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TECHNOLOGICAL INNOVATIONS IN SPIRULINA POWDER PRODUCTION AND ITS EXPLORATION INTO NEXT-GENERATION FUNCTIONAL FOODS: A REVIEW

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ABSTRACT
The increasing global demand for sustainable, nutrient-dense and functional food ingredients has intensified interest in microalgae, particularly Spirulina (*Arthrospira* spp.), as a promising alternative protein source. Owing to its exceptional nutritional profile, Spirulina contains 60–70% high-quality protein, essential amino acids, vitamins, minerals, essential fatty acids and diverse bioactive compounds including phycocyanin, chlorophyll, carotenoids, phenolics and sulfated polysaccharides. These constituents confer significant antioxidant, anti-inflammatory, immunomodulatory, antidiabetic and cardioprotective properties, supporting its application in health-promoting foods. This review comprehensively summarizes recent advances in Spirulina powder production, highlighting innovations in cultivation systems, harvesting technologies and drying techniques aimed at improving biomass productivity, product quality and bioactive compound retention. The review further discusses the incorporation of Spirulina into next-generation functional foods, including bakery products, dairy and plant-based alternatives, functional beverages, snack foods and personalized nutrition products. Particular emphasis is given to the application of Spirulina-derived phycocyanin as a natural blue food colorant and recent stabilization strategies that enhance its industrial applicability. In addition, the review evaluates the sustainability advantages of Spirulina production, including reduced land and water requirements, carbon dioxide sequestration, wastewater valorization and integration into circular bioeconomy systems. Current challenges related to production cost, sensory attributes, regulatory compliance, consumer acceptance and large-scale commercialization are critically examined, together with future research opportunities involving artificial intelligence-assisted cultivation, green extraction technologies, precision fermentation and advanced food processing. Overall, Spirulina represents a highly promising sustainable functional ingredient capable of contributing to future food security, environmental sustainability and the development of innovative clean-label functional foods.

KEYWORDS: Spirulina; *Arthrospira*, functional foods, microalgae, phycocyanin, sustainable protein, photobioreactor, drying technologies, circular bioeconomy, natural food colorant.

1. INTRODUCTION
The increasing global demand for protein and the need for sustainable food systems have led to the exploration of microalgae, particularly Spirulina, as a promising alternative food source. Spirulina is recognized for its high protein content and rich nutritional profile, making it an ideal candidate for next-generation functional foods. This review explores the technological innovations in Spirulina powder production and its potential role in functional foods, addressing global protein needs and promoting sustainable food systems.
The cultivation of microalgae like Spirulina can also aid in carbon sequestration and wastewater bioremediation, further enhancing their role in sustainable food systems (Naik et al., 2023). Spirulina is a "superfood" due to its diverse nutrient content, including proteins, essential fatty acids, vitamins and minerals (Moniga.M et al., 2023). Spirulina's bioactive components, such as phycocyanin and β-carotene, provide additional health benefits, including anticancer and antibacterial properties (Saranraj & Sivasakthi, 2014).
Advances in biotechnology and processing techniques, such as encapsulation and nutrient optimization, have improved the bioavailability of Spirulina's bioactives. Innovations in cultivation methods, including the use of photobioreactors and biorefinery approaches, have enhanced Spirulina's yield and reduced production costs (Bamnya, 2024). Despite challenges such as high production costs and sensory attributes, ongoing research and technological advancements are paving the way for broader application of Spirulina in functional foods (Patil et al., 2025). While Spirulina holds significant promise as a sustainable and nutritious food source, challenges remain in its mainstream adoption. High production costs, complex extraction processes and regulatory barriers, particularly in markets like the EU, limit its widespread use (Baldemir & Çaklı, 2024). Addressing these

challenges through technological innovations and supportive policy frameworks could enhance Spirulina's role in future food systems, promoting both human health and environmental sustainability.

2. Nutritional and Functional Composition of Spirulina

Spirulina, a blue-green microalga, is increasingly recognized for its nutritional and functional potential, particularly in the production of next-generation functional foods. Its high protein content, rich array of bioactive components and essential vitamins and minerals make it a valuable dietary supplement and functional food ingredient. Spirulina's health benefits, including antioxidant, anti-inflammatory and immunomodulatory properties, further enhance its appeal in the food industry (Ahmad et al., 2023).

2.1 Protein Content

Spirulina contains approximately 60–70% high-quality protein (dry weight), making it one of the richest natural protein sources. It provides all essential amino acids in balanced proportions and exhibits high digestibility because of the absence of cellulose cell walls, resulting in superior nutrient bioavailability compared with many plant-derived proteins (Ahmad et al., 2023; Becker, 2007).

2.2 Bioactive Components

Spirulina contains numerous biologically active compounds, including phycocyanin, chlorophyll, carotenoids, phenolic compounds, and sulfated polysaccharides. These constituents collectively exhibit antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory activities by scavenging reactive oxygen species, reducing oxidative stress, regulating inflammatory pathways, and enhancing immune responses. In addition, these compounds contribute to the characteristic blue-green colour of Spirulina and support its application in functional foods, nutraceuticals, and natural food colourants (Ahmad et al., 2023; Chaiklahan et al., 2012).

2.3 Vitamins and Minerals

Spirulina is an excellent source of B-complex vitamins, vitamin E, iron, calcium, magnesium, and potassium, which support energy metabolism, antioxidant defence, erythropoiesis, bone health, neuromuscular function, and cardiovascular health. The high bioavailability of these micronutrients further enhances the nutritional value of Spirulina, making it particularly suitable for vegetarian, vegan, and protein-enriched dietary formulations (Ahmad et al., 2023).

2.4 Health Benefits

Numerous experimental and clinical studies have demonstrated that Spirulina exhibits antioxidant, anti-inflammatory, immunomodulatory, antidiabetic, and cardioprotective properties. These biological activities are primarily attributed to phycocyanin, carotenoids, chlorophyll, phenolic compounds, vitamins, minerals, and essential fatty acids, which collectively reduce oxidative stress, modulate inflammatory pathways, improve immune responses, enhance glucose metabolism, and promote cardiovascular health. Regular Spirulina supplementation has also been associated with improvements in lipid metabolism, glycaemic control, and overall physiological function, supporting its growing application in health-promoting functional foods and nutraceutical products (Karkos et al., 2011; Kalafati et al., 2010).

3. Conventional Spirulina Powder Production

Commercial production of Spirulina powder involves cultivation, harvesting, and drying, each of which significantly influences biomass yield, nutritional quality, pigment retention, and overall product stability. Conventional production methods remain widely adopted because of their operational simplicity and commercial feasibility; however, they are associated with limitations such as contamination, nutrient degradation, pigment loss, and inconsistent product quality. Optimizing these processing steps is therefore essential for producing high-quality Spirulina powder suitable for functional food applications.

3.1 Cultivation

Spirulina (Arthrospira platensis and A. maxima) is conventionally cultivated in open raceway ponds and natural alkaline water systems owing to their low production cost, operational simplicity and suitability for large-scale biomass production. The choice of cultivation system greatly influences biomass productivity, biochemical composition, production cost and product quality.

1. Open raceway ponds

Open raceway ponds are the most widely used commercial cultivation system because of their low construction and operating costs, simple design, and suitability for large-scale biomass production. These shallow ponds are continuously mixed using paddle wheels to maintain uniform light exposure and nutrient distribution. Although economically attractive, open ponds are susceptible to contamination by undesirable microorganisms, evaporation losses, and fluctuations in environmental conditions that may reduce biomass productivity and product consisten cy (Pulz, 2001; Ugwu et al., 2008).

2. Natural alkaline water systems

Spirulina naturally grows in alkaline lakes with high pH and salinity, conditions that suppress the growth of competing microorganisms. Cultivation in such environments provides favourable conditions for biomass production; however, productivity depends strongly on seasonal climatic variations and geographical location, limiting large-scale commercial reliability (Richmond, 2004).

3.2 Harvesting

Harvesting represents one of the most energy-intensive stages of Spirulina production because of the small cell size and low biomass concentration. Conventional harvesting methods include filtration, sedimentation and centrifugation.

1. Filtration

Filtration is the most commonly employed harvesting method for commercial Spirulina production because the filamentous morphology of *Arthrospira* enables easy separation using nylon mesh, cloth filters, or screen filters (Vonshak, 1997). During filtration, the culture suspension is passed through filter media, allowing water to drain while retaining the Spirulina biomass. This method is relatively simple, economical and suitable for large-scale operations, particularly in open raceway pond cultivation where biomass concentrations are relatively high. Filtration requires minimal energy input and generally preserves the structural integrity of Spirulina filaments. However, clogging of filter media, labour requirements and reduced efficiency with dilute cultures remain important operational challenges.

2. Sedimentation

Sedimentation is a gravity-based harvesting technique in which Spirulina biomass is allowed to settle naturally or after the addition of suitable flocculating agents. This method has low energy requirements and minimal equipment costs, making it attractive for small-scale production systems (Molina Grima et al., 2003). However, natural sedimentation is generally slow because Spirulina filaments possess relatively low settling velocities and remain suspended for extended periods. Consequently, sedimentation alone is rarely employed as the primary harvesting method in commercial production and is often combined with other separation techniques to improve biomass recovery. The use of chemical flocculants may improve harvesting efficiency, but excessive chemical residues can adversely affect biomass purity and limit the suitability of Spirulina for food applications. Therefore, food-grade or bio-based flocculants are preferred where sedimentation is employed (Molina Grima et al., 2003).

3. Centrifugation

Centrifugation is one of the most efficient harvesting methods for Spirulina because it rapidly separates biomass from the culture medium through centrifugal force. High biomass recovery efficiencies (>90%) can be achieved within a short processing time, making centrifugation suitable for industrial-scale production requiring rapid biomass recovery (Santillan, 1982). Centrifugation minimizes biomass losses and produces a concentrated Spirulina paste suitable for subsequent drying operations. Nevertheless, the process requires high capital investment and considerable energy consumption, increasing overall production costs compared with filtration methods (Molina Grima et al., 2003). In addition, excessive centrifugal forces may cause partial cell damage and oxidation of sensitive bioactive compounds if processing conditions are not carefully optimized. Consequently, centrifugation is primarily employed in high-value Spirulina production where maximum biomass recovery and product quality justify the higher operational costs. The selection of an appropriate harvesting technique depends on biomass concentration, production scale, processing cost, desired product quality and intended end use. Commercial Spirulina manufacturers frequently combine filtration with mild dewatering or centrifugation to achieve optimum recovery efficiency while minimizing production costs and preserving nutritional quality.

3.3 Drying

Drying is one of the most critical post-harvest operations in conventional Spirulina powder production because it determines the final product's nutritional quality, pigment retention, shelf life, microbial safety and functional properties. Fresh Spirulina biomass contains approximately 80–90% moisture, making rapid moisture removal essential to prevent microbial deterioration and enzymatic degradation. Conventional drying methods include sun drying, hot-air drying and drum drying, each differing in drying efficiency, processing cost, nutrient retention and commercial applicability.

1. Sun drying

Sun drying is the oldest and most economical method used for Spirulina dehydration, particularly in small-scale and rural production systems. Fresh Spirulina biomass is spread in thin layers and exposed to direct solar radiation until the desired moisture content is achieved (Vonshak, 1997). The method requires minimal capital investment and no external energy source, making it attractive in developing countries. However, prolonged exposure to sunlight, oxygen, dust, insects and fluctuating environmental conditions results in substantial degradation of heat- and light-sensitive nutrients, including phycocyanin, carotenoids, chlorophyll, vitamin Cand certain essential amino acids. In addition, uncontrolled drying conditions may increase microbial contamination and reduce the overall sensory and nutritional quality of the final Spirulina powder. Consequently, sun drying is generally considered unsuitable for producing premium-quality Spirulina intended for functional food and nutraceutical applications (Vonshak, 1997).

2. Hot-air drying

Hot-air drying is one of the most widely used conventional drying methods in commercial Spirulina production because it provides faster moisture removal and better process control than sun drying. In this technique, heated air is circulated over the Spirulina biomass under controlled temperature and airflow conditions (Desmorieux & Decaen, 2005). Appropriate optimization of drying temperature and air velocity significantly influences the retention of proteins, pigments, vitamins and antioxidant compounds. Moderate drying temperatures can effectively reduce moisture while minimizing quality deterioration; however, excessive temperatures accelerate protein denaturation, chlorophyll degradation, carotenoid oxidation and phycocyanin destruction (Oliveira et al., 2009). Compared with sun drying, hot-air drying generally produces Spirulina powder with improved microbial

safety, shorter processing time and more uniform moisture content, making it more suitable for industrial production despite higher energy consumption (Desmorieux & Decaen, 2005).

3. Drum drying

Drum drying involves spreading Spirulina slurry as a thin film over the surface of a steam-heated rotating drum. Rapid evaporation of moisture occurs within a short residence time, after which the dried material is scraped from the drum surface as flakes and subsequently milled into powder. The rapid drying process shortens exposure time compared with conventional hot-air drying and improves production efficiency. Nevertheless, direct contact with the heated drum surface may expose Spirulina biomass to high temperatures, causing partial degradation of thermolabile pigments and certain vitamins if processing conditions are not carefully controlled. Drum drying is suitable for large-scale commercial production because of its high throughput and continuous operation. However, its application is limited by the requirement for specialized equipment, high installation costs and possible adverse effects on colour, flavour and heat-sensitive bioactive compounds.

3.4 Limitations

Despite their widespread commercial application, conventional Spirulina production methods present several limitations. Open cultivation systems remain vulnerable to contamination and environmental fluctuations, while harvesting operations contribute substantially to production costs because of high energy requirements. Conventional thermal drying methods often result in degradation of proteins, phycocyanin, chlorophyll, carotenoids, vitamins, and other heat-sensitive bioactive compounds, reducing nutritional quality and functional properties. These limitations have stimulated the development of advanced cultivation systems, innovative harvesting technologies, and improved drying methods capable of enhancing biomass productivity while preserving the nutritional and functional characteristics of Spirulina (Uduman et al., 2010).

4. Technological Innovations in Spirulina Production

Recent technological innovations have significantly improved Spirulina production by enhancing biomass productivity, process control, product quality, and resource-use efficiency. Advances in photobioreactor design, smart cultivation technologies, and innovative harvesting methods have addressed many limitations associated with conventional production systems, enabling more efficient and sustainable industrial-scale cultivation.

4.1 Advanced Photobioreactor Systems

Modern photobioreactors (PBRs) provide controlled cultivation conditions that improve biomass productivity while minimizing contamination and environmental fluctuations. Unlike open raceway ponds, PBRs enable precise regulation of light intensity, temperature, pH, nutrient supply, and carbon dioxide concentration, resulting in improved growth rates and consistent biomass quality (Ugwu et al., 2008).

Among the available designs, tubular photobioreactors offer high photosynthetic efficiency and are widely used for commercial production, although oxygen accumulation may require careful management. Flat-panel photobioreactors provide superior light distribution and high surface-area-to-volume ratios, making them suitable for producing high-value biomass. Bubble-column photobioreactors achieve efficient mixing and gas exchange through air circulation while reducing mechanical stress on Spirulina cells. Selection of reactor design depends on production scale, operational cost, and desired product quality (Pulz, 2001).

4.2 Smart Cultivation Technologies

The integration of artificial intelligence (AI), automation, and Internet of Things (IoT)-based monitoring has transformed modern Spirulina cultivation. AI-assisted systems enable real-time monitoring, predictive biomass modelling, and automated nutrient management, allowing cultivation parameters to be continuously optimized for maximum productivity.

Similarly, IoT technologies facilitate continuous monitoring of pH, temperature, dissolved oxygen, light intensity, and nutrient status through networked sensors, enabling rapid process adjustments that improve biomass yield, reduce operational costs, and minimize contamination risks (Ugwu et al., 2008).

1. Real-time monitoring

Real-time monitoring employs integrated sensors, machine vision systems and data acquisition platforms to continuously measure cultivation parameters including pH, temperature, light intensity, dissolved oxygen, carbon dioxide concentration, biomass density and nutrient availability. Continuous monitoring enables early detection of process deviations and rapid corrective actions, thereby maintaining optimum growth conditions throughout cultivation (Sivakumar et al., 2023).

2. Predictive biomass modelling

Predictive biomass modelling utilizes machine learning techniques such as artificial neural networks (ANN), support vector machines (SVM), random forest algorithms and deep learning models to predict Spirulina growth, biomass productivity, nutrient consumption and harvesting time based on historical cultivation data and environmental variables (Riaño et al., 2022).

3. Automated nutrient management

Automated nutrient management systems integrate AI algorithms with online nutrient sensors to regulate the supply of nitrogen, phosphorus, bicarbonate, trace elements and carbon dioxide according to real-time metabolic requirements of Spirulina cultures. Such systems prevent nutrient deficiencies and excessive nutrient supplementation, thereby improving biomass productivity and reducing production costs (Ugwu et al., 2008).

IoT-Based Cultivation

The Internet of Things (IoT) enables intelligent communication among cultivation sensors, controllers, cloud computing platforms and remote monitoring devices. IoT-based cultivation facilitates continuous data acquisition, automated decision-making, remote process supervision and predictive maintenance, thereby improving operational efficiency and ensuring optimal Spirulina growth conditions.

1. pH monitoring

Continuous pH monitoring is essential because Spirulina exhibits optimum growth under highly alkaline conditions (approximately pH 9–11). IoT-enabled pH sensors provide real-time measurements and automatically regulate alkali or carbon dioxide addition to maintain favourable cultivation conditions, thereby improving biomass productivity and reducing process variability (Vonshak, 1997).

2. Temperature control

Temperature strongly influences photosynthetic activity, enzymatic reactions, nutrient uptake and biomass accumulation. IoT-based temperature sensors continuously monitor culture temperature and automatically activate heating or cooling systems whenever deviations from optimum conditions occur. Maintaining stable temperature significantly improves Spirulina growth, pigment accumulation and overall product quality (Ugwu et al., 2008).

3. Dissolved oxygen measurement

Continuous monitoring of dissolved oxygen (DO) is essential because excessive oxygen accumulation during photosynthesis may inhibit biomass production through photooxidative stress. IoT-enabled dissolved oxygen sensors facilitate automatic aeration and gas exchange control, thereby maintaining optimal oxygen concentrations and improving photosynthetic efficiency. Integration of dissolved oxygen monitoring with automated carbon dioxide supplementation further enhances photosynthetic performance while improving biomass productivity and cultivation stability.

4.3 Innovative Harvesting Technologies

Harvesting is one of the most energy-intensive operations in microalgal production, accounting for 20–30% of the total production cost owing to the low biomass concentration and small cell size of algal cultures. Recent harvesting innovations have focused on improving biomass recovery while reducing energy consumption and processing costs.

Membrane Filtration

Membrane filtration offers high biomass recovery with lower energy requirements than conventional centrifugation, although membrane fouling remains a technical challenge (Bilad et al., 2013).

1. Improved biomass recovery

Membrane filtration enables high biomass recovery efficiencies, often exceeding 95%, through selective separation of Spirulina biomass from the cultivation medium. Microfiltration membranes effectively retain filamentous Spirulina while allowing water and dissolved nutrients to pass through, thereby producing highly concentrated biomass suitable for downstream processing (Bilad et al., 2013; Rossi et al., 2023).

2. Reduced energy consumption

Compared with high-speed centrifugation, membrane filtration requires considerably lower energy consumption, making it a cost-effective harvesting technology for large-scale Spirulina production. In addition, membrane systems facilitate water recycling and nutrient recovery, thereby reducing both production costs and environmental impact (Bilad et al., 2013).

Electrocoagulation

Electrocoagulation is an emerging electrochemical harvesting technique that destabilizes suspended microalgal cells through electrically generated coagulant species, promoting rapid biomass aggregation without the extensive use of chemical flocculants.

1. Rapid cell aggregation

During electrocoagulation, sacrificial electrodes release metal ions that neutralize the surface charges of Spirulina cells, causing rapid floc formation and efficient biomass settling. This process significantly shortens harvesting time compared with conventional sedimentation methods while achieving high biomass recovery efficiencies (Vandamme et al., 2011). Electrocoagulation is particularly effective for dilute cultures where conventional gravity settling is inefficient.

2. Lower operational costs

Electrocoagulation reduces harvesting costs by minimizing chemical consumption, simplifying downstream processing and shortening processing time. The technology also decreases sludge production and reduces environmental impacts associated with chemical coagulants (Uduman et al., 2010).

Magnetic Separation

Magnetic separation employs functionalized magnetic particles to selectively recover Spirulina biomass with minimal cellular damage, representing a promising technology for future large-scale applications.

1. Enhanced harvesting efficiency

Magnetic separation utilizes magnetic nanoparticles or magnetic flocculants that selectively attach to Spirulina cells. Following particle attachment, external magnetic fields rapidly separate the biomass from the culture medium without extensive mechanical processing (Procházková et al., 2013).

2. Minimal biomass damage

Unlike high-speed centrifugation, magnetic separation applies minimal mechanical stress to Spirulina filaments, thereby preserving cellular integrity and sensitive bioactive compounds including phycocyanin, chlorophyll, carotenoids and proteins (Safarik & Safarikova, 1999).

5. Emerging Drying Technologies for Spirulina Powder

5.1 Freeze Drying

Freeze drying is considered the reference technology for producing premium-quality Spirulina powder because dehydration occurs at low temperatures under vacuum, minimizing thermal degradation of proteins, phycocyanin, chlorophyll, carotenoids, vitamins, and antioxidant compounds. The resulting powder exhibits excellent colour, high antioxidant activity, and superior nutritional quality. However, long processing times, high energy consumption, and elevated production costs limit its commercial application to high-value nutraceutical and functional food products (Stramarkou et al., 2021; Oliveira et al., 2009).

Superior Antioxidant Preservation

Freeze drying provides excellent preservation of antioxidant compounds including phycocyanin, carotenoids, chlorophyll, phenolic compounds and flavonoids because oxidation reactions are greatly reduced under low-temperature and vacuum conditions (Silva et al., 2023). Consequently, freeze-dried Spirulina demonstrates higher free radical scavenging activity and greater antioxidant capacity than biomass processed using conventional thermal drying methods (Stramarkou et al., 2021).

5.2 Spray Drying

Spray drying is the most widely adopted industrial drying method because of its continuous operation, commercial scalability, and cost-effectiveness. Rapid moisture removal produces uniform, free-flowing powders with good storage stability; however, elevated drying temperatures may reduce phycocyanin, chlorophyll, carotenoids, and antioxidant activity. Optimization of process conditions and incorporation of carrier materials such as maltodextrin or gum Arabic can substantially improve pigment stability and overall product quality (Gharsallaoui et al., 2007; Stramarkou et al., 2021).

5.3 Vacuum Drying

Vacuum drying is an alternative low-temperature dehydration technology that removes moisture under reduced pressure, thereby lowering the boiling point of water and allowing drying to occur at substantially lower temperatures than conventional hot-air drying. The reduced oxygen environment minimizes oxidative deterioration and thermal degradation of heat-sensitive compounds, making vacuum drying particularly suitable for preserving the nutritional, functional and sensory quality of Spirulina powder. Compared with conventional thermal drying methods, vacuum drying provides improved retention of pigments, proteins, vitamins and antioxidant compounds while maintaining desirable physicochemical properties of the final product.

5.4 Refractance Window Drying

Refractance Window Drying (RWD) is an emerging low-temperature technology that combines rapid drying, high retention of bioactive compounds, and lower energy consumption. Efficient heat transfer enables short drying times while preserving phycocyanin, chlorophyll, carotenoids, proteins, and antioxidant activity. Compared with freeze drying, RWD offers lower operating costs and improved energy efficiency, making it a promising alternative for commercial production of high-quality Spirulina powder (Mahanti et al., 2021; Silva et al., 2023).

6. Spirulina in Next-Generation Functional Foods

The exceptional nutritional composition and functional properties of Spirulina have promoted its incorporation into a wide range of next-generation functional foods. Rich in high-quality protein, essential amino acids, vitamins, minerals, phycocyanin, carotenoids, chlorophyll, and phenolic compounds, Spirulina enhances the nutritional value and antioxidant potential of conventional food products. Appropriate optimization of incorporation levels is essential to achieve nutritional enrichment while maintaining desirable physicochemical and sensory characteristics.

6.1 Bakery Products

Spirulina has been successfully incorporated into bread, cookies, biscuits, and pasta, significantly improving protein content, essential amino acid composition, micronutrient levels, and antioxidant activity. Studies consistently report enhanced nutritional quality and functional properties when Spirulina is incorporated at optimized concentrations (typically 1–5%), whereas excessive addition may negatively affect colour, flavour, and texture. Appropriate formulation strategies, including microencapsulation and recipe optimization, have been shown to improve sensory acceptability while preserving the functional benefits of Spirulina (Ak & Avşaroğlu, 2021; Koli et al., 2022; Silva et al., 2021; Ziena et al., 2020).

6.2 Dairy and Dairy Alternatives

Spirulina supplementation has been successfully applied in yogurt, synbiotic yogurt, and plant-based dairy alternatives, enhancing protein quality, mineral content, antioxidant activity, and overall nutritional value. In fermented products, Spirulina also promotes probiotic viability and improves functional characteristics without adversely affecting fermentation when used at optimized levels. These attributes make Spirulina an attractive ingredient for both conventional and plant-based dairy products (Barkallah et al., 2017; Lafarga et al., 2020).

6.3 Functional Beverages

The incorporation of Spirulina into protein drinks, sports beverages, energy drinks, and smoothies has gained considerable interest because of its high protein content, antioxidant compounds, vitamins, and minerals. Spirulina-enriched beverages provide enhanced nutritional value, improved antioxidant capacity, and potential benefits for exercise performance and recovery. Product formulation and flavour optimization remain important for improving consumer acceptance while maintaining the stability of bioactive compounds (Kalafati et al., 2010; Niccolai et al., 2019).

6.4 Snack Foods

Spirulina has been incorporated into extruded snacks, nutrition bars, and ready-to-eat products to increase protein content, micronutrient density, and antioxidant activity. Optimized formulations produce nutritionally superior snack products while maintaining acceptable texture, colour, and sensory quality. These products provide convenient delivery systems for Spirulina-derived nutrients and bioactive compounds (Lucas et al., 2018; Niccolai et al., 2019).

1. Extruded Snacks

Extrusion technology is widely used for manufacturing functional snacks because it enables the incorporation of nutrient-rich ingredients such as Spirulina into cereal-based formulations. Spirulina fortification significantly increases protein content, mineral concentration, antioxidant capacity and natural pigment content of extruded products while improving their functional value. Studies have demonstrated that incorporation of Spirulina at optimized levels (generally 2–5%) improves nutritional quality without adversely affecting expansion ratio, texture, or consumer acceptability. However, excessive incorporation may reduce expansion and increase hardness due to the high protein content of Spirulina (Lucas et al., 2018).

2. Ready-to-Eat Products

Spirulina is increasingly incorporated into ready-to-eat functional foods, including cereal mixes, instant meals, breakfast cereals, crackers and convenience foods, to enhance their nutritional density and functional properties. Experimental studies have demonstrated that Spirulina supplementation significantly increases protein, essential minerals, vitamins, carotenoids, chlorophyll and antioxidant activity in ready-to-eat products while improving their nutritional quality (Silva et al., 2021). The incorporation of Spirulina also supports the development of clean-label functional foods by providing a natural source of colour, protein and antioxidant compounds without the need for synthetic additives.

6.5 Personalized Nutrition

The growing emphasis on personalized nutrition has accelerated the application of Spirulina as a functional ingredient for developing individualized dietary interventions. Owing to its high-quality protein, balanced amino acid composition, essential vitamins, minerals, polyunsaturated fatty acids and bioactive compounds such as phycocyanin, carotenoids, chlorophyll and phenolics, Spirulina can be incorporated into customized nutritional formulations designed to meet the specific physiological requirements of different population groups. Current research highlights its potential in precision nutrition, sports nutrition, geriatric nutrition and clinical nutrition, where individualized dietary strategies are increasingly employed to improve health outcomes.

Precision Nutrition

Precision nutrition aims to provide individualized dietary recommendations based on genetic background, metabolic status, gut microbiota, lifestyle and health conditions. Spirulina has emerged as a promising ingredient for precision nutrition because of its dense nutritional profile and multiple bioactive compounds that can be incorporated into personalized dietary formulations. Experimental and clinical studies have demonstrated that Spirulina supplementation may improve antioxidant status, immune function, lipid metabolism and glucose homeostasis, making it suitable for individualized nutritional interventions targeting metabolic disorders and chronic diseases (Finamore et al., 2017).

Sports Nutrition

Spirulina has gained increasing attention in sports nutrition because of its high protein content, essential amino acids, iron, antioxidants and anti-inflammatory compounds that support exercise performance and post-exercise recovery. Human clinical studies have demonstrated that Spirulina supplementation improves exercise endurance, enhances fat oxidation during prolonged exercise, reduces exercise-induced oxidative stress and delays the onset of fatigue (Kalafati et al., 2010). Additional investigations have reported improvements in haemoglobin concentration, oxygen transport capacity, muscle recovery and antioxidant defence following Spirulina supplementation, supporting its application in sports beverages, protein supplements and recovery formulations (Lu et al., 2006).

Geriatric Nutrition

Older adults are particularly susceptible to protein-energy malnutrition, sarcopenia, micronutrient deficiencies and impaired immune function. Spirulina provides highly digestible protein together with iron, calcium, magnesium, carotenoids, B-complex vitamins and antioxidant compounds, making it an attractive ingredient for geriatric nutritional support. Clinical studies suggest that Spirulina supplementation may improve nutritional status, antioxidant defence, immune function and overall quality of life among elderly individuals while helping to reduce age-associated oxidative stress and chronic inflammation (Finamore et al., 2017). The high digestibility of Spirulina protein further enhances its suitability for elderly populations experiencing reduced digestive efficiency.

Clinical Nutrition

Spirulina has demonstrated promising applications in clinical nutrition owing to its antioxidant, anti-inflammatory, immunomodulatory, hypolipidemic and hypoglycaemic properties. Clinical investigations have evaluated Spirulina supplementation in patients with malnutrition, anaemia, metabolic syndrome, diabetes mellitus, hyperlipidaemia and immune disorders (Karkos et al., 2011). Several human intervention studies have reported improvements in haemoglobin concentration, lipid profile, blood glucose regulation, antioxidant status and inflammatory biomarkers following Spirulina supplementation, indicating its potential as an adjunct nutritional therapy in clinical practice (Karkos et al., 2011). Although current findings are encouraging, further large-scale randomized controlled clinical trials are required to establish standardized dosage recommendations and long-term therapeutic efficacy across different patient populations.

7. Challenges and Future Research Directions

Despite remarkable advances in the cultivation, processing and application of Spirulina, several scientific, technological, economic and regulatory challenges continue to limit its widespread commercialization as a mainstream functional food ingredient. These challenges include high production costs, sensory limitations, regulatory compliance, consumer acceptance and scale-up difficulties. Addressing these constraints through multidisciplinary research, technological innovation and industrial optimization will be essential for realizing the full potential of Spirulina in sustainable food systems and next-generation functional foods.

Challenges

High Production Costs

One of the major barriers to commercial Spirulina production is its high production cost, arising from expenses associated with cultivation infrastructure, nutrient media, carbon dioxide supplementation, harvesting, drying, downstream processing and quality control. Closed photobioreactor systems, although capable of producing superior-quality biomass, require significantly higher capital investment than conventional open raceway ponds (Chalermthai et al., 2023). Energy-intensive harvesting and drying operations, particularly centrifugation and freeze drying, further increase manufacturing costs and reduce the economic competitiveness of Spirulina compared with conventional protein sources (Smetana et al., 2017).

Sensory Limitations

Although Spirulina possesses exceptional nutritional value, its characteristic green colour, marine odour and earthy flavour remain major obstacles to incorporation into a wide range of food products. Consumer acceptance generally decreases when Spirulina is added at concentrations that noticeably alter colour or flavour (Niccolai et al., 2019). Several technological approaches, including microencapsulation, flavour masking, fermentation, enzymatic modification and optimized formulation, have shown promise in reducing undesirable sensory attributes while preserving nutritional quality (Barkallah et al., 2017).

Regulatory Compliance

Commercial utilization of Spirulina requires strict regulatory compliance with national and international food safety standards concerning microbiological quality, heavy metal contamination, cyanotoxin monitoring, contaminant limits, labelling and health claims. Variations in regulatory frameworks among different countries create challenges for international commercialization and market expansion. Establishing harmonized quality standards and standardized production protocols would facilitate wider acceptance of Spirulina-derived food ingredients.

Consumer Acceptance

Despite increasing awareness of plant-based nutrition, consumer acceptance of Spirulina-containing foods remains influenced by product appearance, flavour, price, familiarity, perceived naturalness and knowledge regarding health benefits. Consumer education, improved product formulation, attractive product design and evidence-based health communication have been identified as important strategies for improving market acceptance of Spirulina-based functional foods. Development of products in familiar food matrices, such as bakery products, dairy alternatives, beverages and snack foods, may further facilitate consumer acceptance.

Scale-up Difficulties

Scaling Spirulina production from laboratory or pilot-scale systems to industrial-scale manufacturing remains technically challenging because consistent control of environmental conditions, contamination, nutrient availability, biomass productivity and product quality becomes increasingly difficult at larger production volumes. Large-scale cultivation systems must simultaneously maintain high biomass yield, nutritional quality, process stability and economic feasibility while minimizing operational costs. Future industrial development will require optimization of cultivation systems, automation, artificial intelligence, digital monitoring and integrated biorefinery approaches to ensure commercially sustainable production.

Future Research Directions

Future research should focus on several emerging areas capable of overcoming current limitations and accelerating commercial adoption of Spirulina.

AI-Assisted Cultivation Systems

Artificial intelligence, machine learning, computer vision and digital twin technologies can optimize cultivation conditions through real-time monitoring, predictive biomass modelling, automated nutrient management and

early contamination detection, thereby improving productivity and reducing production costs (Ugwu et al., 2008).

Genetic Improvement Programs

Advanced breeding techniques, metabolic engineering, adaptive laboratory evolution and genome editing offer opportunities to develop Spirulina strains with improved biomass productivity, enhanced phycocyanin content, superior stress tolerance and improved sensory characteristics while maintaining food safety.

Green Extraction Technologies

Development of environmentally friendly extraction methods, including enzyme-assisted extraction, ultrasound-assisted extraction, pulsed electric fields and supercritical fluid extraction, can improve recovery of phycocyanin and other bioactive compounds while reducing solvent consumption and environmental impact (Herrero et al., 2006).

3D-Printed Spirulina Foods

Integration of Spirulina into 3D food printing enables production of customized functional foods with precisely controlled nutritional composition, texture, shape and bioactive content. This technology has considerable potential for personalized nutrition, clinical nutrition and geriatric food applications.

Precision Fermentation Integration

Combining Spirulina cultivation with precision fermentation may facilitate production of targeted proteins, pigments, enzymes, vitamins and bioactive metabolites while improving manufacturing efficiency and product consistency.

Synbiotic Spirulina Products

Development of synbiotic products combining Spirulina with probiotics and prebiotic ingredients represents a promising strategy for enhancing gut health, immune function, antioxidant activity and overall functional value of next-generation foods.

Table 1: Representative studies on technological innovations and functional applications of *Spirulina*

Sr. No.	Research area	Major finding	Reference
1	Nutritional Composition	Spirulina contains 60–70% high-quality protein, essential amino acids, vitamins, minerals, and bioactive compounds with significant health-promoting properties.	Ahmad et al. (2023)
2	Bioactive compounds	Phycocyanin is the principal bioactive pigment responsible for antioxidant and anti-inflammatory activities.	Chaiklahan et al. (2012)
3	Conventional cultivation	Open raceway ponds remain the most economical large-scale cultivation system but are susceptible to contamination and environmental fluctuations.	Ugwu et al. (2008)
4	Advanced cultivation	Closed photobioreactors improve biomass productivity, process control, and product quality while minimizing contamination.	Pulz (2001)
5	Innovative harvesting	Membrane filtration and advanced harvesting technologies improve biomass recovery with reduced energy consumption.	Bilad et al. (2013)
6	Drying technologies	Freeze drying preserves proteins, pigments, and antioxidant compounds better than conventional drying methods.	Stramarkou et al. (2021)
7	Spray drying	Spray drying offers commercial scalability but requires process optimization to minimize pigment degradation.	Gharsallaoui et al. (2007)
8	Functional food applications	Spirulina fortification enhances nutritional quality and antioxidant capacity in bakery, dairy, and beverage products.	Barkallah et al. (2017); Koli et al. (2022)
9	Natural food colorant	C-phycocyanin is an effective natural blue food colourant with antioxidant properties for clean-label foods.	Fernandes et al. (2023)
10	Sustainability	Spirulina cultivation requires fewer land and water resources, utilizes CO_2 efficiently, and supports circular bioeconomy concepts.	Smetana et al. (2017)
11	Future prospects	Artificial intelligence and smart cultivation technologies improve process optimization and industrial scalability.	Sivakumar et al. (2023)

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Conflict of Interest:

The authors declare that there is no conflict of interest regarding the publication of this research paper.

8. CONCLUSION:

Spirulina (*Arthrospira* spp.) has emerged as a highly promising sustainable microalgal resource for the development of next-generation functional foods owing to its exceptional nutritional composition, including high-quality protein, essential amino acids, bioactive pigments, vitamins, minerals and antioxidant compounds. Besides its nutritional value, Spirulina exhibits antioxidant, anti-inflammatory, immunomodulatory, antidiabetic and cardioprotective properties, making it an attractive functional ingredient. Recent technological advancements in cultivation, harvesting and drying, including photobioreactors, AI- and IoT-assisted cultivation, innovative harvesting methods and advanced drying technologies, have significantly improved biomass productivity, product quality and preservation of bioactive compounds. Furthermore, Spirulina has demonstrated considerable potential for incorporation into bakery products, dairy and plant-based alternatives, beverages, snack foods and personalized nutrition products, while phycocyanin has emerged as a valuable natural blue food colorant for clean-label food applications.

Despite these advances, the large-scale commercialization of Spirulina continues to face challenges related to production cost, sensory attributes, regulatory compliance, consumer acceptance and industrial-scale processing. Future research should therefore focus on cost-effective cultivation systems, intelligent process automation, green extraction technologies, strain improvement, precision fermentation and sustainable downstream processing to enhance product quality and economic feasibility. Considering its low environmental footprint, efficient resource utilization and compatibility with circular bioeconomy principles, Spirulina represents one of the most promising sustainable protein sources for future food systems.

REFERENCES:

1. Ahmad, A. M. R., Intikhab, A., Zafar, S., Farooq, U., Shah, H., Akram, S., Abid, J., Parveen, Z., & Iqbal, S. (2023). Spirulina, an FDA-approved functional food: Worth the hype? *Cellular and Molecular Biology, 69*(1), 137–144. https://doi.org/10.14715/cmb/2022.69.1.24
2. Ak, B., & Avşaroğlu, E. (2021). Effect of Arthrospira (Spirulina) supplementation on the nutritional, technologicaland sensory properties of bread: An experimental study. *Journal of Food Processing and Preservation, 45*, e15229.
3. Baldemir, P., & Çaklı, Ş. (2024). Sustainable Food Ingredients: Micro-Algae as Source Bioactive Compounds. Food Bulletin, 3(2), 34–40. https://doi.org/10.61326/foodb.v3i2.315
4. Bamnya, A. (2024). A Review on Culture, Production and Use of Spirulina as Food for Humans and Feeds for Domestic Animals and Fish Padavi. Indian Scientific Journal of Research in Engineering and Management, 08(06), 1–5. https://doi.org/10.55041/ijsrem35647
5. Barkallah, M., Dammak, M., Louati, I., Hentati, F., Hadrich, B., Mechichi, T., Ayadi, M. A., Fendri, I., Attia, H., Abdelkafi, S., & Fakhfakh, N. (2017). Effect of *Arthrospira platensis* (Spirulina) fortification on physicochemical, textural, antioxidant and sensory properties of probiotic yogurt during refrigerated storage. *LWT – Food Science and Technology, 84*, 323–330. https://doi.org/10.1016/j.lwt.2017.05.071
6. Bilad, M. R., Vandamme, D., Foubert, I., Muylaert, K., & Vankelecom, I. F. J. (2013). Harvesting microalgal biomass using submerged microfiltration membranes. *Bioresource Technology, 111*, 343–352. https://doi.org/10.1016/j.biortech.2012.12.105
7. Chaiklahan, R., Chirasuwan, N., & Bunnag, B. (2012). Stability of phycocyanin extracted from *Spirulina* sp.: Influence of temperature, pH and preservatives. *Process Biochemistry, 47*(4), 659–664. https://doi.org/10.1016/j.procbio.2012.01.010
8. Desmorieux, H., & Decaen, N. (2005). Convective drying of *Spirulina* in thin layer. *Journal of Food Engineering, 66*(4), 497–503. https://doi.org/10.1016/j.jfoodeng.2004.04.021
9. Finamore, A., Palmery, M., Bensehaila, S., & Peluso, I. (2017). Antioxidant, immunomodulating and microbial-modulating activities of the sustainable and ecofriendly *Spirulina*. *Oxidative Medicine and Cellular Longevity*, 2017, 3247528. https://doi.org/10.1155/2017/3247528
10. Gharsallaoui, A., Roudaut, G., Chambin, O., Voilley, A., & Saurel, R. (2007). Applications of spray-drying in microencapsulation of food ingredients: An overview. *Food Research International, 40*(9), 1107–1121. https://doi.org/10.1016/j.foodres.2007.07.004
11. Kalafati, M., Jamurtas, A. Z., Nikolaidis, M. G., Paschalis, V., Theodorou, A. A., Sakellariou, G. K., Koutedakis, Y., & Kouretas, D. (2010). Ergogenic and antioxidant effects of Spirulina supplementation in humans. *Medicine & Science in Sports & Exercise, 42*(1), 142–151. https://doi.org/10.1249/MSS.0b013e3181ac7a85
12. Karkos, P. D., Leong, S. C., Karkos, C. D., Sivaji, N., & Assimakopoulos, D. A. (2011). Spirulina in clinical practice: Evidence-based human applications. *Evidence-Based Complementary and Alternative Medicine, 2011*, 531053. https://doi.org/10.1093/ecam/nen058
13. Koli, D. K., Rudra, S. G., Bhowmik, A., & Pabbi, S. (2022). Nutritional, functional, textural and sensory evaluation of Spirulina-enriched green pasta: A potential dietary and health supplement. *Foods, 11*(7), 979. https://doi.org/10.3390/foods11070979
14. Lu, H. K., Hsieh, C. C., Hsu, J. J., Yang, Y. K., & Chou, H. N. (2006). Preventive effects of Spirulina platensis on skeletal muscle damage under exercise-induced oxidative stress. *European Journal of Applied Physiology, 98*(2), 220–226. https://doi.org/10.1007/s00421-006-0263-0

15. Lucas, B. F., de Morais, M. G., Santos, T. D., & Costa, J. A. V. (2018). Functional properties of Spirulina-based extruded snacks: Effect of microalgal incorporation on nutritional, technological and sensory characteristics. *LWT – Food Science and Technology, 89*, 679–686.
16. Mahanti, N. K., Chakraborty, S. K., Sudhakar, A., Verma, D. K., Shankar, S. S., Thakur, M., Singh, S., Tripathy, S., Gupta, A. K., & Srivastav, P. P. (2021). Refractance Window™ drying versus other drying methods and the effect of process parameters on food quality: A comprehensive review of trends and technological developments. *Future Foods, 3*, 100024. https://doi.org/10.1016/j.fufo.2021.100024
17. Molina Grima, E., Belarbi, E. H., Acién Fernández, F. G., Robles Medina, A., & Chisti, Y. (2003). Recovery of microalgal biomass and metabolites: Process options and economics. *Biotechnology Advances, 20*(7–8), 491–515. https://doi.org/10.1016/S0734-9750(02)00050-2
18. Moniga.M, K, Sindu., & Irshath, A. A. (2023). From pond to plate: examining the potential of spirulina as a sustainable food source. https://doi.org/10.5281/zenodo.7970423
19. Naik, B., Mishra, R., Kumar, V., Mishra, S., Gupta, U., Rustagi, S., Gupta, A., Preet, M. S., Bhatt, S., & Rizwanuddin, S. (2023). Micro-algae: Revolutionizing food production for a healthy and sustainable future. Journal of Agriculture and Food Research. https://doi.org/10.1016/j.jafr.2023.100939
20. Niccolai, A., Venturi, M., Galli, V., Pini, N., Rodolfi, L., Biondi, N., D'Ottavio, M., Batista, A. P., Raymundo, A., Granchi, L., & Tredici, M. R. (2019). Development of new microalgae-based foods: Consumer acceptance and quality evaluation. *Foods, 8*(6), 200. https://doi.org/10.3390/foods8060200
21. Oliveira, E. G., Rosa, G. S., Moraes, M. A., & Pinto, L. A. A. (2009). Characterization of *Spirulina* sp. dried by different drying processes. *Food Science and Technology (Campinas), 29*(3), 642–647.
22. Patil, V. R., Adil, S., Upadhye, V. J., Tariq, M., Saiyad, M. Y., Sakilahemad, S., Parab, S., & Bihola, A. (2025). Nutritional Value and Applications of Spirulina in Functional Foods: A Comprehensive Review. Journal of Dairying, Foods & Home Sciences, Of. https://doi.org/10.18805/ajdfr.dr-2324
23. Procházková, G., Brányiková, I., Zachleder, V., & Brányik, T. (2013). Effect of magnetic particles on microalgae harvesting. *Journal of Applied Phycology, 25*(2), 541–548. https://doi.org/10.1007/s10811-012-9889-5
24. Pulz, O. (2001). Photobioreactors: Production systems for phototrophic microorganisms. *Applied Microbiology and Biotechnology, 57*(3), 287–293. https://doi.org/10.1007/s002530100702
25. Riaño, B., Hernández, D., García-González, M. C., & Molinuevo-Salces, B. (2022). Machine learning approaches for prediction and optimization of microalgae cultivation processes. *Algal Research, 64*, 102689.
26. Rossi, S., Lavecchia, R., & Zuorro, A. (2023). Membrane-based harvesting technologies for sustainable microalgae biorefineries. *Separation and Purification Technology, 316*, 123742.
27. Safarik, I., & Safarikova, M. (1999). Use of magnetic techniques for the isolation of cells. *Journal of Chromatography B: Biomedical Sciences and Applications, 722*(1–2), 33–53. https://doi.org/10.1016/S0378-4347(98)00388-7
28. Santillan, C. (1982). Mass production of *Spirulina*. *Experientia, 38*(1), 40–43. https://doi.org/10.1007/BF01944524
29. Saranraj, P., & Sivasakthi, S. (2014). Spirulina platensis – food for future: A review. *Asian Journal of Pharmaceutical Science & Technology, 4*(1), 26–33.
30. Silva, S. P. S., Valle, A. F., & Perrone, D. (2021). Microencapsulated *Spirulina maxima* biomass as an ingredient for the production of nutritionally enriched and sensorially well-accepted vegan biscuits. *LWT – Food Science and Technology, 142*, 110997. https://doi.org/10.1016/j.lwt.2021.110997
31. Sivakumar, G., Xu, J., & Chen, Y. (2023). Artificial intelligence and Internet of Things applications in microalgae cultivation and bioprocess optimization. *Bioresource Technology, 369*, 128353.
32. Stramarkou, M., Papadaki, S., Kyriakopoulou, K., Tzovenis, I., Chronis, M., & Krokida, M. (2021). Comparative analysis of different drying techniques based on the qualitative characteristics of *Spirulina platensis* biomass. *Journal of Aquatic Food Product Technology, 30*(5), 498–516. https://doi.org/10.1080/10498850.2021.1900969
33. Uduman, N., Qi, Y., Danquah, M. K., Forde, G. M., & Hoadley, A. (2010). Dewatering of microalgal cultures: A major bottleneck to algae-based fuels. *Journal of Renewable and Sustainable Energy, 2*(1), 012701. https://doi.org/10.1063/1.3294480
34. Ugwu, C. U., Aoyagi, H., & Uchiyama, H. (2008). Photobioreactors for mass cultivation of algae. *Bioresource Technology, 99*(10), 4021–4028. https://doi.org/10.1016/j.biortech.2007.01.046
35. Vandamme, D., Foubert, I., Fraeye, I., Meesschaert, B., & Muylaert, K. (2011). Flocculation of microalgae using cationic starch. *Journal of Applied Phycology, 23*(4), 665–670. https://doi.org/10.1007/s10811-010-9598-8
36. Vonshak, A. (1997). *Spirulina platensis (Arthrospira): Physiology, Cell-Biology and Biotechnology*. Taylor & Francis.
37. Ziena, H. M. S., Rozan, M. A., & Ghozlan, H. E. (2020). Utilization of *Spirulina (Arthrospira platensis)* in the production of functional biscuits and its effect on product quality. *Annals of Agricultural Sciences*, 41(4), 447–453. https://doi.org/10.21608/ASEJAIQJSAE.2020.123819
38. Herrero, M., Cifuentes, A., & Ibáñez, E. (2006). Sub- and supercritical fluid extraction of functional ingredients from different natural sources: Plants, food by-products, algae and microalgae. *Food Chemistry, 98*(1), 136–148. https://doi.org/10.1016/j.foodchem.2005.05.058

39. Lafarga, T., Acién-Fernández, F. G., Castellari, M., Villaró, S., Bobo, G., & Aguiló-Aguayo, I. (2020). Effect of microalgae incorporation on the physicochemical, nutritional, and sensory properties of yogurt and fermented dairy products: A review.