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Review

Unveiling the Potential of *Spirulina* Biomass—A Glimpse into the Future Circular Economy Using Green and Blue Ingredients

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Abstract: The present work aims to explore *Spirulina* biomass' functional and technological marvels and its components, such as C-phycocyanin (C-PC), in modern food systems from a circular economy perspective, evaluating a decade of insights and innovations. This comprehensive review delves into the pivotal studies of the past decade, spotlighting the vital importance of maintaining stability in various food matrices to unleash the full biological impacts. Through the lens of food science intertwined with circular economy principles, this analysis meets health and environmental requisites and explores the harmonious synergy between food systems, economy, and industry. While *Spirulina* has typically served as a supplement, its untapped potential as a fundamental food ingredient has been unveiled, showcasing its abundant nutritional and functional attributes. Technological hurdles in preserving the vibrant color of C-PC have been triumphantly surmounted through simple temperature control methods or cutting-edge nanotechnology applications. Despite the gap in sensory acceptance studies, the emergence of blue foods introduces groundbreaking functional and innovative avenues for the food industry.

Keywords: bioactive compounds; antioxidant activity; natural dye; technological ingredient; food industry; circular economy

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1. Introduction

In a global scenario encompassing the closely linked triad of climate change, undernutrition, and obesity, and the synergy of these epidemics, i.e., the Global Syndemic [1], the food industry must engage in strategic planning. Complex problems call for elaborate solutions. It takes technological, legal, economic, and strategic effort to reverse the Global Syndemic. To get ahead of such a joint effort, new products (mainly from vegetarian sources) and technologies for food processing are needed, where the production chains respect the environment and the food and nutrition security of the population.

Cyanobacteria of the genus *Spirulina* (*Arthrospira platensis*) have great nutritional composition, mainly due to their high protein content. They are not dependent on land, as with conventional agriculture and livestock farming. *Spirulina* biomass can be cultivated in photobioreactors or opened systems with wastewater [2,3]. Thus, the recovery of promising sources of non-animal proteins and bioactive compounds such as C-PC and allophycocyanin can be carried out respecting the environment and circular economy

concepts since soil biodiversity is protected, pollution is prevented from occurring at the outset, and value-added products are created, such as biofuel, green electricity [3], natural food dye [4,5] and food packaging [6], among others.

C-PC is the most abundant photosynthetic pigment among the *Spirulina* phycobiliproteins and the one with the most expressive antioxidant activity [7], acting on the cellular activation of antioxidant enzymes, inhibition of DNA damage, inhibition of lipid peroxidation, and neutralization of free radicals [7–9]. Anti-inflammatory, anticarcinogenic, and immunomodulatory properties are also reported in the literature [10–12].

Spirulina extract was recognized by the US Food and Drug Administration as a safe ingredient, had its use regulated as a colorant exempt from certification, and was permanently listed for food use by the Code of Federal Regulations (Title 21, Chapter 1, Subchapter A, Part 73) for application in chewing gum, dessert toppings and coatings, frozen desserts, ice cream, yogurt, and cottage cheese, among other food uses [13]. As it is a water-soluble pigment with a strongly fluorescent blue color, C-PC has been remarkably used with a technological function in food science as a stable natural food dye with antioxidant properties in ice cream [4] and even as a texturizing agent in the form of an emulsifier [14,15]. These food applications can be considered substantial, considering that color is associated with the sensory appeal of food [16,17], and color stability is a great challenge for the industry.

C-PC, if regularly consumed as a food product ingredient, can be related to health benefits, and it is in line with healthy eating trends around the world, as 31% of the average global consumers are willing to pay for food without artificial colors [18,19]. On the other hand, blue food is perceived as less natural since the natural blue color is infrequent compared to green, yellow, and red, colors that the industry has already commercialized. Consequently, natural blue food dyes can be considered the future of the food industry that seeks innovations to call consumers' attention in the face of a highly competitive market [20]. Innovative methods such as 3D food printing and electrospinning (Figure 1) can create several new food shapes, adjustable textures, and improve the thermal stability of the bioactive compounds [21,22], respectively. This process, in isolation or combination, will bring unusual colors and food appearances to the market.

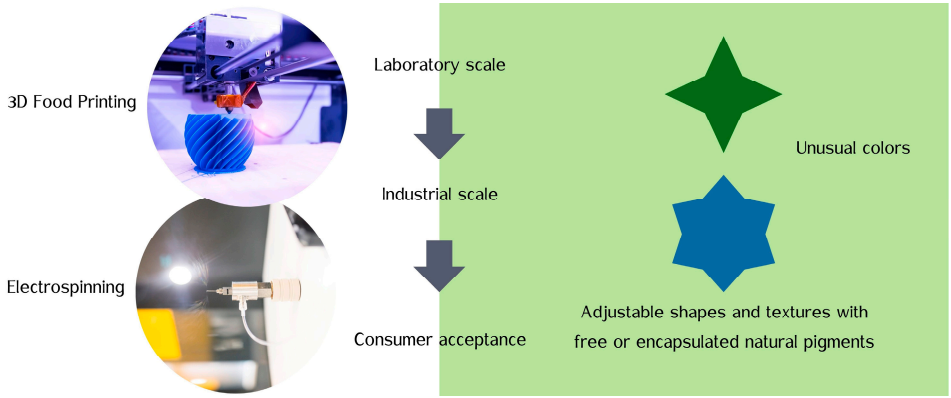


Figure 1. Innovative methods for reaching a competitive mark with new blue and green food colors.

Correspondingly, the present work aims to explore *Spirulina* biomass' functional and technological marvels and its components, such as C-phycocyanin (C-PC), in modern food systems from a circular economy perspective, evaluating a decade of insights and innovations.

2. Materials and Methods

An investigation was carried out in the Elsevier Scopus database to understand the main aspects regarding the contributions of C-PC extracted from *Spirulina* biomass to publications reporting food product development. The search criteria strategy was as follows: ((“Spirulina” AND “platensis” OR “phycocyanin” OR “C-phycocyanin”) AND

("food product" OR "food application" OR "functional food" OR "food technology" OR "incorporation" OR "fortification" OR "enrichment" OR "packaging" OR "biotechnology")). A total of 429 articles were found since 1971; after a limitation time considering the years from 2012 to 2024, 310 articles were evaluated; among these, 69 studies were within this review's scope. The VosViewer 1.6.13 software created the bibliometric network visualization map (Figure 2).

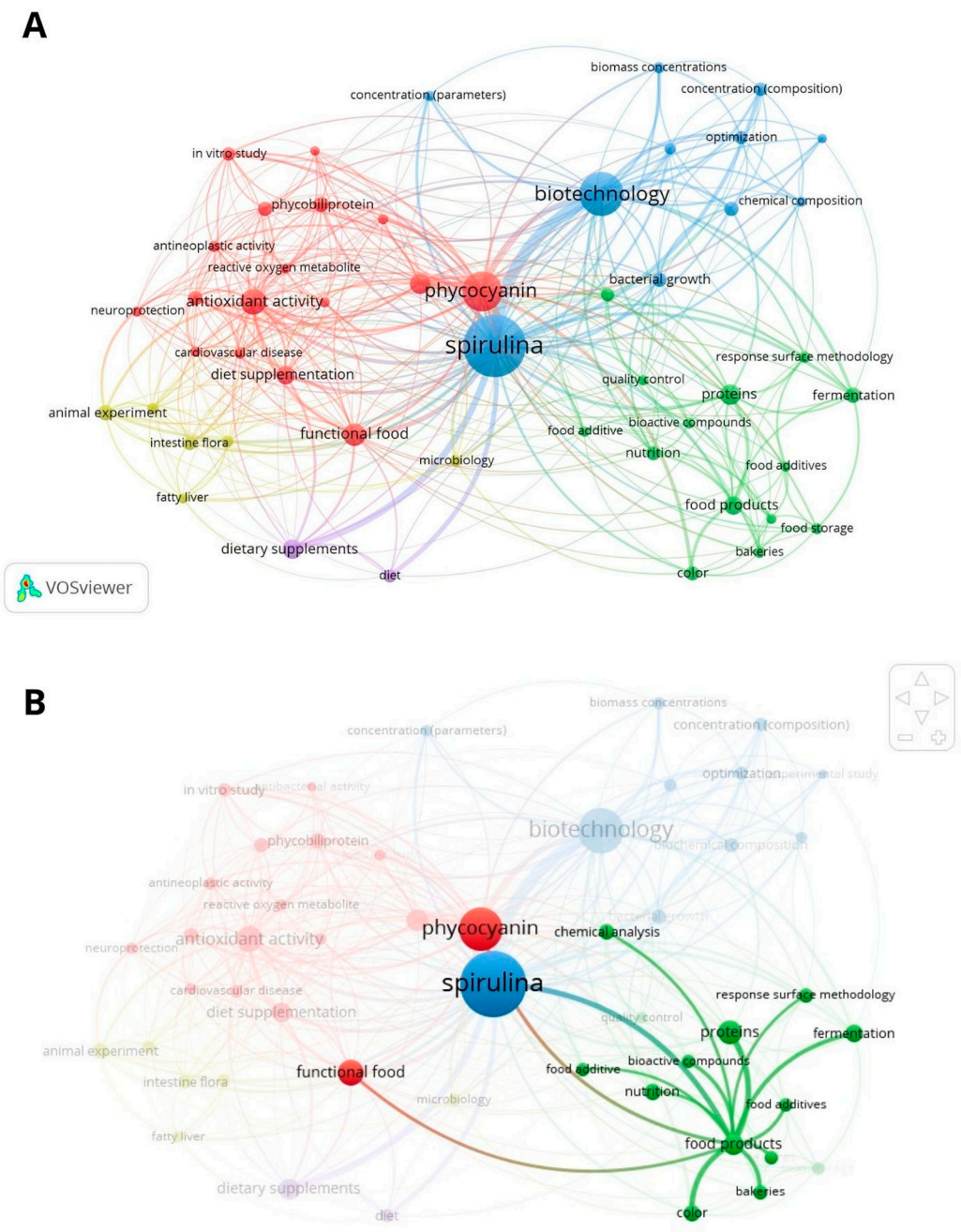


Figure 2. Network visualization map resulting from Scopus keyword insertion "phycocyanin OR *Spirulina* AND food products development" (2012–2024) (**A**); image representing the keyword links of nutritional and technological food usage of phycocyanin from *Spirulina* (**B**)—data from VosViewer software version 1.6.13.

Figure 2A shows five clusters, represented by different colors (blue, red, green, yellow, and purple), where the related terms are described. The terms "*Spirulina*", "biotechnology", and "phycocyanin" are the most relevant, characterized by more prominent labels (nodes)

than the others. Small labels but also essential terms, in red, are related to metabolic characteristics of phycocyanin: "antioxidant activity", "functional food", and "diet supplementation"; in green, representing nutritional and technological food usage of *Spirulina*: "food products", "proteins", "fermentation", "color", "food storage", "quality control", "response surface methodology", and "bakeries" (Figure 2B), which identify the most substantial ties (thick connectors) and weakest connections (thin connectors) that correspond to the most frequent and least frequent co-occurrences between the terms, respectively [23]. Therefore, this analysis was appropriate to incite and elucidate perspectives regarding the terms highlighted and how the scientific literature has addressed C-PC in food applications. Henceforth, the most meaningful studies for this review's aims were covered.

3. Results

3.1. C-PC and Spirulina Biomass Applications in Food-Related Products

Spirulina, a type of microalgae and a common or commercial term encompassing a group of cyanobacteria species with *Arthrospira platensis*, serves as the most prevalent and extensively used strain and has been prevalent in commercial food production for an extensive period. These microalgae have established their reputation as a nutrient-dense food source, mainly due to their elevated protein content. Analysis has revealed that *Spirulina* comprises approximately 20% carbohydrates, 50–70% protein, 5% lipids, 7% minerals, and 3 to 6% moisture. Notably, *Spirulina* contains phycobiliproteins, vividly pigmented and water-soluble proteins. These proteins, specifically allophycocyanin and C-phycocyanin, offer promising value in production potential and multifaceted applications [23].

Spirulina has been notably endorsed by the United Nations for combating hunger and malnutrition in developing nations and is even utilized by the International Space Station to sustain astronauts with essential nutrients and oxygen. Beyond its nutritional value, *Spirulina* exhibits remarkable abilities in carbon fixation, nitrogen fixation, and metal ion adsorption, which have sparked interest in various sectors aiming to address environmental concerns, achieve carbon neutrality, and advance renewable energy sources [24].

C-phycocyanin, a key constituent of the phycobiliprotein family, stands out due to its significant production appeal and diverse usage. This compound finds application not only as a natural dye and food ingredient but also as a therapeutic agent with fluorescence properties. The biomedical community is keenly interested in phycocyanin, recognizing its potential antiviral, anti-tumoral, and anti-inflammatory properties. However, notwithstanding its valuable properties, extracting phycocyanin from *S. platensis* generates substantial by-products that warrant consideration [7].

Synthetic additives generally have better chemical properties and physical stability and are less expensive than natural additives, but the demand for natural foods has increased considerably in recent years. Additionally, the application of natural substances, such as C-PC, has been gaining visibility precisely due to its health benefits, as already mentioned [7,20]. Besides being used as a food additive, C-PC has been used as a fluorescent marker to monitor cells and macromolecules in biomedical research [25], to develop medication [26], to elaborate innovative packaging [6], and in nanotechnology [27,28]. Those are only some potential applications of this bioproduct that demand different purities. In this context, other target compounds are present (e.g., proteins and polyunsaturated fatty acids) in the same biomass that C-PC is obtained from, which makes *Spirulina* a significant matrix to be extensively exploited in the food industry while attenuating production costs and rising above the gap of the natural additives for protein fortification, coloring, and texturing, or even substituting conventional plastic food packaging. The biggest obstacles to applying *Spirulina* more widely in foodstuff are the consistency of the dry biomass, its solid green color, and its slight fishy odor [29].

On this matter, *Spirulina* fermentation resulted in overall smell improvement, thus being beneficial for off-flavor reduction [30]; hence, it is another strategy for food incorporation. Furthermore, adding C-PC or isolated/concentrated *Spirulina* proteins to foods can help increase palatability and consumer acceptance [31,32].

Most studies handle the incorporation of *Spirulina* biomass into food products, intending to improve the product's nutritional profile. Bakery, pasta, and dairy products are the main studied matrices for new product development [29]. Table 1 summarizes the incorporation of *Spirulina* into food products in the last five years, using robust methodologies to analyze *Spirulina*'s role in the outcomes. Studies with isolated proteins or polysaccharides from *Spirulina* were excluded from Table 1. Antioxidant activity and sensory acceptability are only sometimes analyzed, representing a gap in food science research. However, the included studies in the present review provide an overview regarding *Spirulina* biomass applications in food, notably for increasing the protein content and/or as a texture improver for softening [33] or hardening [34], depending on the interactions between the polymers applied in the formulations. For instance, carboxymethyl cellulose and maltodextrin led to softening, due to their hydrophilic behavior, in a rice coating loaded with *Spirulina*.

Table 1. *Spirulina* has been incorporated into food products in recent years.

Food Product	Technological Function	*Spirulina* Ratio	Physicochemical Characteristics	Antioxidant Activity	Main Effects	Reference
Fermented whey-based sports beverage	Nutritional composition, probiotic profile, rheology, and sensory acceptance	0.25%, 0.5%, and 0.75% (*w*/*w*)	Total solids, protein, fiber, vitamins, and minerals were higher in the samples containing *Spirulina* and insignificant differences in fat or ash compared to the control samples	[1] TPC: 65.15, 68.19, and 70.05 mg [2] GAE/100 g in the samples loaded with *Spirulina* versus 60.75, 63.80 GAE/100 g in the control samples	0.5% of *Spirulina* resulted in good sensory acceptance. *Spirulina* are directly related to textural quality of the final products and pH decrease. All fermented beverage samples presented more than 7 log CFU/mL probiotic bacteria throughout storage	[35]
Vegan emulsions	Nutritional composition, natural pigment, and stabilizing agent	3% (*w*/*w*) proteins in the emulsions were composed by residual biomass (after extracting C-phycocyanin) at 0%, 25%, 50%, 75%, and 100%) and chickpea protein	Predominantly elastic behavior; shear tinning behavior typical of protein-stabilized emulsions. Emulsions with 100% residual biomass showed highest adhesiveness and firmness; at 75% and 50%, these parameters decreased; at 25%, no significant difference were assed compared to control.	[3] DPPH ranged from 15.4 ± 0.16 to 43.0 ± 1.5 and [4] FRAP from 169.38 ± 5.75 to 343.91 ± 21.12, respectively	Residual biomass led to a decrease in droplet sizes of the emulsions and improved the antioxidant activity of the formulations. The formulations' color was stable alongside 30 days of tests	[32]
Vegan snacks	Nutritional composition and sensorial attributes	0%, 4%, and 8% combined with finger millet and gram flour	Moisture content ranged from 1% to 3%; ash from 1% to 3.5%; from 2% to 4.5% in the extruded product. The percentage of protein increased with the addition of the *Spirulina* powder	-	Protein denaturation diminished with *Spirulina* incorporation in the snacks, observed after the frying process. *Spirulina* increased the protein and ash content while decreased the fat content due to high fiber and protein of the formulations. The shelf life that maintained the sensory attributes in acceptable scores was 90 days. The overall acceptability decreased as the storage time increased	[36]
Ricotta cheese	Nutritional composition, microstructure improvement, and sensorial attributes	0%, 0.25%, 0.5%, 0.75%, and 1.0% (*w*/*w*)	Total solids, protein, fat, ash, carbohydrate, fiber, minerals, and pH showed a significant increase; however, the acidity was comparatively lower compared to control samples	TPC: 7.03 ± 0.08 mg *versus* 5.11 ± 0.07 mg (GAE/g); DPPH: 20.27 ± 0.80% *versus* 15.25 ± 0.41% in the samples with *Spirulina* at 1% and control ricotta cheese	*Spirulina* led to increment in hardness at the start and the end of 21 days of storage, while decreased cohesiveness, gumminess, and chewiness values. Incorporation of 0.75% was the optimum concentration for structure and sensory acceptance	[34]
Buttermilk	Nutritional composition and fermentation process improvement	0%, 0.25%, 0.5%, and 1%	Protein significantly increased from 1.71 to 1.83 g/100 g and fat was not affected comparing control and 0.25% *Spirulina* concentration	DPPH ranged from 41.99% to 48.19%; TPC ranged from 2.44 to 4.21 mg/g GAE both essays for control and 0.25% *Spirulina* loaded	The best sensory acceptance was achieved for buttermilk containing 0.25% *Spirulina*. The microbial findings from this study indicate that *Spirulina* might promote the proliferation of lactic acid bacteria for prebiotic algae-based	[37]

Table 1. *Cont.*

Food Product	Technological Function	*Spirulina* Ratio	Physicochemical Characteristics	Antioxidant Activity	Main Effects	Reference
Soy protein isolate hydrogel	Rheological properties and microstructure improvement	0% to 8%	Hydrogels presented predominantly elastic behavior and as the concentration of *Spirulina* increased, the entanglement of molecules within the hydrogel also rose	-	Pre-thermal treatment followed by high-speed shearing led to *Spirulina* cell wall damage, releasing protein and carbohydrates that formed dense hydrogels. *Spirulina* enhanced the rigidity and compactness of the hydrogels	[38]
Biscuit	Texture parameter improvement	0%, 1%, 2.5%, and 4%	*Spirulina* at 4% improved protein and amino acid content (e.g., alanine, lysine, glutamic acid, aspartic acid, arginine, serine, threonine, tryptophan, and valine) of biscuits	-	Hardness and crispness of the biscuits were improved at 4% *Spirulina* incorporation. The same were observed in the color, aroma, taste, and texture parameters	[39]
White chocolate	Nutritional composition and sensory attributes	0.5%, 1%, 2%, and 4%	Improved viscosity at all concentrations, except compared to control	-	No significant ($p > 0.05$) difference in sensory acceptance compared to control	[40]
Kefir	Nutritional composition and functional properties	0.05%, 0.1%, 0.5%, 1%, and 2% (w/v)	-	DPPH: 22.2% for 1% concentration sample	The overall acceptability decreased as the *Spirulina* ratio increased	[41]
Rice coating	Nutritional composition texture and sensorial attributes	2% *Spirulina*, combined with 20% maltodextrin and 1% carboxymethyl cellulose (w/v)	*Spirulina* incremented the protein content in 64.5% compared to control samples. Moisture content increased up to 67.4% because of the hydrophilic behavior of maltodextrin, carboxymethyl cellulose and proteins.	TPC: 137.3 µg GAE/g and FRAP: 3.8 mg Fe^{2+}/g	Hardness, adhesiveness, springiness, gumminess, and chewiness decreased in the samples with *Spirulina* due to the presence of these other polymers. The softness was appreciated. Overall acceptability of 7.1, corresponding to like moderately. Unfavorable odor in the rice fortified with 3 to 5% (w/v) *Spirulina*	[33]
Crostini	Nutritional composition	6%	-	-	C-PC was protected from thermal degradation by tocopherol	[42]
Vegan kefir (soy- or almond-milk-based)	Nutritional composition and functional properties	0.25% and 0.50%	No significant color differences ($p > 0.05$)	DPPH: 12.03 ± 4.41 was the greatest value (soy milk at 0.5%) [5] ABTS: 46.90 ± 2.41 was the greatest value (soy milk at 0.25%)	*Spirulina* improved the prebiotic potential and bioactive quality of food	[43]
Emulsion	Low-fat oil-in-water food emulsions and coloring	1% (*Dunaliella*; *Chlorella* or *Spirulina*)	*Spirulina*: pH slightly decreased during storage; the emulsion were stable	-	*Spirulina*: greenish color differences from 25 to 60 days of storage were observed	[44]
Gluten-free fresh pasta	Nutritional composition, rheological and functional properties, and appearance	2 and 3%	Higher antioxidant activity; high digestibility in vitro; good mechanical properties	DPPH: 70.33% ± 4.36 and [6] VCEAC: 0.77 µg/g ± 0.02	*Spirulina* biomass enhanced the nutritional quality of pasta without affecting its cooking and texture quality properties	[45]
Pasta	Nutritional composition	10, 30, and 50% of *Spirulina*-soy-extrudate	-	-	Generally, pasta was accepted Familiarity with *Spirulina* was related to acceptance	[46]
Milk and fermented soy beverages	Boost on fermentation	0.25% and 0.50%	The lightness was increased at both concentration	-	*Spirulina* improved lactic acid bacteria strains and viscosity at 0.25%	[47]
Pasta	Nutritional composition and rheological and functional properties	0.25, 0.5, 0.75, and 1%	Improved mineral content	-	Greater color, aroma, and overall acceptability of pasta (0.25% *Spirulina*) compared to the control	[48]
Yogurt	Nutritional composition, functional properties, and coloring	0.1, 0.3, and 0.5% oven-dried biomass and 1, 5, and 10% fresh biomass	pH decreased with biomass incorporation; water-holding capacity ranged from 53 to 62%	-	Yogurt products showed the ability to retain water after the fermentation process	[49]

Table 1. *Cont.*

Food Product	Technological Function	*Spirulina* Ratio	Physicochemical Characteristics	Antioxidant Activity	Main Effects	Reference
Bread	Nutritional composition	2, 4, and 6%	-	DPPH: 16.51 ± 0.85 at 6% *Spirulina* biomass ratio was the greatest value	The overall acceptability decreased as the *Spirulina* ratio increased	[50]
Crostini	Nutritional composition, functional properties, and appearance	2%, 6% and 10%	Improved protein, phycocyanin, and total phenolic content	DPPH: ranged from 57% to 61% and VCEAC: from 0.60 to 0.64 µg/g	Color and global acceptance were greater at 2% *Spirulina* concentration and lower than the control	[51]
Ayran (Yogurt)	Boost on fermentation capability and probiotic bacteria	0.25%, 0.5%, and 1%	Improved protein at 1%. Viscosity decreased in the first seven days of storage, then it increased	-	Enhancement in the growth of probiotic bacteria and nutritional value of ayran	[52]
Yogurt	Nutritional composition, rheological properties, and coloring	0.25, 0.5, 0.75, and 1%	Higher antioxidant activity, protein, fat, and dietary fiber contents were reported	DPPH: 52.41 ± 2.61 at 0.25% *Spirulina*	0.25% *Spirulina* concentration was the best formulation. The color showed no tendency to lighten during storage	[53]

[1] total phenolic compounds; [2] gallic acid equivalent; [3] 2,2-diphenyl-1-picrylhydrazyl; [4] 2,4,6-tri(2-pyridyl)-1,3,5-triazine; [5] 2,2-azino-bis(ethylbenzo-thiazoline-6-sulfonic acid) diammonium salt; [6] vitamin C equivalent antioxidant capacity.

Improved texture with better viscosity, reduced syneresis [53], and improved shelf life are attributes acquainted with *Spirulina* biomass incorporation into food products because of greater water-holding capacity, as observed in vegan products [32] and milk-based products, such as yogurt [49,53] and ayran [52]. These authors also obtained yogurt with stable acidity and color for both formulations; thus, the fermentation process is stimulated by *Spirulina* biomass. Corroborative results showed increased lactic acid bacteria and confirmed its potential in producing novel functional fermented dairy products. Fermented *Spirulina* was related to immunomodulatory advantages in vivo; thus, commonly consumed products such as yogurts are interesting application matrices.

Considering the extraction of C-PC, the study conducted by Pan-utai et al. [49] evaluated fresh and dried biomass. The authors observed that fresh biomass was less processed since it did not have a drying process among its obtainment steps, thus saving electricity and presenting a higher C-PC concentration in the final product [49].

Other aspects frequently associated with biomass incorporation as ingredients are the nutritional composition booster and color stability [54] of *Spirulina*-added products. Nutritional enrichment was identified, particularly in protein and mineral content, and a brown tonality was observed due to the baking process [44]. A green color is typically anticipated when *Spirulina* is incorporated into food products. Nevertheless, depending on the other ingredients used and heat application during processing, the resultant color can shift to a brown hue. This color alteration can impact the acceptability of the products among consumers.

On the other hand, the blue color associated with C-PC from *Spirulina* was preserved after the baking process in crostini [42,51]. The authors affirmed that the preservation was due to the protective action of tocopherol in extra virgin olive oil, which is one of the ingredients. Hence, relatively simple methods, such as adding olive oil or even sugar, can be an alternative to mitigate the loss of C-PC, a bioactive compound, during thermal processing.

Meeting the consumer's demands through delivering novel products must be planned. It involves sensory acceptance evaluation, which was only sometimes carried out in the literature connected with *Spirulina*-biomass- or C-PC-added products. Sometimes, the number of non-trained panelists was modest (e.g., 20 individuals), and there needed to be more details about the methodology, such as in the study coordinated by El Baky et al. [55]. In this context, investigating the consumer's willingness to buy novel products is the distinctive aspect of these investigations, and it was reported in only one study [51],

considering the evaluated literature. The authors concluded that consumers would buy crostini at 2% of *Spirulina* concentration.

Amarante et al. [4] added C-PC obtained from *Spirulina* to ice cream. They observed antioxidant activities 2 to 13 times higher than the control ice cream after in vitro digestion, indicating that the compound remained active in the final product. Another dairy product that successfully received 2 and 4% C-PC was plain yogurt [56]. C-PC maintained color stability in this matrix, did not influence the starter culture, improved the texture, and decreased syneresis. Also, a sensory evaluation demonstrated that 4% C-PC-added yogurt had the best overall acceptability. Besides the coloring function, C-PC presented emulsifying and stabilizing activity in ice cream (concentration of 0.13 mg/mL), contributing to better nutritional food quality without influencing the overall acceptability [15].

Blue isotonic and tonic beverages commercialized without any coloring additive (control) were studied by Belén García et al. [57]. The control received lower amounts of C-PC (<1.12 mg/mL) to reach a color compatible with the blue commercialized products, which contain artificial colorants (i.e., brilliant blue E-133). They presented good color stability during analysis time (11 days), over a wide range of pH (3 to 9), and C-PC did not affect the viscosity of the elaborated products.

These results are significant due to the inclusion of C-PC in products already commercialized, showing the concrete way the food industry can reinvent itself. So far, refrigerated products are the most accessible options for incorporating C-PC as a natural blue dye due to the consequent color preservation under refrigerated temperatures. Referring to baked products, it was found that in 3% C-PC-added biscuits and 0.3, 0.6, and 0.9% *Spirulina* biomass biscuits, oxidation was reduced during 30 days of storage time and the final products presented antioxidant activity, especially at time zero [55]. The sensory acceptance showed no significant differences, but the number of panelists was limited. As the thermal degradation of C-PC was pointed out in the literature [28], its incorporation in baked products seems more difficult. The whole *Spirulina* biomass combined with tocopherol could protect the C-PC molecule more efficiently in this product, as Niccolai et al. found [42,51].

In terms of balance, the application of *Spirulina* biomass and C-PC in foods is very discrete, and due to their remarkable potential, it is challenging to understand why so few products have been developed in the last years. Academics and food industry decision-makers must incite the use of these bioproducts to formulate food products because of their nutritional characteristics and because they equalize ultra-processed product consumption.

The downstream processing of intracellular bioproducts, such as C-PC, involves a series of crucial steps, including cell separation, cell rupture, product extraction, at least one purification step, and the final refinement of the product. It is imperative to employ selective methods for cell rupture and extraction to enhance the purification process of intracellular products like C-PC. These methods effectively disrupt the cell walls, thereby increasing porosity and preventing the release of contaminants, ultimately leading to a high purity of the desired bioproduct without compromising the extraction yield. Furthermore, purifying certain products often necessitates using multiple purification techniques in succession, which can escalate production costs and result in substantial product losses. Therefore, exploring innovative approaches to streamline the purification process is essential. Precipitation and ultrafiltration, characterized by their cost-effectiveness and moderate resolution, can offer high recovery rates. However, depending on the value-added nature of the bioproduct, the utilization of more expensive high-resolution techniques may be justified if they ensure high product recovery. Among the high-resolution techniques, ion exchange chromatography (IEC) stands out as a commonly employed method for protein separation. Recent studies have demonstrated that employing IEC with pH gradient elution yields C-PC with exceptional purity, purification factor, and recovery rates, underscoring its effectiveness in bioproduct refinement [5]. All these steps make this bioproduct more sensitive to external agents, such as the action of light and changes in temperature and pH, making its addition to food a major technological challenge and increasing its production costs [58,59]. Additionally, maintaining the stability of this biomolecule when added to

the food matrix is also a considerable challenge since it is sensitive to heat and changes in pH [60,61].

More recently, we have observed in the literature an important movement to improve the stability of phycocyanin through different methods, including the use of nanotechnology [62–64], stabilization through the formation of emulsions [64], the addition of sugars or hydrocolloids [64,65], the use of high pressures [66], and the combination, among others, of the cited techniques. This trend makes us believe that we will have at least partially overcome these difficulties in the coming years.

3.2. Health Effects

Scientific insights have demonstrated that *Spirulina* biomass' health effects are mainly due to its nutritional value, including its macronutrients (primarily proteins and fatty acids), micronutrients (such as chromium, copper, and zinc), and bioactive compounds, such as carotenoids, chlorophylls, and phycocyanin [67]. Accordingly, Ashaolu et al. [27] have classified C-PC as a "super functional" ingredient due to its content of precious substances.

C-phycocyanin (C-PC) is recognized as a food colorant by ANVISA (National Health Surveillance Agency, Brazilian legislation) and the FDA (Food and Drug Administration in Code of Federal United States Regulations). In both regulations, C-PC, as a food ingredient, must be obtained exclusively by the filtered aqueous extraction of dried *Arthrospira platensis* biomass [68,69]. Furthermore, some differences in specifications are observed in legislation. ANVISA allows the use of C-PC as a food additive (the maximum limit of use) in (1) candies and confectionery (0.38%), (2) ice cream and cold desserts (0.38%), (3) sugared coatings for sweets and confectionery products (0.38%), (4) powders for the preparation of drinks (0.035 g in every 200 mL), (5) powders for the preparation of soups and sauces (0.50%), and (6) fruit preparation for yogurts (0.50%). The material published by the FDA [69] specifies that C-PC must be free from arsenic, mercury, and microcystin toxin impurities.

Ferrazzano et al. [70] have defined functional foods as technologically developed ingredients that amplify specific effects on human health. Promising sources of functional foods, such as C-PC from cyanobacteria, are a dietary resource for preventing diseases. The content below describes in vivo and in vitro studies regarding the effects of *Spirulina* and C-PC on health.

An et al. described using probiotics Lactobacillus plantarum and Bacillus subtilis to ferment *Spirulina* [71]. These probiotics improved *Spirulina*'s immunomodulatory activity, enhancing Kunming mice's splenic lymphocyte cell proliferation compared with non-fermented *Spirulina*. Besides that, molecular metabolites were accumulated during *Spirulina* fermentation, and the fractions, called "peptides fermented *Spirulina*", were characterized according to their size as low (L-PFS, <3 kDa), medium (M-PFS, 3–5 kDa), and high (H-PFS, 5–10 kDa). These studies demonstrate the initial potential and immunomodulatory advantages of *Spirulina* fermented food product development. However, further studies are necessary to understand the stability of fermented *Spirulina* as a food ingredient.

Researchers are evaluating *Spirulina*'s potential over other chronic diseases in the same line of work. The study developed by Aissaoui et al. [72] confirmed *Spirulina*'s antidiabetic potential by administering 0.1 g of *Spirulina* powder diluted in 1 mL of distilled water by oral gavage for 50 days in alloxan-induced diabetic rats. The investigation demonstrated that the *Spirulina* aqueous extract treatment comprised 16.54 ± 0.12% of C-PC. It showed a better antihyperglycemic effect when compared to the controls and a more powerful impact than metformin, the primary antihyperglycemic drug used in diabetes mellitus regulation [72]. The authors believed that the antihyperglycemic effect of *Spirulina* was either due to the presence of potent antioxidant bioactive molecules, mainly C-PC, chlorophyll, and carotenoids, which may help the increment of insulin secretion from the islet β-cells, or due to the promotion of blood glucose transport to the peripheral tissues [72,73]. The peptides and polypeptides generated by the digestion of *Spirulina* proteins could also be responsible for the antidiabetic effect, but these antihyperglycemic consequences were not elucidated.

Spirulina has gained notoriety for its anti-obesogenic potential as a dietary supplement. Moradi et al. [74] have summarized the effects of *Spirulina* supplementation in a systematic review and meta-analysis of five randomized clinical trials for weight management. Still, no statistical differences were seen in body mass index (BMI) or waist-to-hip ratio between groups divided into *Spirulina* and control, including 145 and 133 subjects, respectively. The findings on weight reduction regarding *Spirulina* supplementation showed better results in obese than overweight individuals. The possible mechanisms involving the *Spirulina* effect can be related to several aspects, such as their composition [75], the reduction in cholesterol absorption, microbial modulation by changing the gut microbiota composition, the decrease in insulin resistance, oxidative stress, and inflammatory conditions, mainly due to *Spirulina* bioactive compounds as C-PC and β-carotene, and appetite hormonal regulation [74].

Studies may need to be conducted longer to robustly prove Spirulina's positive effect on body weight and other health responses. Zhao et al. [76] compared anti-obesity effects in mice fed a high-fat diet (45% of the calories from lipids) plus 2 g/kg per diet of *Spirulina platensis* (WSP), *Spirulina platensis* protein (SPP), or *Spirulina platensis* protein hydrolysate (SPPH). The results demonstrated that while SPP was the best for lowering glucose (39.6%), SPPH was the best for weight reduction (39.8%) and total cholesterol reduction (20.8%) among the three supplements. The authors highlighted that the compositional differences in protein fraction may explain the difference between WSP, SPP, and SPPH's effects. These results were lower than those of Ragaza et al. [77], who reported 60–70% protein by dry weight of *Spirulina* biomass powder.

In addition to the compositional components, the gut–brain–liver axis has a vital role in understanding how the gene changes in brain and liver tissues are related to SPPH-treated obese mice, mainly after SPPH intervention, which have displayed different gene expressions that are associated with lipid metabolism, e.g., Acadm (acyl-coenzyme A dehydrogenase), Retn (resistin), Fabp4 (fatty acid binding protein 4), Ppard (peroxisome proliferator-activated receptor gamma), and Slc27a1 (solute carrier family 27 member 1) [76]. These inferences could also explain the results of the Yousefi et al. [75] study, which described the better effect of *Spirulina* supplementation on obese than overweight individuals.

Both obesity and overweight are recognized as disruptors of female fertility, mainly because neuroendocrine mechanisms interfere with ovarian functions and can affect the ovulation rate and endometrial receptivity [78]. Wen et al. [79] conducted the first study demonstrating that C-PC could help improve fertility in obese female mice by renewing ovary and oocyte quality. For experimental analysis, mice were divided into three groups: (1) control (CTRL): standardized regular diet (oral) with 0.4 mL of standard saline solution (administered intragastrically); (2) high-fat diet (HFD): standardized high-fat diet (oral); (3) high-fat diet with phycocyanin (HFD + PC): HFD (oral) plus C-PC administered intragastrically each day at a dose of 500 mg/kg/day (dissolved in ultrapure water at a concentration of 50 mg/mL). After C-PC administration, an increment in litter size and offspring survival rates, improvement of the level of ovarian antioxidant enzymes, and reduction in the occurrence of follicular atresia were observed, indicating a potential essential strategy for the clinical treatment of obesity-related infertility in females [79] by the modulation of food intake, one of the lifestyle factors that can positively or negatively impact fertility [78].

In the most recent study by Salgado et al. [11], in vitro and in silico trials were performed to understand the main anti-melanoma action exerted by C-PC at 4.01 analytical purity grade. The requirement for C-PC food application is at least 0.7, but the authors preferred to use 5.73 times higher than the required food purity grade in the experiments. C-PC from *Spirulina* had no cytotoxic effect on non-tumor cells at concentrations of 100, 200, or 400 μg/mL, maintaining cell viability, which is a great result since the normal cells were unaffected by C-PC. The authors affirmed that C-PC acts in the cell invasion pathway of melanoma cells by binding to essential proteins. One of them is N-cadherin, a cell adhesion molecule that potentiates the invasiveness of melanoma cells, decreasing cell migration

and invasion [80]. It is assumed that the F-chain of C-PC is responsible for its antioxidant properties, showing interaction with most of the tested targets and being more stable with N-cadherin and Bcl-2 (a cellular protein that inhibits apoptosis). C-PC's ability to bind to the main cellular targets was verified by online tools (NCBI Blast, PRISM, and Protein Data Bank) and software (UCSF Chimera X) [80].

Although, ideally, more studies should explore the great potential of *Spirulina* and C-PC to improve human health, considering all the available reports regarding the effect of C-PC and even the consumption of *Spirulina* biomass. It is a fact that these bioproducts are indeed a great ally. More than that, the regular consumption of products containing *Spirulina* could change the scenario of non-transmissible chronic diseases in a very positive way by preventing their impact on the human body and on the public and private healthcare systems.

3.3. Knowledge Gaps and Further Research

Environmental concerns, including climate change and ecosystem degradation, drive the transition towards more sustainable production and consumption methods. Circular and resource-efficient economic models are being adopted to promote reuse, waste reduction, and efficient resource utilization, replacing traditional linear models. The aim is to balance economic growth and environmental protection, leading to industry revitalization, the modernization of production systems, enhanced ecological conservation, and increased biodiversity. The concern towards sustainable industries benefits the environment and holds significant economic potential, with collaborations between businesses and organizations driving growth and change [81].

Harnessing valuable biomass such as cyanobacteria presents a promising alternative strategy to curb the environmental impact of human development while simultaneously enhancing the value of the end products. Cyanobacteria species like *Arthrospira* (*Spirulina*) *platensis* exhibit remarkable metabolic flexibility, enabling them to synthesize beneficial compounds like lipids and antioxidants by adapting to specific environmental cues such as light intensity, salinity, nutrient availability, and pH levels [77]. Their unique ability to assimilate chemical oxygen demand and nutrients from certain wastewaters positions cyanobacteria as pivotal players in advancing circular economy applications [3].

The impact of climate change on food systems highlights the challenges posed by extreme climate events that threaten food production, availability, prices, quality, and safety. With almost half of the food currently produced breaching planetary boundaries, the projected global population growth and increased food demand present long-term challenges demanding sector transformation. A shift towards fair, healthy, and low-carbon food systems, advocating for a green business model involving carbon sequestration by farmers and producers, must be prioritized. Transitioning towards plant-based diets and innovative climate-resilient products like *Spirulina* and other algae and microalgae offer significant CO_2 mitigation potential and environmental benefits. Carbon dioxide removal technologies, including carbon capture and utilization, are crucial in achieving carbon neutrality and limiting the rise in global temperature [82]. This information further reinforces how imperative it is to promote *Spirulina* and its components as ingredients in food and as a protagonist in biotechnological products.

As mentioned throughout the manuscript, C-PC is already applied in a few commercialized food products, mainly refrigerated, such as fruit and vegetable juices and smoothies, ice creams, and yogurts, as "*Spirulina* extract". However, the blue color of C-PC is one feature that limits its application in food due to the "unnatural" aspect perceived by some consumers. For this reason, the products currently being developed and commercialized are aimed at younger consumers more interested in the innovative and health-improving aspects of food products. Nevertheless, marketing strategies could easily overcome this limitation, as they have in the case of *Spirulina* itself, for example. Many food products containing *Spirulina* are commercialized, emphasizing its health benefits, and its blue–green color indicates the presence of antioxidant ingredients.

More studies must report the sensory acceptance of *Spirulina* biomass and C-PC-added food products. Additionally, a sensory analysis with and without allegation must be conducted, creating market strategies based on the results.

Another aspect worth considering is the extraction and purification processes for C-PC obtainment. As Becker [83] mentioned, the consistency of the dry biomass of microalgae can be a significant drawback for its application in foods. Additionally, studies have shown that up to 50% of C-PC can be lost during its extraction from the dry biomass of *Spirulina*, possibly due to its poor thermal stability and peripheral position in the thylakoid membrane of the phycobilisome [84,85]. Therefore, it is recommended that C-PC is extracted from *Spirulina*'s fresh/wet biomass, ensuring the highest extraction yield and purity possible and minimizing the amount of biomass in the C-PC extract, which facilitates application or eventual purification processes that may be needed [5]. Moreover, using water or buffer as extraction solvents is suggested following green chemistry principles [9].

There is also an urge for more studies investigating the rheological properties of C-PC alone and when added to food matrices [28,32], which are crucial to characterize the stability of these products. Moreover, we have also identified gaps regarding evaluating the antioxidant activity of C-PC in food matrices after the digestion process, either in vitro or in vivo. This investigation is of the utmost importance in formulating food products with health benefit appeal since digestion can decrease the scavenging activities of cyanobacteria extracts [86].

Regarding technological options to deal with *Spirulina* biomass and C-PC in the food industry, micro- or nanoencapsulation and 3D printing are available. Along these lines, microencapsulated C-PC improved thermal stability at 60 °C, 70 °C, and 80 °C [87] due to C-PC and sodium alginate electrostatic interactions, an alternative for protecting bioactive compounds [22].

Although the literature is still very scarce regarding the use of C-PC and *Spirulina* biomass for smart food packaging and 3D printing, more research is needed in this area to learn better strategies to improve the physical, structural, and mechanical properties of films and coatings, and the rheological properties and antioxidant activity of 3D-printed food.

Finally, it is essential to focus attention on the full use of *Spirulina*, i.e., fully utilizing the biomass after obtaining the great value-added C-PC; after all, other nutritionally exciting compounds such as carotenoids, proteins, and fatty acids [67] are present and cannot be prevented from contributing to the good nutrition of the population. The same fatty acids, if isolated, can be used to produce biodiesel, for example, creating opportunities for partnerships between companies from different sectors, respecting the circular economy and, consequently, optimizing the use of natural resources and reducing the production of waste in a challenging world scenario, as the preservation of the environment and food security for the population are significant concerns.

4. Conclusions

Over recent years, a surge of studies has focused on integrating *Spirulina* biomass into food products, yet notable gaps persist. Critical areas demanding attention include rheological characterization, antioxidant activity post-in vitro digestion, sensory assessments, and consumer acceptance of novel offerings. Similarly, C-PC utilization in food formulations and active packaging still needs to be explored. With blue-hued foods being a rarity, incorporating C-PC presents a gateway to introducing innovative products in a fiercely competitive market landscape. Noteworthy strides have been made in integrating C-PC into existing commercial products, showcasing the food industry's potential for reinvention. Embracing the narrative of human health benefits through environmentally conscious production practices holds promise for garnering heightened consumer interest. The appeal initially resonates with younger demographics accustomed to vibrant-colored treats like candies and toppings. Refrigerated items are the primary avenue for incorporating C-PC as a natural blue dye, owing to its color stability under chilled conditions. This study is pivotal as it uncovers pathways to extend the application of C-PC as a natural

dye to heat-processed food items. Enhancing C-PC's stability through novel approaches, such as combining it with vegetable oils in baked goods, shows promise. At the same time, advanced technologies like nanotechnology and microencapsulation offer exciting avenues for bolstering stability and enabling novel applications such as smart food packaging.

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