization is a mechanical cell disruption technique that employs high shear forces to rupture the cell wall and release intracellular phycocyanin. Compared with simple mixing, homogenization provides more effective disruption due to its higher mechanical intensity, resulting in improved extraction efficiency. The method is relatively rapid, inexpensive, and easily adaptable to laboratory and pilot-scale operations. However, prolonged homogenization generates heat, which can accelerate phycocyanin denaturation and decrease pigment purity. In addition, mechanical disruption often releases significant quantities of cellular debris, necessitating subsequent clarification and purification steps. Therefore, careful optimization of homogenization speed, extraction time, and temperature is essential to maximize pigment recovery while minimizing degradation (Ilter *et al.*, 2018; Pan-Utai & Iamtham, 2019; Silveira *et al.*, 2007) [15, 16, 12].

Bead Milling

Bead milling is an efficient mechanical extraction technique in which microalgal cells are disrupted through collisions with rapidly moving beads within a milling chamber. The repeated impact between the beads and biomass effectively breaks the cell wall, allowing the release of intracellular phycocyanin. Extraction efficiency is influenced by bead material, bead size, filling ratio, agitation speed, and processing duration. Glass beads with high filling densities (approximately 80-85%) have been reported to provide efficient cell disruption while maintaining relatively low energy consumption. Bead milling is capable of processing biomass at high concentrations and is considered suitable for large-scale industrial applications. Nevertheless, the crude extract generally contains considerable cellular debris, resulting in relatively low purity and requiring additional purification procedures to obtain food- or pharmaceutical-grade phycocyanin (Günerken *et al.*, 2015; Garcia *et al.*, 2019; Montalescot *et al.*, 2015) [17, 18, 19].

Ultrasonication

Ultrasonication is an emerging non-thermal extraction technology that utilizes high-frequency ultrasonic waves to generate cavitation bubbles within the extraction medium. The collapse of these bubbles produces localized shear forces and microjets that disrupt the microalgal cell wall, thereby enhancing the diffusion of phycocyanin into the solvent. Compared with conventional extraction methods, ultrasonication offers shorter extraction times, lower solvent consumption, and improved extraction efficiency. When extraction conditions such as ultrasonic power, treatment time, and temperature are properly optimized, ultrasonication effectively preserves the structural integrity and antioxidant activity of phycocyanin. However, excessive ultrasonic intensity or prolonged exposure may generate localized heating and free radicals, leading to pigment degradation. Consequently, optimization of operational parameters is crucial for achieving high extraction yield and quality (Tavanandi & Raghavarao, 2020; Choi & Lee, 2018; Li *et al.*, 2020) [20, 21, 22, 13].

Factors Affecting Extraction and Stability of Phycocyanin

The extraction efficiency and stability of phycocyanin are strongly influenced by several physicochemical and processing parameters. Since phycocyanin is a water-soluble and thermolabile phycobiliprotein, its structural integrity can be readily affected by extraction conditions. Optimizing factors such as biomass form, temperature, light exposure, pH, extraction solvent, biomass-tosolvent ratio, and the use of stabilizing agents is essential for maximizing pigment yield, purity, and functional properties. Proper control of these parameters minimizes protein denaturation and pigment degradation while improving the commercial feasibility of phycocyanin production (Jaeschke *et al.*, 2021; Yuan *et al.*, 2022) [8, 7].

Biomass Form

The physical state of *Arthrospira platensis* biomass significantly influences the extraction efficiency of phycocyanin. Both fresh and dried biomass have been employed for pigment recovery; however, dried biomass is generally preferred because of its longer storage stability and ease of handling. Prior rehydration of dried biomass before extraction has been shown to improve cell permeability, thereby enhancing phycocyanin release. Nevertheless, conventional drying at temperatures above 60 °C can cause irreversible protein denaturation and substantial pigment degradation. Therefore, mild drying techniques such as freeze-drying or vacuum drying are recommended to preserve pigment quality and maximize extraction efficiency (Jaeschke *et al.*, 2019; Tavanandi & Raghavarao, 2020) [23, 20].

Temperature

Temperature is one of the most critical factors governing both the extraction process and the stability of phycocyanin. Moderate temperatures facilitate the diffusion of intracellular pigments into the extraction medium, thereby improving extraction efficiency. However, excessive heat accelerates protein unfolding, chromophore degradation, and discoloration of the pigment. Experimental studies have demonstrated that phycocyanin remains relatively stable at temperatures up to approximately 45 ^ °C , whereas significant degradation occurs between 47 °C and 70 °C . Consequently, extraction and storage are generally recommended below 45 ^ °C to maintain pigment stability, antioxidant activity, and characteristic blue coloration (Antelo *et al.*, 2008; Böcker *et al.*, 2019; Su *et al.*, 2014) [24, 25, 26].

Light

Light intensity and spectral quality play a significant role in both phycocyanin biosynthesis during cultivation and pigment stability after extraction. Red light has been reported to enhance photosynthetic activity and stimulate higher phycocyanin production in *Arthrospira platensis* compared with blue light. Conversely, prolonged exposure of extracted phycocyanin to visible light, particularly at high intensities, accelerates photodegradation by promoting oxidative damage to the chromophore-protein complex. Therefore, phycocyanin extracts should be processed and stored under dark or low-light conditions to minimize pigment degradation and preserve antioxidant properties (Walter *et al.*, 2011; Choi & Lee, 2018; Wu *et al.*, 2016) [27, 21, 28, 29].

pH

The stability of phycocyanin is highly dependent on the pH of the extraction medium because pH influences protein conformation and chromophore integrity. Acidic conditions, particularly within the pH range of 3.0-4.0, promote protein precipitation and accelerate pigment degradation, resulting in substantial losses in color intensity and functional activity. In contrast, phycocyanin exhibits maximum stability under slightly acidic to neutral conditions, with an optimum pH range of approximately 5.5-7.0. Maintaining the extraction buffer within this range is essential for preserving the native protein structure and minimizing denaturation during processing and storage (Chaiklahan *et al.*, 2012; Patil & Raghavarao, 2007; Antelo *et al.*, 2008) [30, 31, 24].

Extraction Solvent

The choice of extraction solvent has a direct influence on the solubility, recovery, and stability of phycocyanin. Buffer systems provide better control of pH and ionic strength than distilled water, thereby improving protein stability throughout extraction. Sodium phosphate buffer (pH 6.8-7.0) is the most widely employed solvent because it consistently produces high extraction yields and pigment purity. Potassium phosphate buffer and calcium chloride solutions have also demonstrated satisfactory extraction performance, whereas acetate buffer generally results in comparatively lower pigment recovery. Therefore, solvent selection should consider both extraction efficiency and longterm stability of the extracted pigment (Jaeschke *et al.*, 2021; Pan-Utai & Iamtham, 2019; Gorgich *et al.*, 2020) [8, 16, 32, 23].

Biomass-to-Solvent Ratio

The biomass-to-solvent ratio is an important processing parameter that determines extraction yield, pigment concentration, and process economics. Increasing the solvent volume generally enhances mass transfer and improves phycocyanin recovery; however, excessive solvent dilution may simultaneously increase the extraction of contaminating proteins, thereby reducing pigment purity. Several studies have reported that biomass-to-solvent ratios ranging from 1:6 to 1:10 provide an appropriate balance between extraction efficiency and purity, although the optimal ratio varies according to biomass characteristics and extraction technique. Consequently, optimization of the biomass-to-solvent ratio is essential for achieving maximum pigment recovery while minimizing processing costs and downstream purification requirements (Tavanandi & Raghavarao, 2020; Jaeschke *et al.*, 2021; Pan-Utai & Iamtham, 2019) [20, 8, 16, 23].

Purification Techniques of Phycocyanin

Purification is an essential downstream processing step following the extraction of phycocyanin, as the crude extract contains various impurities, including contaminating proteins, carbohydrates, lipids, nucleic acids, and cell debris. The primary objective of purification is to enhance pigment purity while preserving its structural integrity, biological activity, and characteristic blue color. The required purity level depends on the intended application. Food-grade phycocyanin generally requires a purity ratio (A_{620}/A_{280}) of ≥0.7 , reagent-grade preparations require a purity of ≥3.9, and analytical-grade phycocyanin typically exceeds a purity ratio of 4.0. The selection of an appropriate purification strategy is therefore crucial to obtain high-quality phycocyanin suitable for food, pharmaceutical, cosmetic, or biomedical applications (de Morais *et al.*, 2018; Ashaolu *et al.*, 2021; Jaeschke *et al.*, 2021) [6, 33, 8].

Centrifugation

Centrifugation is the initial clarification step employed after extraction to separate insoluble cellular debris from the phycocyanin-containing supernatant. High-speed centrifugation effectively removes disrupted cell fragments and suspended particles, thereby reducing turbidity and facilitating subsequent purification processes. Although centrifugation does not significantly increase phycocyanin purity, it is an indispensable pretreatment that improves the efficiency of downstream purification techniques by minimizing particulate contaminants (de Morais *et al.*, 2018; Jaeschke *et al.*, 2021) [6, 8].

Ammonium Sulphate Precipitation

Ammonium sulphate precipitation is one of the most widely adopted methods for the partial purification and concentration of phycocyanin. This technique utilizes the principle of selective protein precipitation based on differences in protein solubility under increasing salt concentrations. Typically, sequential precipitation using 20-30% ammonium sulphate removes undesirable proteins, whereas phycocyanin is selectively precipitated at approximately 50-65% saturation. The recovered precipitate is subsequently dissolved in phosphate buffer for further purification. This method is simple, economical, and suitable for laboratory and pilot-scale production; however, complete removal of residual salt requires subsequent dialysis (Patil & Raghavarao, 2007; Pan-Utai & Iamtham, 2019) [31, 16].

Dialysis

Dialysis is commonly performed after salt precipitation to eliminate ammonium sulphate, lowmolecular-weight impurities, and other dissolved contaminants from the phycocyanin solution. In this technique, the protein solution is enclosed within a semi-permeable membrane that allows diffusion of salts and other small molecules into an external buffer while retaining the larger phycocyanin molecules. Dialysis improves protein purity and restores suitable buffer conditions for subsequent purification or analytical procedures. Although highly effective, the process is relatively slow and generally requires several hours to days at low temperatures to prevent pigment degradation (de Morais *et al.*, 2018; Pan-Utai & Iamtham, 2019) [6, 16].

Membrane Filtration

Membrane-based separation techniques, including ultrafiltration and microfiltration, are increasingly employed for phycocyanin purification due to their operational simplicity and scalability. These pressure-driven processes separate biomolecules according to molecular size, allowing concentration of phycocyanin while simultaneously removing low-molecular-weight impurities and residual cellular components. Membrane filtration offers several advantages, including reduced processing time, minimal thermal exposure, lower chemical consumption, and improved retention of biological activity. Consequently, it is considered a promising alternative for industrial-scale purification of phycocyanin (Ashaolu *et al.*, 2021; Jaeschke *et al.*, 2021) [33, 8].

Chromatographic Purification

Chromatographic techniques represent the most effective purification methods for obtaining highpurity phycocyanin suitable for pharmaceutical, analytical, and diagnostic applications. Ionexchange chromatography is the most commonly employed approach because phycocyanin possesses charged amino acid residues that facilitate selective binding to ion-exchange resins. Gel filtration chromatography further separates proteins based on molecular size, whereas hydrophobic interaction chromatography exploits differences in protein surface hydrophobicity. These chromatographic methods significantly enhance pigment purity while preserving its native conformation and fluorescence properties. However, their relatively high operational cost and longer processing time often limit their application to high-value products (Patil & Raghavarao, 2007; Ashaolu *et al.*, 2021; de Morais *et al.*, 2018) [31, 33, 6].

Applications of Phycocyanin

Phycocyanin is a naturally occurring blue phycobiliprotein predominantly isolated from *Arthrospira platensis* (*Spirulina*). Owing to its intense blue color, excellent water solubility, high nutritional value, antioxidant potential, and non-toxic nature, phycocyanin has gained considerable commercial and scientific attention. Beyond its application as a natural colorant, phycocyanin exhibits multiple biological activities, including antioxidant, anti-inflammatory, immunomodulatory, anticancer, hepatoprotective, and neuroprotective effects. These multifunctional properties have led to its widespread utilization in the food, nutraceutical, pharmaceutical, cosmetic, and biomedical sectors. The increasing consumer preference for natural ingredients and clean-label products has further accelerated the demand for phycocyanin in various industrial applications (de Morais *et al.*, 2018; Ashaolu *et al.*, 2021; Yuan *et al.*, 2022) [6, 33, 7].

Food Industry

The food industry represents the largest commercial application of phycocyanin due to its vibrant blue color and excellent safety profile. It is widely used as a natural food colorant to replace synthetic dyes in beverages, dairy products, confectionery, bakery products, ice cream, yogurt, candies, chewing gum, desserts, and functional foods. Unlike synthetic colorants, phycocyanin is biodegradable, non-toxic, and environmentally sustainable, making it highly attractive for cleanlabel food formulations. In addition to its coloring properties, phycocyanin enhances the nutritional value of foods by contributing antioxidant activity, thereby improving product functionality.

However, its application is limited in thermally processed foods because of its sensitivity to high temperature, acidic pH, and prolonged light exposure. Consequently, stabilization techniques such as encapsulation, controlled pH, and low-temperature processing are commonly employed to improve its industrial applicability (de Morais *et al.*, 2018; Eriksen, 2008; Ashaolu *et al.*, 2021) [6, 10, 33].

Nutraceuticals

Phycocyanin has emerged as an important nutraceutical ingredient owing to its diverse healthpromoting properties. Numerous experimental and clinical studies have demonstrated that phycocyanin exhibits potent antioxidant, anti-inflammatory, immunomodulatory, and free radicalscavenging activities, thereby reducing oxidative stress and protecting cellular components against damage. Regular consumption of phycocyanin-containing dietary supplements has been associated with improved immune function, enhanced liver protection, cardiovascular health, and metabolic regulation. Furthermore, its ability to inhibit lipid peroxidation and reduce inflammatory mediators makes it a promising functional ingredient for preventing chronic diseases associated with oxidative stress. Consequently, phycocyanin is increasingly incorporated into health supplements, functional beverages, protein powders, and fortified foods intended to promote overall well-being (Belay *et al.*, 1993; Ashaolu *et al.*, 2021; Yuan *et al.*, 2022) [34, 33, 7].

Pharmaceuticals

The pharmaceutical potential of phycocyanin has attracted significant research interest because of its broad spectrum of biological activities. Scientific investigations have demonstrated that phycocyanin possesses antioxidant, anti-inflammatory, antimicrobial, hepatoprotective, neuroprotective, and anticancer properties. It has been reported to inhibit the proliferation of various cancer cell lines by inducing apoptosis and regulating cell-cycle progression. Additionally, phycocyanin suppresses the production of inflammatory cytokines and reactive oxygen species, thereby reducing tissue damage associated with inflammatory disorders. Preclinical studies have also indicated its therapeutic potential in liver diseases, diabetes, cardiovascular disorders, neurodegenerative diseases, and acute lung injury. Although these findings are promising, further clinical trials are necessary to establish standardized dosage, efficacy, and long-term safety for pharmaceutical applications (Cherng *et al.*, 2007; Leung *et al.*, 2013; Liu *et al.*, 2000; de Morais *et al.*, 2018) [35, 36, 37, 6].

Cosmetics

The cosmetic industry has increasingly adopted phycocyanin as a natural bioactive ingredient because of its antioxidant, anti-aging, anti-inflammatory, and skin-protective properties. Phycocyanin effectively scavenges reactive oxygen species generated by ultraviolet radiation and environmental pollutants, thereby minimizing oxidative damage to skin cells. These properties contribute to improved skin hydration, enhanced collagen protection, delayed wrinkle formation, and reduced pigmentation. Moreover, its intense natural blue color enables its use as a coloring agent in cosmetic formulations, including facial masks, creams, lotions, shampoos, soaps, and personal care products. As consumer demand for plant-based and naturally derived cosmetic ingredients continues to increase, phycocyanin has become an attractive alternative to synthetic pigments and antioxidants (de Morais *et al.*, 2018; Ashaolu *et al.*, 2021) [6, 33].

Conclusion

Arthrospira platensis is a promising sustainable source of nutrients and the natural blue pigment Cphycocyanin with broad industrial applications. Advances in cultivation, extraction, and purification technologies have improved its commercial potential; however, challenges related to pigment stability and cost-effective large-scale production remain. Future research should focus on sustainable processing, enhanced stabilization techniques, and industrial-scale applications to maximize the utilization of phycocyanin in clean-label food products and health-related industries.

References

1. Lafarga T. Cultured microalgae and compounds derived thereof for food applications: Strain selection and cultivation, drying, and processing strategies. Food Reviews International. 2020;36(6):559-583.https://doi.org/10.1080/87559129.2019.1655513
2. Lim HR, Khoo KS, Chew KW, Chang CK, Munawaroh HSH, Kumar PS, *et al.* Perspective of *Spirulina* culture with wastewater into a sustainable circular bioeconomy. Environmental Pollution. 2021;284:117492.https://doi.org/10.1016/j.envpol.2021.117492
3. AlFadhly NKZ, Alhelfi N, Altemimi AB, Verma DK, Cacciola F. Tendencies affecting the growth and cultivation of genus *Spirulina*: An investigative review on current trends. Plants. 2022;11(22):3063.https://doi.org/10.3390/plants11223063
4. Paniagua-Michel J. Microalgal Nutraceuticals. In: Kim SK, editor. Handbook of Marine Microalgae: Biotechnology Advances. Academic Press; 2015:255-267.https://doi.org/10.1016/B978-0-12-800776-1.00017-0
5. Sorrenti V, Castagna DA, Fortinguerra S, Buriani A, Scapagnini G, Willcox DC. *Spirulina* microalgae and brain health: A scoping review of experimental and clinical evidence. Marine Drugs. 2021;19(6):293.https://doi.org/10.3390/md19060293
6. Dasgupta T, Banerjee S, Yadav PK, Rao AR. Chemomodulation of carcinogen metabolising enzymes, antioxidant profiles and skin and forestomach papillomagenesis by *Spirulina platensis*. Molecular and Cellular Biochemistry. 2001;226(1-2):27-38.https://doi.org/10.1023/A:1012721332221
7. Yuan B, Li Z, Shan H, Dashnyam B, Xu X, McClements DJ, *et al.* A review of recent strategies to improve the physical stability of phycocyanin. Current Research in Food Science. 2022;5:2329-2337.https://doi.org/10.1016/j.crfs.2022.11.021
8. Jaeschke DP, Teixeira IR, Marczak LDF, Mercali GD. Phycocyanin from *Spirulina*: A review of extraction methods and stability. Food Research International. 2021;143:110314.https://doi.org/10.1016/j.foodres.2021.110314
9. Glazer AN. Phycobiliproteins—a family of valuable, widely used fluorophores. Journal of Applied Phycology. 1994;6(2):105-112.https://doi.org/10.1007/BF02186064
10. Eriksen NT. Production of phycocyanin—a pigment with applications in biology, biotechnology, foods and medicine. Applied Microbiology and Biotechnology. 2008;80(1):1-14.https://doi.org/10.1007/s00253-008-1542-y
11. Sekar S, Chandramohan M. Phycobiliproteins as a commodity: Trends in applied research, patents and commercialization. Journal of Applied Phycology. 2008;20(2):113-136.https://doi.org/10.1007/s10811-007-9188-1
12. Silveira ST, Burkert JFDM, Costa JAV, Burkert CAV, Kalil SJ. Optimization of phycocyanin extraction from *Spirulina platensis* using factorial design. Bioresource Technology. 2007;98(8):1629-1634.https://doi.org/10.1016/j.biortech.2006.05.050
13. Tavanandi HA, Mittal R, Chandrasekhar J, Raghavarao K. Simple and efficient method for extraction of C-Phycocyanin from dry biomass of *Arthrospira platensis*. Algal Research. 2018;31:239-251.https://doi.org/10.1016/j.algal.2018.02.008
14. Chentir I, Hamdi M, Li S, Doumandji A, Markou G, Nasri M. Stability, biofunctionality and bio-activity of crude phycocyanin from a two-phase cultured Saharian *Arthrospira* sp. strain. Algal Research. 2018;35:395-406.https://doi.org/10.1016/j.algal.2018.09.013
15. Ilter I, Akyıl S, Demirel Z, Koç M, Conk-Dalay M, Kaymak-Ertekin F. Optimization of phycocyanin extraction from *Spirulina platensis* using different techniques. Journal of Food Composition and Analysis. 2018;70:78-88.https://doi.org/10.1016/j.jfca.2018.04.007
16. Pan-Utai W, Iamtham S. Extraction, purification and antioxidant activity of phycobiliprotein from *Arthrospira platensis*. Process Biochemistry. 2019;82:189-198.https://doi.org/10.1016/j.procbio.2019.04.014
17. Günerken E, D'Hondt E, Eppink M, Garcia-Gonzalez L, Elst K, Wijffels R. Cell disruption for microalgae biorefineries. Biotechnology Advances. 2015;33(2):243-260.https://doi.org/10.1016/j.biotechadv.2015.01.008
18. Garcia ES, Lo C, Eppink M, Wijffels R, van den Berg C. Understanding mild cell disintegration of microalgae in bead mills for the release of biomolecules. Chemical Engineering Science. 2019;203:380-390.https://doi.org/10.1016/j.ces.2019.04.010
19. Montalescot V, Rinaldi T, Touchard R, Jubeau S, Frappart M, Jaouen P, *et al.* Optimization of bead milling parameters for the cell disruption of microalgae: Process modeling and application to *Porphyridium cruentum* and *Nannochloropsis oculata*. Bioresource Technology. 2015;196:339-346.https://doi.org/10.1016/j.biortech.2015.07.095
20. Tavanandi HA, Raghavarao K. Ultrasound-assisted enzymatic extraction of natural food colorant C-Phycocyanin from dry biomass of *Arthrospira platensis*. LWT. 2020;118:108802.https://doi.org/10.1016/j.lwt.2019.108802
21. Choi WY, Lee HY. Kinetic analysis of stabilizing C-phycocyanin in the *Spirulina platensis* extracts from ultrasonic process associated with effects of light and temperature. Applied Sciences. 2018;8(9):1662.https://doi.org/10.3390/app8091662
22. Li Y, Zhang Z, Paciulli M, Abbaspourrad A. Extraction of phycocyanin—A natural blue colorant from dried spirulina biomass: Influence of processing parameters and extraction techniques. Journal of Food Science. 2020;85(3):727-735.https://doi.org/10.1111/1750-3841.15058
23. Jaeschke DP, Mercali GD, Marczak LDF, Müller G, Frey W, Gusbeth C. Extraction of valuable compounds from *Arthrospira platensis* using pulsed electric field treatment. Bioresource Technology. 2019;283:207-212.https://doi.org/10.1016/j.biortech.2019.03.076
24. Antelo FS, Costa JA, Kalil SJ. Thermal degradation kinetics of the phycocyanin from *Spirulina platensis*. Biochemical Engineering Journal. 2008;41(1):43-47.https://doi.org/10.1016/j.bej.2008.03.012
25. Böcker L, Ortmann S, Surber J, Leeb E, Reineke K, Mathys A. Biphasic short time heat degradation of the blue microalgae protein phycocyanin from *Arthrospira platensis*. Innovative Food Science & Emerging Technologies. 2019;52:116-121.https://doi.org/10.1016/j.ifset.2018.12.009

26. Su CH, Liu CS, Yang PC, Syu KS, Chiuh CC. Solid-liquid extraction of phycocyanin from *Spirulina platensis*: Kinetic modeling of influential factors. Separation and Purification Technology. 2014;123:64-68.https://doi.org/10.1016/j.seppur.2013.12.016
27. Walter A, De Carvalho JC, Soccol VT, De Faria ABB, Ghiggi V, Soccol CR. Study of phycocyanin production from *Spirulina platensis* under different light spectra. Brazilian Archives of Biology and Technology. 2011;54(4):675-682.https://doi.org/10.1556/ABot.49.2007.1-2.14
28. Wu HL, Wang GH, Xiang WZ, Li T, He H. Stability and antioxidant activity of food-grade phycocyanin isolated from *Spirulina platensis*. International Journal of Food Properties. 2016;19(10):2349-2362.https://doi.org/10.1080/10942912.2015.1114945
29. Wu Q, Liu L, Miron A, Klímová B, Wan D, Ku□a K. The antioxidant, immunomodulatory, and anti-inflammatory activities of *Spirulina*: An overview. Archives of Toxicology. 2016;90(8):1817-1840.https://doi.org/10.1007/s00204-016-1744-5
30. Chaiklahan R, Chirasuwan N, Bunnag B. Stability of phycocyanin extracted from *Spirulina* sp.: Influence of temperature, pH and preservatives. Process Biochemistry. 2012;47(4):659-664.https://doi.org/10.1016/j.procbio.2012.01.015
31. Patil G, Raghavarao KSMS. Aqueous two-phase extraction for purification of Cphycocyanin. Biochemical Engineering Journal. 2007;34(2):156-164.https://doi.org/10.1016/j.bej.2006.11.026
32. Gorgich M, Passos ML, Mata TM, Martins AA, Saraiva MLM, Caetano NS. Enhancing extraction and purification of phycocyanin from *Arthrospira* sp. with lower energy consumption. Energy Reports. 2020;6:312-318.https://doi.org/10.1016/j.egyr.2020.11.150
33. Ashaolu TJ, Samborska K, Lee CC, Tomas M, Capanoglu E, Tarhan Ö, Taze B, Jafari SM. Phycocyanin, a super functional ingredient from algae; properties, purification characterization, and applications. International Journal of Biological Macromolecules. 2021;193(Pt B):2320-2331.https://doi.org/10.1016/j.ijbiomac.2021.11.064
34. Belay A, Ota Y, Miyakawa K, Shimamatsu H. Current knowledge on potential health benefits of *Spirulina*. Journal of Applied Phycology. 1993;5(2):235-241.https://doi.org/10.1007/BF00004024
35. Cherng SC, Cheng SN, Tarn A, Chou TC. Anti-inflammatory activity of Cphycocyanin in lipopolysaccharide-stimulated RAW 264.7 macrophages. Life Sciences. 2007;81(19-20):1431-1435.https://doi.org/10.1016/j.lfs.2007.09.009
36. Leung P, Lee H, Kung Y, Tsai M, Chou T. Therapeutic effect of C-phycocyanin extracted from blue green algae in a rat model of acute lung injury induced by lipopolysaccharide. Evidence-Based Complementary and Alternative Medicine. 2013:Article 916590.https://doi.org/10.1155/2013/916590
37. Liu Y, Xu L, Cheng N, Lin L, Zhang C. Inhibitory effect of phycocyanin from *Spirulina platensis* on the growth of human leukemia K562 cells. Journal of Applied Phycology. 2000;12(2):125-130.https://doi.org/10.1023/A:1008132210772
38. Acker JP, McGann LE. Protective effect of intracellular ice during freezing? Cryobiology. 2003;46(2):197-202.https://doi.org/10.1016/S0011-2240(03)00025-1
39. Adjali A, Clarot I, Chen Z, Marchioni E, Boudier A. Physicochemical degradation of phycocyanin and means to improve its stability: A short review. Journal of Pharmaceutical Analysis. 2022;12(3):406-414.https://doi.org/10.1016/j.jpha.2022.03.001
40. Aftari RV, Rezaei K, Mortazavi A, Bandani AR. The optimized concentration and purity of *Spirulina platensis* C-phycocyanin: A comparative study on microwave-assisted and ultrasound-assisted extraction methods. Journal of Food Process Preservation. 2015;39(6):3080-3091.https://doi.org/10.1111/jfpp.12573
41. Batista AP, Raymundo A, Sousa I, Empis J. Rheological characterization of coloured oil-in-water food emulsions with lutein and phycocyanin added to the oil and aqueous phases. Food Hydrocolloids. 2006;20(1):44-52.https://doi.org/10.1016/j.foodhyd.2005.02.009
42. Credence Research. Algae products market size, growth and forecast 2028. 2023.https://www.credenceresearch.com/report/algae-products-market
43. Escalante FME, Pérez-Rico DA, Alarcón-Jiménez JL, González-Morales E, Guerra-Álvarez LF, Ramírez-Vázquez JC, *et al.* Phycocyanin thermo-photostability: An accelerated life-test analysis. Journal of the Mexican Chemical Society. 2020;64(3):218-229.https://doi.org/10.29356/jmcs.v64i3.1162
44. Faieta M, Neri L, Sacchetti G, Di Michele A, Pittia P. Role of saccharides on thermal stability of phycocyanin in aqueous solutions. Food Research International. 2020;132:109093.https://doi.org/10.1016/j.foodres.2020.109093
45. Ferreira-Santos P, Nunes R, De Biasio F, Spigno G, Gorgoglione D, Teixeira JA, *et al.* Influence of thermal and electrical effects of ohmic heating on C-phycocyanin properties and biocompounds recovery from *Spirulina platensis*. LWT. 2020;128:109491.https://doi.org/10.1016/j.lwt.2020.109491
46. Gantt E. Phycobilisomes: Light harvesting pigment complexes. BioScience. 1975;25(12):781-788.https://doi.org/10.2307/1297221
47. Hardy RR. Purification and coupling of fluorescent proteins for use in flow cytometry. In Weir DM, editor. Handbook of Experimental Immunology (4th ed.). Blackwell Scientific Publications; 1986.
48. Kato T. Blue pigment from *Spirulina*. New Food Industry. 1994;29:17-21.
49. Khandual S, Sanchez EOL, Andrews HE, de la Rosa JDP. Phycocyanin content and nutritional profile of *Arthrospira platensis* from Mexico: Efficient extraction process and stability evaluation of phycocyanin. BMC Chemistry. 2021;15:Article 24.https://doi.org/10.1186/s13065-021-00749-x
50. Kronick MN, Grossman PD. Immunoassay techniques with fluorescent phycobiliprotein conjugates. Clinical Chemistry. 1983;29(9):1582-1586.
51. Kulkarni SU, Badakere SS, Oswald J, Kamat MY. Fluorescent phycocyanin from *Spirulina platensis*: Application for diagnosis. Biotech Lab International. 1996:14-16.
52. Kupka M, Scheer H. Unfolding of C-phycocyanin followed by loss of non-covalent chromophore-protein interactions. 1. Equilibrium experiments. Biochimica et Biophysica Acta

(BBA) - Bioenergetics. 2008;1777(1):94-103.https://doi.org/10.1016/j.bbabio.2007.10.009
53. McCarty MF. 'Iatrogenic Gilbert syndrome'—a strategy for reducing vascular and cancer risk by increasing plasma unconjugated bilirubin. Medical Hypotheses. 2007;69(5):974-994.https://doi.org/10.1016/j.mehy.2006.12.069
54. Minkova KM, Tchernov AA, Tchorbadjieva MI, Fournadjieva ST, Antova RE, Busheva MC. Purification of C-phycocyanin from *Spirulina* (*Arthrospira*) fusiformis. Journal of Biotechnology. 2003;102(1):55-59.https://doi.org/10.1016/S0168-1656(03)00004-X
55. Mishra SK, Shrivastav A, Mishra S. Effect of preservatives for food grade C-PC from *Spirulina platensis*. Process Biochemistry. 2008;43(3):339-345.https://doi.org/10.1016/j.procbio.2007.12.012
56. Namasivayam SKR, Shivaramakrishnan K, Bharani RSA. Potential antioxidative protein-pigment complex *Spirulina platensis* mediated food grade phycocyanin C - Extraction, purification, antioxidative activity and biocompatibility. Indian Journal of Biochemistry & Biophysics. 2019;56(3):230-239.
57. Ores JDC, de Amarante MCA, Kalil SJ. Co-production of carbonic anhydrase and phycobiliproteins by *Spirulina* sp. and *Synechococcus nidulans*. Bioresource Technology. 2016;219:219-227.https://doi.org/10.1016/j.biortech.2016.07.112
58. Pott RWM. The release of the blue biological pigment C-phycocyanin through calciumaided cytolysis of live *Spirulina* sp. Coloration Technology. 2019;135(1):17-21.https://doi.org/10.1111/cote.12365
59. Prasanna R, Sood A, Suresh A, Nayak S, Kaushik BD. Potentials and applications of algal pigments in biology and industry. Acta Botanica Hungarica. 2007;49(1-2):131-156.https://doi.org/10.1556/ABot.49.2007.1-2.14
60. Romay C, González R. Phycocyanin is an antioxidant protector of human erythrocytes against lysis by peroxyl radicals. Journal of Pharmacy and Pharmacology. 2000;52(4):367-368.
61. Sathyasaikumar KV, Swapna I, Reddy PVB, Murthy CRK, Roy KR, Dutta Gupta A, *et al.* Co-administration of C-phycocyanin ameliorates thioacetamide-induced hepatic encephalopathy in Wistar rats. Journal of the Neurological Sciences. 2007;252(1):67-75.https://doi.org/10.1016/j.jns.2006.10.014
62. Chen T, Zheng W, Yang F, Bai Y, Wong YS. Mixotrophic culture of high seleniumenriched *Spirulina platensis* on acetate and the enhanced production of photosynthetic pigments. Enzyme and Microbial Technology. 2006;39(1):103-107.https://doi.org/10.1016/j.enzmictec.2005.10.001
63. Thoren KL, Connell KB, Robinson TE, Shellhamer DD, Tammaro MS, Gindt YM. The free energy of dissociation of oligomeric structure in phycocyanin is not linear with denaturant. Biochemistry. 2006;45(39):12050-12059.https://doi.org/10.1021/bi061140+
64. Uday Bhaskar S, Gopalaswamy G, Raghu R. A simple method for efficient extraction and purification of C-phycocyanin from *Spirulina platensis* Geitler. Indian Journal of Experimental Biology. 2005;43(3):277-279.
65. Vadiraja BB, Madyastha KM. C-phycocyanin: A potent peroxyl radical scavenger *in vivo* and *in vitro*. Biochemical and Biophysical Research Communications. 2000;275(1):20-25.https://doi.org/10.1006/bbrc.2000.3270
66. Wang H, Liu Y, Gao X, Carter CL, Liu ZR. The recombinant β subunit of Cphycocyanin inhibits cell proliferation and induces apoptosis. Cancer Letters. 2007;247(1-2):150-158.https://doi.org/10.1016/j.canlet.2006.04.002
67. Wicaksono HA, Satyantini WH, Masithah ED. The spectrum of light and nutrients required to increase the production of phycocyanin *Spirulina platensis*. IOP Conference Series: Earth and Environmental Science. 2019;236:012008.https://doi.org/10.1088/1755-