# Commercial Applications of *Chlorella* sp. and *Spirulina* sp.

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Microalgae are a large and polyphyletic group of $O_2$-evolving photosynthetic microorganisms, mostly aquatic, comprising prokaryotic cyanobacteria and eukaryotic members. Estimates of the world microalgal production are around 50.000 t/year, *Chlorella* sp. and *Spirulina* sp. accounting for more than 90% of the total microalgal biomass production. These microorganisms have been widely recognized for their nutritional and therapeutic properties; therefore, a significant growth of their market is expected, especially in the nutraceutical, food, and beverage segments.

microalgae cyanobacteria *Chlorella* sp. *Spirulina (Arthrospira)* sp. nutritional value aquaculture cosmetics skin care

## 1. Introduction

The *Chlorella* sp. market is expected to grow at a Compound Annual Growth Rate (CAGR) of 6.3% from 2021 to 2028, reaching USD 412.3 million by 2028 [1]. In terms of value, the Spirulina market is much larger and is expected to reach USD 1.1 billion by 2030, at a CAGR of 9.4% from 2023 to 2030 [2]. For both markets, the main growth drivers include: (1) the consumers' greater tendency toward a protein-rich diet; (2) increasing awareness for health and wellness; (3) the growth of the nutraceutical industry; (4) an increase in vegetarianism; (5) a growing demand for natural food colors and other microalgal sourced products, such as omega-3 fatty acids; and (6) the development of innovative Chlorella food and beverage products, and products that include Spirulina as an ingredient.

Europe held the largest share of the overall Chlorella market in 2021 [1], where it is cultivated in closed production systems (fermenters or photobioreactors) [3][4][5][6][7][8]. Light can support the growth of *Chlorella* sp. in the photobioreactors (autotrophic conditions), while sugar-based growth is done in the dark inside fermenters (heterotrophic nutrition). The heterotrophic mode for the cultivation of *Chlorella* sp. is expected to grow significantly in the next few years due to higher productivity and a lower risk of contamination, water consumption, and use of space [1]. As photosynthetic organisms, microalgae have the ability to convert light energy into chemical energy. However, many species, such as *Chlorella* sp., *Spirulina* (*Arthrospira*) sp., can also assimilate and oxidize organic carbon molecules, extracting energy from them [9]. This process can occur both in the absence of light, a condition known as heterotrophy, or in the presence of light, referred to as mixotrophy and photoheterotrophy. Although North America is expected to hold the largest share of the Spirulina market in 2030, the market in Europe is

expected to register the fastest growth until 2030 [2]. Spirulina is cultivated in raceways, in autotrophic conditions, normally inside greenhouses in Europe and outdoor pounds elsewhere in the world [8][10][11].

*Chlorella vulgaris* held the largest share of the overall market in 2021, but the *Chlorella pyrenoidosa* or *Chlorella sorokiniana* segment is expected to grow significantly in the next few years [1]. Presently, *Chlorella* sp. is a genus from the class Trebouxiophyceae, phylum Chlorophyta, and kingdom Plantae [12]. The taxonomy of *Chlorella* sp. has been evolving for decades and currently represents a group of morphologically similar species of polyphyletic origin rather than a natural genus [13]. A total of 14 species are now assigned to the genus *Chlorella*, including both *C. vulgaris* and *C. sorokiniana*. Conversely, *C. pyrenoidosa* is no longer a valid name and most strains formerly identified as *C. pyrenoidosa* have been renamed, although *C. pyrenoidosa* strains in the literature and listed in culture collections can be found; in this case, *C. pyrenoidosa* refers to strains of uncertain taxonomic status, which have not been examined for reassignment yet [13]. In this research, researchers will consider the name *C. pyrenoidosa* as it appears in the literature or web sources.

Regarding *Spirulina* sp., a clarification is necessary. Both *Spirulina* sp. and *Arthrospira* sp. include cyanobacterial species very similar to each other, but the two genera are taxonomically distinct [14]. Many species listed in the past as *Spirulina* sp. have more recently been included in the genera *Arthrospira* sp., comprising all those grown commercially and sold as Spirulina [14][15]. Therefore, the trade name continues as Spirulina with no italics. The most important species of *Arthrospira* sp. exploited for commercial mass cultivation include *Arthrospira maxima*, *Arthrospira fusiformis*, and *Arthrospira platensis*.

## 2. Human Food and Nutrition

In 2021, the nutraceutical sector dominated the Chlorella market, due to the distinct properties and benefits of Chlorella as a “healthy food” that contributes to a healthy immune system and body [1]. The increasing consciousness regarding health and well-being, as well as the expansion of the nutraceutical industry, highly contribute to maintaining the nutraceutical segment atop the Chlorella global market. Regarding Spirulina, the nutraceutical segment accounted for the largest share of the market, but the food and beverages segment is expected to grow significantly up to 2030, mainly due to the increasing demand for phycocyanin [2].

The current dominance of the nutraceutical sector in both Chlorella and Spirulina markets is justified by their high nutritional value. Although their microalgal composition varies with culture age and cultivation conditions [16][17][18], *Chlorella* sp. and *Spirulina* (*Arthrospira*) sp. are characterized by their high protein content, low fat, suitable amino-acid profile, high concentration of vitamins (including B12), omega-3 and omega-6 fatty acids, minerals (potassium, calcium, magnesium, selenium, zinc, and others), and bioactive compounds (**Table 1**).

**Table 1.** Nutrient composition of Chlorella and Spirulina [15][19][20][21][22][23][24][25][26].

| Nutrient Composition | Chlorella | Spirulina |
|---|---|---|
| **Macronutrient (% dry weight)** | | |

| Nutrient Composition | Chlorella | Spirulina |
|---|---|---|
| Protein | 42–65.5 | 52–72 |
| Carbohydrate | 8.1–65 | 9–25 |
| Lipid/fat | 1.6–40 | 1–8 |
| Fiber | 1.6–6 | 2–18 |
| Minerals/Ash | 6.3–27.3 | 3–13 |
| **Essential amino acids (mg/g protein)** | | |
| Leucine | 40–95 | 56–84 |
| Phenylalanine | 20–96 | 29–48 |
| Lysine | 35–82 | 35–51 |
| Valine | 28–78 | 29–54 |
| Isoleucine | 1.0–44 | 1.2–41 |
| Threonine | 40–62 | 30–62 |
| Histidine | 10–35 | 6.0–28 |
| Methionine | 6.0–58 | 16–28 |
| Tryptophan | 1.0–24 | 10–20 |
| **Other amino acids (mg/g protein)** | | |
| Aspartic acid | 38–109 | 54–118 |
| Serine | 13–95 | 23–68 |
| Glutamic acid | 76–137 | 70–105 |
| Glycine | 60–105 | 39–78 |
| Alanine | 82–159 | 51–108 |
| Cysteine | 2.0–35 | 2.0–6.0 |
| Tyrosine | 13–84 | 30–48 |
| Arginine | 47–74 | 4.0–77 |
| Ornithine | 1.2–1.3 | nr |

| Nutrient Composition | Chlorella | Spirulina |
|---|---|---|
| Proline | 27–85 | 20–41 |
| **Fatty acids (FA)** | | |
| Saturated | 25–33 [1] | 45–56 [1] |
| | | 63–66 [2] |
| Unsaturated | 60–70 [1] | 41–52 [1] |
| | | 33.8–37.1 [2] |
| PUFA | 36–65 [1] | 30–42 [1] |
| | | 23.1–24.5 [2] |
| ω-3 | | 0.1–0.22 |
| Alpha-linolenic acid (essential FA) | 14–19.3 [1] | nr |
| ω-6 | | 23.1–24.5 [2] |
| Linoleic acid (essential FA) | 11–21 [1] | 16–17 [1] |
| **Vitamins (mg/100 g)** | | |
| B1 (Thiamine) | 1.5–2.4 | 3.5 |
| B2 (Riboflavin) | 4.8–6.0 | 3.2 |
| B3 (Niacin) | 23.8 | 12.1 |
| B5 (Pantothenic acid) | 1.3 | 0.4–25 |
| B6 (Pyridoxine) | 1.0–1.7 | 0.78 |
| B7 (Biotin) | 191.6 | 64 |
| B9 (Folic acid) | 0.61–26.9 | 0.033 |
| B12 (Cobalamin) | 0.1–125.9 | 0.012–0.24 |
| C (Ascorbic acid) | 15.6–100.0 | nr |
| E (Tocopherol) | 6.0–2787.0 | 2.8–75 |
| A (Retinol) | 13.2 | nr |
| K | 0.033 | 2 |

20288; Meticulous Research: Maharashtra, India, 2022.

2. Meticulous Market Research Pvt. Ltd. Spirulina Market by Product Type (Powder, Tablets, Capsules, Flakes, Phycocyanin), Distribution Channel (Business Channel, Consumer Channel),

Currently, Chlorella and Spirulina are mainly sold as powder, as well as tablets, extracts, capsules, or flakes [1][2]. In these forms of commercialization, both Chlorella and Spirulina are sold without any further processing of the biomass, which is only collected and dried.

Although both Chlorella and Spirulina are traded as highly valuated dietary supplements, they have been incorporated in ice creams, snacks, muffins, crackers, bars, cookies, pastry cream, bread, smoothies and other beverages, pasta and noodles, yoghurts, jelly gums, and others [23][27][28]. Additionally, it is noteworthy that some companies have actively engaged in the development of food supplements and nutraceutical ingredients with very high added value. For example, Algomed® and Spirugrass® [29][30]. The first is an extract renowned for its elevated phycocyanin content, supplemented with polysaccharides, amino acids, and more. On the other hand, Spirugrass® is a biorefining byproduct of Spirulina characterized by its abundance of amino acids, iron, vitamin K, and beta-carotenes.

Chlorella is mainly used as a source of chlorophyll pigments (**Table 2**). Thus, the incorporation of *Chlorella* sp. into certain processed foods, providing them with functional and nutritional value, imparts an intense green color that may not be suitable for the specific food product. Consequently, some companies have been actively involved in the development of honey/gold and white Chlorella as alternative solutions to meet and enhance the emerging consumption demands [31][32][33][34]. On the contrary, Spirulina contains phycocyanin, a highly valued pigment known for its natural blue coloration in food (**Table 2**).

Phycocyanin is a blue pigment synthesized by cyanobacteria, including *Arthrospira* sp. and *Spirulina* sp. In the food industry, it is mainly used as a natural coloring agent in confectionery products, frostings, ice cream and frozen desserts, gelatin, dessert coatings and toppings, beverage mixes and powders, custards, yogurts, puddings, cottage cheese, breadcrumbs, and ready-to-eat cereals [2]. Additionally, it displays antioxidant activity. The phycocyanin market is projected to reach USD 279.6 million by 2030, growing at a CAGR of 28.1% from 2023 to 2030 [35]. This market growth is driven by the increasing adoption of phycocyanin for nutraceuticals and the rising demand for natural blue colorants. Phycocyanin is one of the few natural blue colorants approved in the U.S., Europe, and Asia.

**Table 2.** Pigment content of *Chlorella* sp. and *Spirulina* (*Arthrospira*) sp. (mg $g^{-1}$ dw) [20][28][36][37][38][39][40][41][42].

| Pigment | *Chlorella* sp. | *Spirulina* sp. |
|---|---|---|
| **Chlorophylls** | 1.16–24.0 | 3.01–17.0 |
| Chlorophyll-a | 0.25–18.3 | 2.7–10.8 |
| Chlorophyll-b | 0.07–6.81 | 0.21–0.42 |
| **Pheophytins** | 9.73–26.93 | 8.24–13.49 |


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| Pigment | *Chlorella* sp. | *Spirulina* sp. |
|---|---|---|
| Pheophytin-a | 2.31–5.64 | nr |
| **Carotenoids** | 0.24–8.21 | 0.23–6.5 |
| **Carotenes** | nr | nr |
| β-carotene | 0.007–7.18 | 0.02–2.5 |
| **Xanthophylls** | nr | 2.5–4.7 |
| Astaxanthin | 0.25–6.8 | 0.095–0.72 |
| Canthaxanthin | 0.67–1.17 | 0.44–0.65 |
| Lutein | 0.052–13.8 | 0.12–1.03 |
| Violaxanthin | 0.010–0.037 | nr |
| Zeaxanthin | 0.074–7.00 | 0.028–2.0 |
| **Phycobiliproteins** | | |
| Phycocyanin | Absent | 95–251 |

nr—not referenced.

Carotenoids are lipophilic compounds found in *Chlorella* sp. and *Spirulina* sp., which have seen an increased growth in market potential through their uses in foods, pharmaceuticals, cosmetics, animal feed, and as dietary supplements [43]. For instance, carotenoids (β-Carotene) derived from *Chlorella* sp. are sold at USD 300–700 per kg in the open market [44]. Carotenoids such as lutein have also shown great health-promoting properties such as anti-inflammatory properties, and it has been shown that this bioactive pigment can promote or prevent age-related macular disease which is the leading cause of blindness and vision impairment [45].

## 3. Aquaculture and Aquarists

In 2020, the global aquaculture animal production reached 87.5 million tonnes, worth USD 264.8 billion, and it is expected to reach 106 million tonnes in 2030 [46]. Sustainable and innovative aquaculture development remains critical to supply the growing demand for aquatic animal foods. To support this trend, the exploitation of alternative, non-traditional protein and oil sources, such as microalgae, for aquafeeds and feeding is necessary. In fact, the nutritional composition and profile of both *Chlorella* sp. and *Spirulina* (*Arthrospira*) sp., as outlined in the preceding, offer advantages when used as a supplement in fish and other aquatic animals.

In aquaculture, microalgae can be introduced in two distinct stages: as food for zooplankton, which then serves as nourishment for fish and their larvae; and incorporated into feed for the nutrition of adult fish and as a substitute for

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## 4. Cosmetics and Skin Care

Bioactive compounds and lipids produced from microalgae are increasingly being recognized as potential alternatives to conventional synthetic ingredients in the cosmetic and skin care sectors [55][56]. As such, extracts from microalgae or specific bioactive compounds can be integrated into the production of a wide range of cosmetic products, including eyeliners, lipsticks, eye shadows, moisturizers, facial cleansers, shampoos, sunscreens, and beauty masks.

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| Bioactive Compound | Biological Activity |
|---|---|
| Carotenoids | Scavenges free radicals, fights wrinkles, delays aging, soothes eye skin.<br>Antioxidant, anti-inflammatory.<br>Provides blue light and UV protection.<br>β-Carotene serves as a natural colorant in cosmetics.<br>Lutein promotes regeneration of normal retinal blood vessels. |
| Vitamin C | Prevents melanin deposits, whitens the skin.<br>Repairs the skin barrier, capillaries, and photo-aging skin, reduces erythema and telangiectasia, and lightens skin wrinkles.<br>Stimulates collagen synthesis in the skin. |
| Vitamin E | Antioxidant.<br>Repairs the skin barrier, treats some skin diseases. |
| Polysaccharides | Antioxidant, antibacterial.<br>Good film-forming properties, reduces water evaporation on the skin surface and provides a moisturizing effect. |
| Peptides | Anti-inflammatory.<br>Protects skin , reduces UVB and UVC-effects. |
| Flavonoids<br>Phenols | Antioxidant activity.<br>Stimulates collagen synthesis in the skin, reduces wrinkle formation. |

Microalgal lipids play a crucial role in cosmetics, serving various functions [56][59]. They are used as moisturizing agents, emollients, surfactants, emulsifiers, texturizers, color and fragrance carriers, preservative carriers, and bioactive ingredients. The types of microalgal lipids commonly used in cosmetics include triacylglycerides, waxes, ceramides, phospholipids, sterols, as well as hydrogenated, esterified, and oxidized lipids. Each of these lipids bring unique properties to cosmetic formulations, making them versatile and valuable ingredients in the industry.

With the increasing demand for safe and eco-friendly cosmetics and skin care products, ingredients derived from *Chlorella* sp. and *Spirulina* (*Arthrospira*) sp. are set to take on a significant role in the industry. Their potential to provide efficient and sustainable alternatives makes them an appealing option for both cosmetic manufacturers and consumers in search of innovative and conscientious solutions. In this regard, major companies in the cosmetic

industry made in recovering stressful conditions affecting fish and shellfish species, especially cream and serum (Table 4).

**Table 4.** Examples of cosmetics marketed by major cosmetic companies.

| Manufacturer | Product | Ingredient | Ref. |
|---|---|---|---|
| Estée Lauder | Perfectionist Pro | *Chlorella vulgaris* extract | [60] |
| Thalgo | Activ Refining Blocker | *C. vulgaris* extract | [61] |
| | Spiruline Boost collection (booster concentrate, antipollution gel-cream, detoxifying serum, and booster shot mask) | *Spirulina platensis* extract | [62][63][64][65] |
| Institut Esthederm | Intensive Spiruline collection (serum and crème) | *Spirulina maxima* extract | [66][67] |
| Nuxe | Merveillance LIFT collection (night cream, firming cream, lift eye cream, and firming-activating serum) | *C. vulgaris* oil | [68] |
| Algenist | Blue Algae Vitamin C™ Dark Spot | Blue vitamin C, phycocyanin extracted from *S. platensis* extract | [69] |

Furthermore, it is worth noting that certain companies have been actively involved in the creation of exclusive or even patented ingredients for use in cosmetics. For instance, Algenist created the Blue Algae Vitamin C™, an active L-Ascorbic acid with a blue color, from Spirulina [70]. AlgoSource formulated Spiruderm®, a liquid Spirulina extract highly concentrated in phycocyanin, used as an active ingredient for skin moisturizing and re-densifying, and fine lines smoothing [71].


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