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REVIEW

Spirulina in the 21st century: Five reasons for success in Europe

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Abstract

The commercialised Spirulina (scientific name, *Limnospira* spp.), a filamentous multicellular blue-green cyanobacterium, is increasingly cultivated and utilised worldwide, including in Europe, as food and feed, due to its high nutritional value and health benefits. Its global usage has surged nearly tenfold over the past two decades, with annual production levels reaching around 30,000 tonnes of biomass according to FAO. The growing popularity of Spirulina stems from a rising demand but also from general acceptance as a protein alternative and a healthier and more sustainable source of food, thereby underlining the nutritional limitations and environmental impacts of conventional agricultural systems. Recognised as a healthy and safe food product, Spirulina is listed in the EU Food Catalog and, since 2017, has been officially categorised under the existing "Marine Algae" EU category and hence incorporated into the RCE 889/2008 EU regulation of organic products. The evolution of Spirulina research topics, on the number of large-scale cultivation sites and use of safe industrial processing technologies have brought Spirulina biomass to a global international scale providing safe products now able to be marketed under official EU regulation. Looking ahead, Spirulina's application has extended beyond the sole nutritional supplement benefit to become an ingredient in mainstream foods and a source of bioactive molecules. This expansion is propelled by technological advancements, exemplified by innovations such as strain selection to better adapt to local growth conditions and enhance nutritional value, improved cultivation technologies coupled with cost-effective production methods, and product developments aimed at expanding Spirulina markets in the 21st Century.

Keywords *Limnospira* · *Arthrospira* · Regulatory · Spirulina · Superfood · Sustainability · Taxonomy

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Introduction

Spirulina, a name still commonly used in trade, marketing, and even research, often alongside the scientific name, is a microalga belonging to the genus *Limnospira,* earlier known as *Arthrospira* (Tables 1 and 2).

Several species of *Arthrospira* have been recognized, *A. platensis* and *A. maxima,* being the two main species produced commercially. Genetic studies in the past few years proposed the re-classification of the commercially used species *Arthrospira* as *Limnospira* (Nowicka-Krawczyk et al. 2019; Santos et al. 2023)]. Furthermore, very recent studies concluded that despite their morphological and physiological differences, *A. platensis* and *A. maxima* represent in fact, the same species, *Limnospira platensis (*Roussel et al. 2023). *Limnospira* is morphologically characterized by regularly coiled trichomes with visible cross-walls. The tightness of the spirals, arrangement of spirals, cell and trichome dimension, and apices of the trichome were considered as main taxonomic criteria, but can vary considerably depending on cultivation conditions, with even short straight filament observed in some cases (Fig. 1). This species is proposed to be divided into sub-species based on their morphological and physiological plasticity, determining its adaptability to a variety of environments. Such re-classification should eventually require the extension of the "Novel Food "status to strains now listed under the genus name *Limnospira* (Champenois et al. 2015). For simplicity Spirulina naming will further on be used instead of *Arthrospira,* or more correctly *Limnospira*.

The Foundations and evolution of Spirulina Cultivation

While ancient records of harvesting blooms of Spirulina from natural lakes for local consumption were identified in Africa and South America, first attempts to artificially cultivate Spirulina biomass began in the 1960 s with the very first cultivation initiative led by Geneviève Clément working at the French Petroleum Institute (IFP). By combining previous studies from the IFP, ethnologists and botanists (Jean Leonard, P. Compère) performed the first systematic study detailing the physiology and growth requirements of Spirulina (Vonshak and Tomaselli 2022). Outcomes were part of the Ph.D. thesis undertaken by Zarrouk (1966) in Paris, France. At the Sosa Texcoco Company carbonate production

Table 1 The historical record of Spirulina in Europe

1827	Pierre Jean François Turpin (1775-1840), a French artist and botanist, first isolated what appears to be a *Spirulina* from a freshwater sample (Ragaza et al. 2020)
1844	Veit Brecher Wittrock (1839-1914) and Carl Fredrik Otto Nordstedt (1838-1924) two Swedish botanists reported a helical, septal, blue-green microalga near the city of Montevideo, which was named *Spirulina platensis* (Thor et al. 2005)
1852	Ernst Stizenberger (1827-1895) a German physician and lichenologist wrote the first taxonomic report where he named *Arthrospira* as a new genus, based on the septa presence, helical form, and multicellular structure (Tomaselli 1997)
1892	Maurice-Augustin Gomont (1839-1909) a French phycologist distinguished the aseptate form of the *Spirulina* genus and the septal form of the *Arthrospira* genus and confirmed the studies of Stizenberger (Maza et al. 2019)
1932	Lothar Geitler (1899-1990) an Austrian botanist and cytologist reunified the genera *Arthrospira* and *Spirulina* based on their common helical morphology, under the name *Spirulina* (Geitler 1932; Tomaselli 1997)
1989	Richard W. Castenhoz and John B. Waterbury, in the USA, reclassified *Spirulina* and *Arthrospira* into two distinct genera (Castenhoz and Waterbury 1989; Waterbury 2006)
2019	Nowicka-Krawczyk et al. (2019) reclassifies several species of *Arthrospira,* including *Arthrospira maxima* as *Limnospira*.
2023	Santos et al. (2023) reclassify *Arthrospira platensis* as *Limnospira platensis*

Table 2 Scientific research landmarks in Spirulina taxonomy and genetics

1979	Ultrastructure and genetic (percentage of G+C, 16S rRNA gene sequence) evidence, showed that *Arthrospira* and *Spirulina* were distinct organisms (Herdman et al. 1979; Guglielmi et al. 1993; Nelissen et al. 1994)
1991	Chemotaxonomically, those two genera were also shown to be different, as the *Arthrospira* fatty acids profile included γ-linolenic acid (GLA), that is absent in *Spirulina* (Cohen and Vonshak 1991)
1999	The 16 s RNA work by Scheldeman et al. (1999), allowed differentiation of *Arthrospira platensis* and A*rthrospira maxima*
2022	A phylogenetic study based on the cpcA-cpcB locus revealed that the closest relative of the *Arthrospira* genus is *Planktothrix* and that they are not closely related (Manen and Falquet 2002)
2023	Meta-analytic synthesis coupled with several phylogenetic analyses shows that the genus *Limnospira* is mono-specific (Roussel et al. 2023)

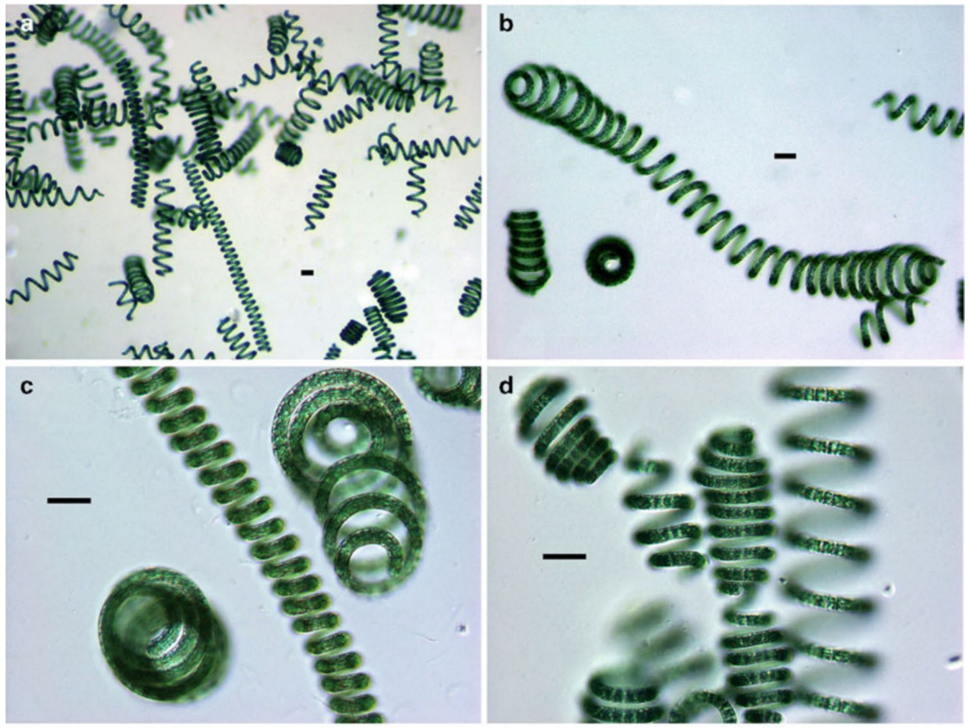

Fig. 1 Illustrative examples of morphological variability of *Limnospira* sp. (**a-d**). Scale bar = 20 µm (Photo from C. Sili. from Sili et al. 2012)

site in Mexico, Spirulina had been identified as impeding the carbonate evaporation process, but then was recognized as a valuable resource, by the French manager of Sosa Texcoco, Mr. Durand Chastel, who established the first large-scale commercial Spirulina biomass production plant in 1974.

There is a long history behind the development of microalgae cultivation, with early international research, in the US, Japan, Germany and other countries, described by Burlew (1953) in the book: "Algal culture, from laboratory to pilot plant". This research led to the first pilot plant in Japan, followed by the establishment of a commercial *Chlorella* production facility in the same location in 1960. At that same time an international effort was brought together in order to develop microalgae cultivation for protein products in Germany (Soeder and Binsack 1978).

Since this period, over 2.500 papers including "Spirulina" in the title were recovered in the Pubmed data base, of which 18% originated from European countries in the 2020s, a figure which has now risen to 25% thereby highlighting an acceleration EU research topics on Spirulina (Fig. 2). A broader search through Google Scholar lists 144.000 references and Google Patents 13.300 patents, when searching for 'spirulina'.

Spirulina production in large scale have spread throughout different countries, notably in China and in the US who both produce, to date, more that 50% of the world

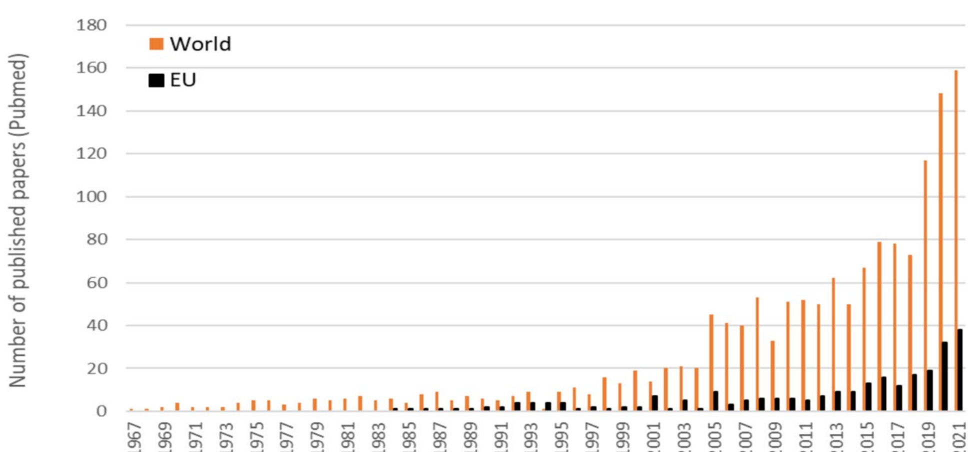

Fig. 2 Number of published papers (Pubmed research request: "Spirulina" in Title) without location identity (orange bars) and with location identity of EU countries (black bars). Total 1967 to 2021 = 1.480 worldwide with 260 in the EU

production. A global figure is often published around 20,000 tonnes per year but often without the Asian production volumes which can fluctuate widely, estimated from 10,000 tonnes per year upwards.

Many advances have been made and the following books regarding or including Spirulina have been published:

1980. "*The Secrets of Spirulina*" by Hills (1980). Published by University of the Trees Press, Boulder, California

1980. "*Algae biomass: Production and use*" by Shelef and Soeder (1980). Published by Elsevier/North Holland Biomedical Press. The first comprehensive book about microalgae, including several Spirulina papers.

1985. "*Biotechnology & Utilization of Algae: The Indian Experience*" by Venkatraman and Becker (1985).

1985. "*Biotecnologie per la Produzione di Spirulina*" (in Italian), by Tomaselli (1985). Published by Consigli Nazionale Delle Ricerche (CNR), Italy.

1986. "*Algoculture: la Spirulina, un espoir pour le monde de la faim*", in French (Algoculture: *Spirulina*, hope for a hungry world), by Fox (1986). Published by Edisud, France. The first specific book about Spirulina cultivation**.**

1986. "*Micro-Algal Biotechnology*" by Borowitzka and Borowitzka (1986). Published by Cambridge University Press, Cambridge, UK.

1993." *Spirulina, Algae of Life*", Bulletin Special No. 12. Published in French by Institute Oceanographique, Société Océanographique de Monaco (1993). Reports on Spirulina cultivation around the world.

1996. "*Spirulina – Production & Potential*" by Fox (1996). Published by Editions Edisud, La Calade, R.N.7, 13090 Aix-en-Provence, France. This book provides practical information on growing Spirulina.

1996. "*Cultivez Votre Spiruline – Manuel de Culture Artisanale de la Spirulina*" by Mialot (1996), in French. Published by Antenna technologie. The author developed small scale Spirulina projects in Europe and Africa.

1997. "*Production of Spirulina rich in GLA and sulpholipids*" by Durand-Chastel (1997).

1997. "*Spirulina platensis (Arthrospira) Physiology, Cell Biology and Biotechnology*" by Vonshak (1997), Ben Gurion University, Israel. Published by Taylor & Francis.

1997. "*Earth Food Spirulina: How this remarkable blue-green algae can transform your health and our planet*" by Henrikson (1997). Published by Ronore Enterprises, Inc.

2007 "*Spirulina in Human Nutrition and Health*" by Gershwin and Belay (2007), Published by CRC Press.

2021. "*Spirulina World Food: How this microalga can transform your health and our planet*" by Henrikson (2021). Published by Ronore Enterprises, Inc.

Through the years, Spirulina culturing conditions have been extensively optimized, and it is well established today that this alkalophilic alga is able to grow at high pH and carbonate levels, with a maximum growth rate obtained at pH between 9.5–9.8 and an optimum growth temperature around 30 °C (Habib and Parvin 2008). The fact that Spirulina thrives under high pH and carbonate alkalinity conditions, gives it a competitive advantage over other algae, reducing contamination. This explains the success of Spirulina large-scale monoalgal cultures in outdoor ponds. The evolution and key milestones related to Spirulina production and industrialization can be described as the following:

AD 300 AMERICAS - Several records show evidence about Spirulina harvesting by Mayas of Central America (300-900 AD) (Piccolo and Short 2014).

AD 800 AFRICA - Spirulina believed to have been used as food in North Africa since at least the 9 th century (Small 2011).

1519. AMERICAS - First historical records of Spirulina food consumption by the Aztecs (as illustrated in the Florentine Codex) (De Obeso Fernandez Del Valle and Scheckhuber 2021).

1940. AFRICA - French botanist Pierre Dangeard report on the consumption of dihe (dried lake harvested Spirulina) by the Kanembu people, Lake Chad (Soni et al. 2017).

1964. AFRICA - The Belgian botanist Jean Leonard recognized the connection between the algal blooms in lake Chad and dried cakes sold in the market (Koru 2012).

1965. EUROPE - Reference Spirulina patent FR6175 A 'Method of culturing algae in an artificial medium' by Genevieve Clement, Michel Rebeller, Claude Zarrouk (Clement et al. 1965).

1966. EUROPE – Claude Zarrouk (1896-1968), PhD thesis on physical and chemical factors influencing *Spirulina maxima* growth and photosynthesis (Zarrouk 1966).

1973. AMERICAS - First large-scale Spirulina cultivation with 300 t year^{-1} started by the French Director Hubert Durand-Chastel of Sosa Texcoco (Mexico), a large salt and carbonates production company. Spirulina was exported to Japan and then the US, with the company closing in 1995 (due to problems related to salt production) (Damessa 2021).

1977. AMERICAS - founding of Proteus Corp., (later renamed Earthrise Nutritionals LLC) by Larry Switzer and in 1979, with Robert Henrikson 1979 building the first U.S. Spirulina farm. In 1986 it became a subsidiary of Dainippon Ink and Chemicals (now DIC Corp) (Norsker et al. 2010)

1977. ASIA - The Japanese Dainippon Ink Corporation (DIC) start the first Spirulina production plant in Bangkok, Thailand, which closed about 20 years later (Belay 2013).

Today DIC is one of the largest Spirulina producers in the world, owning a production company in Hainan, China and Earthrise Nutritionals LLC.

1979. ASIA - The first Chinese algae society: On October 16, 1979, Hu Hongjun and other 20 leading algae researchers organized by China's - the Chinese Society of Phycology (CSP) inaugural meeting in Wuhan Hongshan (Ang 2012).

1980s. AFRICA, ASIA - French non-governmental organizations support small Spirulina production systems in Africa and Asia with simple and effective growing and processing technology developed in France. Upon returning to France, several aid workers working on these projects, started small scale production in France (see below).

1980s. ASIA - Spirulina research at the Shri A.M.M. Murugappa Chettiar Research Centre, Madras, later set up a semi-commercial unit at Saveriarpuram in Tamil Nadu (Priya Sethu 1996).

1983. EUROPE - The company Sanatur GmbH in Singen, Germany, started to import and trade Spirulina (Sallam and Steinbüchel 2009).

1983. AMERICAS - Cyanotech Corp. was founded by Dr. Gerald Cysewski, in Washington State and in 1985 started producing Spirulina in Hawaii. In 1988 its shares were listed on the NADAQ stock exchange (Moorhead and Capelli 1993).

1985. ASIA - First Spirulina company in China. Chenghai alkaline Lake, in the Yong-shen County, Yunnan Province. Project led by Prof. Hong-Jun Hu (Chen et al. 2016)

1988. ASIA - Myanmar Pharmaceutical Industries produces about 150 dry tonnes of Spirulina per year on several alkaline volcanic lakes that enjoy natural Spirulina blooms. Technical and management support from Otto Pulz from IGV, Germany (Damessa 2021).

1989. EUROPE - Foundation of Antenna Technologies by Denis von der Weid in Geneva. Currently with more than 40 projects underway in over 20 countries (Marcel et al. 2011).

1990s. EUROPE - Spirulina micro-farms start to emerge in France. Several hundred such commercial projects are currently operating.

1992. ASIA - Yunnan Spirin Co., Ltd was established and become one of the largest providers of Spirulina in the world with 1.000 t year^{-1} with 400.000 m^2 greenhouses (Chen et al. 2016).

1996. ASIA - Parry Nutraceuticals began Spirulina production in Tamilnadu and expanded into astaxanthin from *Haematococcus* in 2003 (Grewe and Griehl 2012).

2003. AMERICAS - Cyanotech and Earthrise Nutritionals receive FDA notification that Spirulina microalgae are generally recognized as safe (GRAS) (Amin et al. 2024).

2004. AFRICA - The United Nations Food and Agriculture Organization (FAO) reported in the Kanem region of Chad, the local market price ranged from US$0.80 to US$2 kg^{-1} with estimated annual production of more than 250 t year^{-1} (https://openknowledge.fao.org/server/api/core/bitstreams/06c859c6-a71b-43fc-89a9-eb99c8920ab7/content, accessed on 01 Apr 2025).

2005. EUROPE - A Spirulina school was established at the CFPPA Center in Hyères (France) for microfarming that becomes a global phenomenon in Europe, beyond France with more than 300 micro-farms in 2020 from Bulgaria to Lithuania, UK, Iceland, Germany, Switzerland, Italy, Spain, Greece and Portugal (Charpy et al. 2008).

2005. ASIA - Parry Nutraceuticals obtained the first HACCP certification for Spirulina production (https://www.prnewswire.com/news-releases/parry-organic-spirulina-first-to-receive-fda-gras-status-for-organic-spirulina-ingredient-177461581.html, accessed on 01 Apr 2025)

2009. EUROPE - The full Spirulina genome was sequenced in by Antenna Technologies and two private Swiss companies (Birot et al. 2012).

2009. ASIA - Ordos Xinyuli Spirulina Industry Group Co., Ltd. spent 120 M€ to build the largest Spirulina industrial park in the world, in Otuokeqi, Inner Mongolia of China with an area of 826 ha (Lu et al. 2011).

2009 EUROPE - a group of artisan producers in France gathered together in order to establish common guidelines for a sustainable production practice able to guarantee safe and qualitative Spirulina. "*La Fédération des Spiruliniers de France (FSF)*" counts more than 100 producers and has opened up to other neighboring countries: Spain, Italy, Portugal (Fig. 3) (personal communication).

2014 EUROPE - Elephant Vert France (www.elephant-vert.com, accessed on 01 Apr 2025) with a turnover of 11 M€ is currently the largest European Spirulina trade company (personal communication).

In Europe, during the last 40 years several specialized algae companies have established Spirulina utilization or production and/or related products as their main business, such as Flamant vert, Elephant vert, Sanatur GmbH. To date, the JRC algae database has reported a total of 213 Spirulina producing enterprises located in 15 European countries, with 62% located in France represented by small production units. Marcus Rohrer Spirulina (www.marcusrohrerspirulina.org) brand, produced in Hawaii and traded by Giuriati Group International BV (www.giuriati-inter

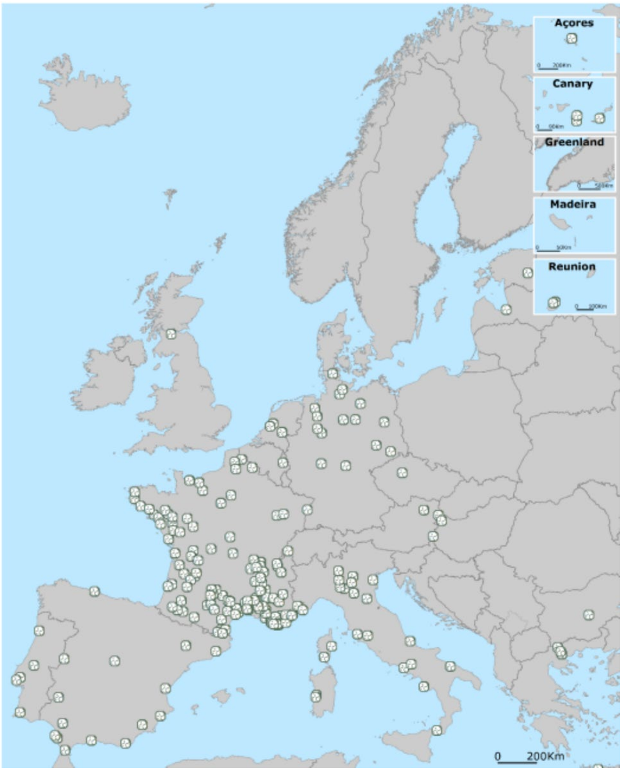

Fig. 3 Spirulina production plants in the EU from JRC algae database

national.com) is currently the main Spirulina source in The Netherlands.

Healthy, safe and sustainable: a prerequisite for consuming and marketing Spirulina in the EU

The biochemical composition of Spirulina varies with growth conditions, but it must be highlighted that levels found in literature also depend on the analytical methods used to quantify the compounds. Dried Spirulina contains about 5% water, 20–25% carbohydrates, 8% fats, with multiple unsaturated fatty-acids, and above 50% crude protein (N content × 6.25), with high levels of several essential amino acids (Colla et al. 2004; Gutiérrez-Salmeán et al. 2015; Liestianty et al. 2019; Koli et al. 2022) (Table 3). Spirulina is also rich in vitamins and minerals and provides 12,113.6 J g^{-1}. However, it should be noted that the use of the factor of 6.25 to estimate protein content, used for conventional foods, is not applicable to Spirulina, or algae, or other Novel Foods, with a factor near 5 being more relevant (Laurens et al. 2020). Other health benefits also include antioxidant properties notably when the cultivated biomass is enhanced with phycocyanin (Jung et al. 2019). Furthermore, most of cyanobacteria such as Spirulina are known to have both Fe-superoxide dismutase (SOD) and Mn-SOD enzymes (Sannasimuthu et al. 2018), some of the most ubiquitous protective enzymes recognised for scavenging superoxide radicals.

For a long time, Spirulina was considered a vitamin B12 source (Kumudha and Sarada 2015) but newer analytical methods revealed it to be a mixture of B12 analogues, with about 30% being in the metabolizable vitamin B12 form, the remainder being analogues that can impair absorption of this vitamin instead (Herbert and Drivas 1982; Van de Berg et al. 1991; Watanabe et al. 1999; Kumudha et al. 2010). Spirulina products are, for this reason, no longer allowed to be advertised as a source of vitamin B12.

Doses up to 19 g day^{-1} of Spirulina biomass have been used safely for up to 2 months with doses of 10 g day^{-1} used safely for up to 6 months. Some mild side effects that include nausea, vomiting, diarrhea, abdominal discomfort, fatigue, headache, and dizziness are reported by a few participants in such studies (Gutiérrez-Salmeán et al. 2015; Grosshagauer et al. 2020).

Commercialised cyanobacteria based products from reliable sources are free of contaminants such as microcystins (of which there are more than 140 variants), or are well below the tolerable daily intake (TDI) of 0.04 μg kg^{-1} day^{-1} which was set by the World Health Organization (WHO) for chronic exposure (Garcia et al. 2010).

Spirulina content of nucleic acids is about 4–6% of its dry weight, lower than that of other single-cell protein sources (for example yeast contains about 20% of its dry matter as nucleic acids) and hence does not represent a health risk.

Table 3 Amino acids, fatty acids, minerals and vitamin average content of Spirulina

Amino acids	Essential fatty acid profile	Minerals and vitamins
Spirulina contains essential amino acids: • leucine (55 mg g^{-1}, • tryptophane (10 mg g^{-1}), • methionine (14 mg g^{-1}) • phenylalanine (28 mg g^{-1}) • lysine (30 mg g^{-1}) • thionine (33 mg g^{-1}) • isoleucine (36 mg g^{-1}) • valine (45 mg g^{-1})	The lipids of Spirulina include: • gamma-linolenic acid • alpha-linolenic acid • linoleic acid • stearidonic acid • eicosapentaenoic acid (EPA) • docosahexaenoic acid (DHA) • arachidonic acid (ARA)	The vitamin and minerals content in Spirulina (100 g) includes: • thiamine (vitamin B1) (207% daily value, DV) • riboflavin (vitamin B2) (306% DV) • niacin (vitamin B3) (85% DV) • iron (219% DV) • manganese (90% DV)

Table 4 Spirulina marketing regulations in EU

European Food law compliance	Quality	Contamination
The global requirements for Spirulina trade in Europe require that Spirulina is in compliance with the European Union's (EU) mandatory legal requirements for natural ingredients for health products. If Spirulina is used in food supplements, it must also be compliant with EU food supplement legislation (UE) 2023/915 and the European General Food Law Regulation (EC) No 178/2002 (https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32002R0178, accessed on 01 Apr 2025)	Quality is very important in Spirulina trade. Buyers have specific requirements which go further than mandatory legislation and standards. The buyer requirements are outlined in buyer specifications. They can concern active ingredients such as phycocyanin content and moisture content along with its levels of contaminants and residues such as heavy metals. The importance of quality management in the health products sector is expected to increase in the future.	Contamination with other cyanobacteria and/or by cyanotoxins, bacteria or metallic trace elements is another key issue in Spirulina production. According to Regulation No 629/2008 emanated by the EC in agreement with the USP DSC[1], the maximum limits for trace metal elements in food supplements in Europe are: lead (3 mg kg^{-1}), cadmium (1 mg kg^{-1} for food supplements in general and 3 mg kg^{-1} for food supplements containing algae) mercury (0.1 mg kg^{-1}) (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008R0629, last access 27 Dec 2024). [1]USP DSC: United States Pharmacopeia- Dietary Supplements Compendium
Documentation	Labeling and packing	Certifications
The Documentation required for Spirulina export and trade in Europe requires well-structured and organised product and company documentation to be used to verify compliance. European Spirulina trade for health products usually requires the following documents: (1) Safety Data Sheets (SDS) including: (a) product description; (b) classification; (c) hazard identification; (d) information on safety measures; (2) Technical Data Sheets (TDS), including: (a) product description; (b) product classification; (c) quality analysis; (d) information on applications; (e) certificates; (3) Certification of Analysis (CoA), including: (a) data mentioned in the TDS; (b) the pre-shipment sample that was approved by the buyer; (c) contractual agreements with the buyer.	Labelling and packaging for Spirulina trade or export in the European market requires to comply with the following labelling requirements: (1) the supplier name; (2) address and telephone number of supplier; (3) product name; (4) batch code; (5) place of origin; (6) date of manufacture; (7) expiry date; (8) weight; (9) recommended storage conditions; (10) the name and/or code of the inspection body and (11) the certification number.	Organic ingredients are increasingly important in Europe, including Spirulina and Chlorella. Several certification agencies can help with the conversion process to organic production. For information on the EU organic certification https://agriculture.ec.europa.eu/farming/organic-farming/organics-glance_en. Spirulina is considered an agricultural product (live or unprocessed) and thus falls within the scope of the organic legislation under Article 1(2) of Regulation (EC) No 834/2007. Some trades require certification for maximum Residue Levels (MRLs) for pesticides and polycyclic aromatic hydrocarbons (PAH); contaminants in and microbiological contamination, food hygiene/HACCP, food irradiation, traceability and extraction solvents.

Spirulina has never shown any toxicity, neither acute nor chronic, with higher amount of biomass used during such toxicological tests than any recommended human consumption (Hutadilok-Towatana et al. 2010) (https://www.anses.fr/en/system/files/NUT2007sa0315t2.pdf, accessed on 01 Apr 2025).

The US Food and Drug Administration (FDA) accepted the GRAS status for Spirulina following the first request GRAS Notification: "Spirulina" microalgae on March 8, 2002, by Cyanotech Corporation and Earthrise Nutritionals, Inc., for use from 0.5–3 g of Spirulina per serving size and for a total of 6 g of dry Spirulina per day.

On the 30th of November 2017, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) issued an information document regarding Spirulina safety recommendations (Godlewska et al. 2019):

(1). advises individuals suffering from phenylketonuria (a rare genetic disease related to the amino acid phenylalanine accumulation) or predisposed to associated allergic outbreaks not to consume this food supplement.

(2). emphasizes that *Spirulina* is not a reliable source of vitamin B12 for strict vegans as it is mostly in the form of an inactive analogue.

(3). consumption of 5 g day^{-1} of Spirulina provides between 7 and 8.5 mg of beta-carotene, similar to the maximum daily intake of beta-carotene from food supplements, estimated at 7 mg day^{-1} (Chen et al. 2008).

(4). regarding possible contamination with cyanotoxins (especially microcystins, see above), bacteria or trace metals, the ANSES points to the importance of controlling the quality of water used at the different stages of production process.

Table 5 Spirulina cultivation, processing and derived products

Levels	Factor	Description
Cultivation	Culture	There is a wide range of possible culture media formulations even in specific wastewater
		Reactor configurations include photobioreactor, and fermenters, with raceways the dominant
	Carbon source	Bicarbonate is the most common carbon source
		CO_2 as an additional or exclusive carbon source can also be used
	Mixotrophic	There is an increasing interest in mixotrophic cultivation with bacterial control using pH changes
		Research into Spirulina fermentation is still in the first steps but includes GMO approaches
	Enriched cultivation	The production of Selenium rich Spirulina is available in industrial scale
		Bioavailable mineral enrichment of Spirulina is a current topic of research
		The cultivation for radio labeled isotopes has already been in commercial scale for more than 30 years
	Extreme cultivation	The cultivation of Spirulina near the tolerance values is being explored for high-value molecules
		Salt tolerant Spirulina is already available in industrial scale aiming high phycocyanin content biomass
Processing	Fresh biomass	Fresh, refrigerated or frozen biomass is the most recent trend for new commercial Spirulina products
	Drying	Solar drying is the conventional solution for small scale to preserve cell integrity
		Spray drying is the large-scale solution but induces small crack in the cell wall resulting in polyphenol release. Encapsulation techniques during spray-dying can be developed to avoid that problem (Da Silva et al. 2019).
		Drying Spirulina with a continuous infrared-assisted 'refractance window' dryer equipped with a photovoltaic-thermal solar collector is an option to avoid cell wall rupture (Agustina et al. 2019). Freeze drying is an expensive solution for high end products
	Selective extraction	Nucleic acid extraction can be developed as for yeast in order to have high dose (> 10 g day). Spirulina products
		Phycocyanin extraction mostly as blue coloring agent for the food industry
		Phycoerythrin extraction can be explored under different conditions of light; may be under selective wavelengths of light
	Biorefinery	Hydrolyzed biomass is being developed and used for different applications providing free amino acids
		The fractionation and related purification are being developed as a form of multi-product
Product	Agriculture	Hydrolyzed Spirulina for biostimulants and other active ingredients is already in the market (Plaza et al. 2018)
		Spirulina filtrate can be applied for seed soaking and for foliar spray and the homogenate can be used for seed coating
	Aquaculture	Aquaculture activities as a supplement to diet mainly for fish larvae and juveniles of both zooplankton and fish (Hammer 1981)
	Feed ingredient	Spirulina is useful for the manipulation of chicken egg and meat color through accumulation of lutein and zeaxanthin within egg yolks and meat (Dadheech et al. 2010)
	Food supplements	Over 200 different Spirulina-based food supplements are currently available on Amazon and other platforms, with an estimated over 500 products, often combined with other algae and or minerals.
	Food ingredients	Wide range of products containing Spirulina: pasta, hamburgers, energy bars, etc.
		Use of Spirulina and phycocyanin in beverages is increasingly popular in Europe
	Cosmetics	Studies showed antioxidant potential, immediate benefits on the skin microrelief and hydration and skin compatibility of formulations containing Spirulina extract
	Pharmaceuticals	Chelating agents for radiation therapy, radio labelled isotopes for medical tracing
		GMO Spirulina is being considered as carrier for specific pharmaceutical molecules

At the EU level, Spirulina is only related to dietary supplement regulation stipulating maximum levels of contaminants such as PAH (UE 2023/915). On the other hand, Spirulina is listed in the EU Food Catalog and since 2017, has been officially included in the existing "Marine Algae" category and in the RCE 889/2008 EU regulation of organic products.

European production and marketability

Spirulina can be produced and marketed all over the world without restrictions. Spirulina is recognized in the EU as a dietary supplement. Now *Limnospira* sp. is on the market as a food or food ingredient and since it was proved to be consumed to a significant degree before 15 May 1997, it is

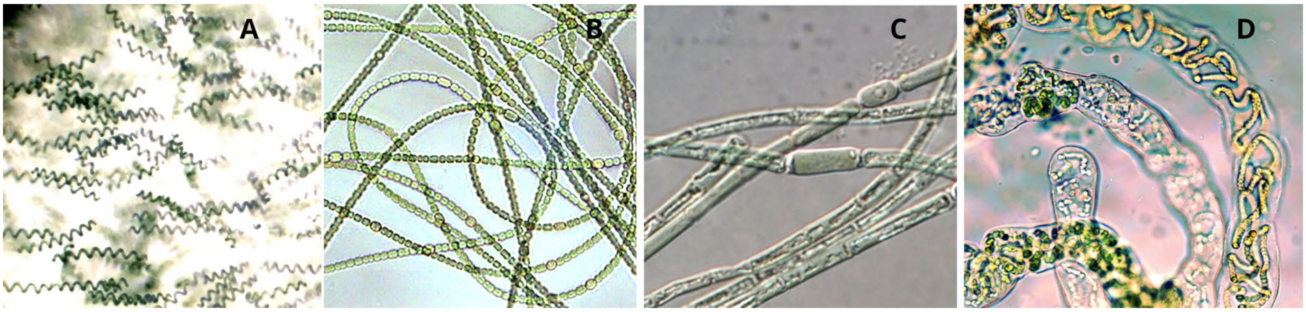

Fig. 4 Illustrative examples of cyanobacteria with *Spirulina*-like characteristics. (A) *Limnospira* (formerly *Arthrospira, e.g.* Spirulina (from https://www.spirulinedumaseole.fr*),* (B*) Anabaena* (from https://algaeplanet.com/fr/usda-sees-rising-star-for-anabaena-cylindrica/*),* (C*) Aphanizomenon*, (D) *Nostoc* (from Arianna Rizzo)

not subject to the Novel Food Regulation (EC), No. 258/97. However, legislation in some EU member states may restrict the access of Spirulina to country specific markets whether for food or food ingredient applications, therefore legislation should be verified for each EU country before commercialization (Table 4). Spirulina Algae Powder is classified by the European Chemicals Agency as EC/List no.: 921-131-8.

In the United States, algal biomass is classified as 'a dietary supplement' with Spirulina listed in the GRAS category. This implies it can be used as both a nutritional supplement and a food ingredient. In addition, the use of Spirulina-derived phycocyanin as a food coloring agent was approved by the FDA (Food and Drug Administration) a decade ago and is today produced in the USA by Earthrise Nutritionals LLC.

Parry Agro (now Parry Nutraceuticals) obtained the ISO 9001 and 14001 certifications in 2005. Parry Organic Spirulina is the first and currently the only Spirulina product on the market able to meet all standards for certification under the rigorous United States Dietary Ingredient Verification Program (USP DIVP) and can label USP Verified Mark.

Table 6 Spirulina EU projects funded since 2015 to 2021 (by Cordis search, https://cordis.europa.eu, accessed on 01 Apr 2025)

Year	Project Name	Application
2015	Springwave2014	Food
2015	ReSpirA	Food
2015	EASY	Production
2016	SABANA	Biorefinery
2017	agroCYAN ECO	Production
2017	BIOSEA	Feed
2018	SpiralG	Biorefinery
2018	CAP-SAliPharm	Food
2018	FODIAC	Pharma
2019	ProFuture	Food/Feed
2021	SCALE	Food
2021	EASYTRAIN	Feed

Parry Organic Spirulina also complies with Good Manufacturing Practices (cGMP) regulations and with the provisional (2011) USP monograph for Spirulina (Marles et al. 2011). Companies like Earthrise Nutritionals are also FSSC 22000 certified which involves the management of the process and product to guarantee safety. Earthrise Spirulina is also non-GMO verified which is required by some customers in Europe and the United States.

Innovation: from potential to reality

Spirulina is currently being used as a dietary supplement or as a whole food. As an ecologically nutrient-rich dietary supplement, Spirulina has also been investigated to address food security and malnutrition, and as dietary support in long-term space flights or missions to Mars. In the late 1980 s and early 90 s, both NASA (CELSS Project) and the European Space Agency (MELiSSA Project) suggested Spirulina as one of the primary foods to be cultivated during long-term space missions (Soni et al. 2017).

Extensive laboratory studies have improved cultivation conditions by defining optimal growth conditions such as light saturation between 150–400 μmol photons m^{-2} s^{-1}, an optimal growth temperature in the range of 30–38 °C, and tolerance to up to 0.2M of NaCl, but significantly reduced growth at salt concentrations above 0.75M NaCl (Sirakov et al. 2015; Kim et al. 2018) (Table 5). Moreover, the knowledge acquired in controlled cultivation conditions can help modulate the biochemical composition of *Limnospira*, for instance by enhancing the production of the high-value protein, phycocyanin (Fernandes et al. 2023; Pineda-Rodríguez et al. 2023)

Although *Limnospira* is generally regarded as a photoautotrophic organism, it may exhibit mixotrophic and even heterotrophic growth in the presence of organic carbon sources (such as glucose and acetate) (Russo et al. 2024; Baraldi et al. 2025). This metabolic plasticity can open the

Table 7 Spirulina (*Limnospira* species) habitat, geographic and genetic diversity

Diversity of Habitats	Geographic diversity	Phenotypic diversity
Limnospira is found in soil, marshes, freshwater, brackish water, seawater, and thermal springs. *L. platensis* and *L. maxima* occur naturally in tropical and subtropical lakes with alkaline pH and high concentrations of carbonate and bicarbonate.	*L. platensis* occurs in Africa, Asia and South America, whereas *L. maxima* is confined to Central America (Ciferri 1983). The largest presence of Spirulina was found in Lake Texcoco in Mexico, and currently in Central Africa around Lakes Chad, Niger, and in East Africa along the Great Rift Valley (Sasson 1997). Lakes Bodou and Rombou in Chad have a stable monoculture of *Limnospira* dating back centuries. It is also a major species in Kenya's Lakes Nakuru and Elementeita and Ethiopia's Lakes Aranguadi and Kilotes.	*L. maxima and L. platensis* fall into two weak clusters and species level difference could not be assigned. *L. maxima*: diameter of the helix of 50 to 60 µm and pitch of 80 µm; cell dimensions 4–6 µm. *L. platensis*: values >35 to 50 µm and 60 pm; cell dimensions 6–8 µm (Delrue et al. 2017)

door to new production pathways as well as potential new downstream markets. For instance, mixotrophic growth, which is the synergistic contribution of photoautotrophic growth using light energy, and heterotrophic growth consuming organic carbon sources, has been suggested as an alternative strategy for the production of *Limnospira* (Karssa et al. 2018; Plaza et al. 2018).

The knowledge and innovations developed for Spirulina can be extended to other microalgal species showing similar characteristics (Fig. 4), for instance, by providing a multi-product approach implemented with similar ready-to-use technologies (Da Silva et al. 2019). Interestingly, other cyanobacteria species have recently been approved for food application, such as *Aphanizomenon* in the EU and in the US, *Nostoc* in China, with references for consumption in Europe and *Anabaena* holds high potential for aquaculture feed. Such species could be the next target for innovation by Spirulina producers.

Since 2015, the EU has recently invested in 12 R&D projects related to Spirulina biomass production and applications, i.e., up to 3 funded innovation projects per year (Table 6). Target applications focus mainly on food and feed, highlighting the interest for the noticeable protein content as a source of more sustainable and alternative agro-resource. Spirulina biorefinery projects are now targeting plant and animal health which is a first in the EU.

Spirulina : a multinational available strain

Limnospira species have been isolated mainly from alkaline, brackish and saline waters in tropical and semitropical regions (Table 7), which shows the ability of these species to adapt to freshwater–alkaline conditions as well as saline–alkaline and even hypersaline environments. The alkaline soda lakes, apparently with unfavorable conditions (high pH such as 8.5–11, high content of sodium carbonate Na_2CO_3) are extremely productive due to high ambient temperatures, high light irradiance and unlimited supply of carbon. There are more than 60 known large (> 10 km^2) alkaline lakes across the world (Jenkin et al. 1936): more than 20 in Africa, mostly in Ethiopia, Kenya, Tanzania, Botswana, Chad and Sudan; also more than 20 in Asia, mostly in China, India, Russia, Turkey, Mongolia and Myanmar; over 10 in North America, mostly in USA, Canada and Mexico; but just a few in Europe, in Hungary, Austria and Serbia. A characteristic feature of the majority of soda lakes is the permanent or seasonal colored blooms of these phototrophic microorganisms. Most records of *Limnospira* species have been observed during blooms in alkaline water, however some species

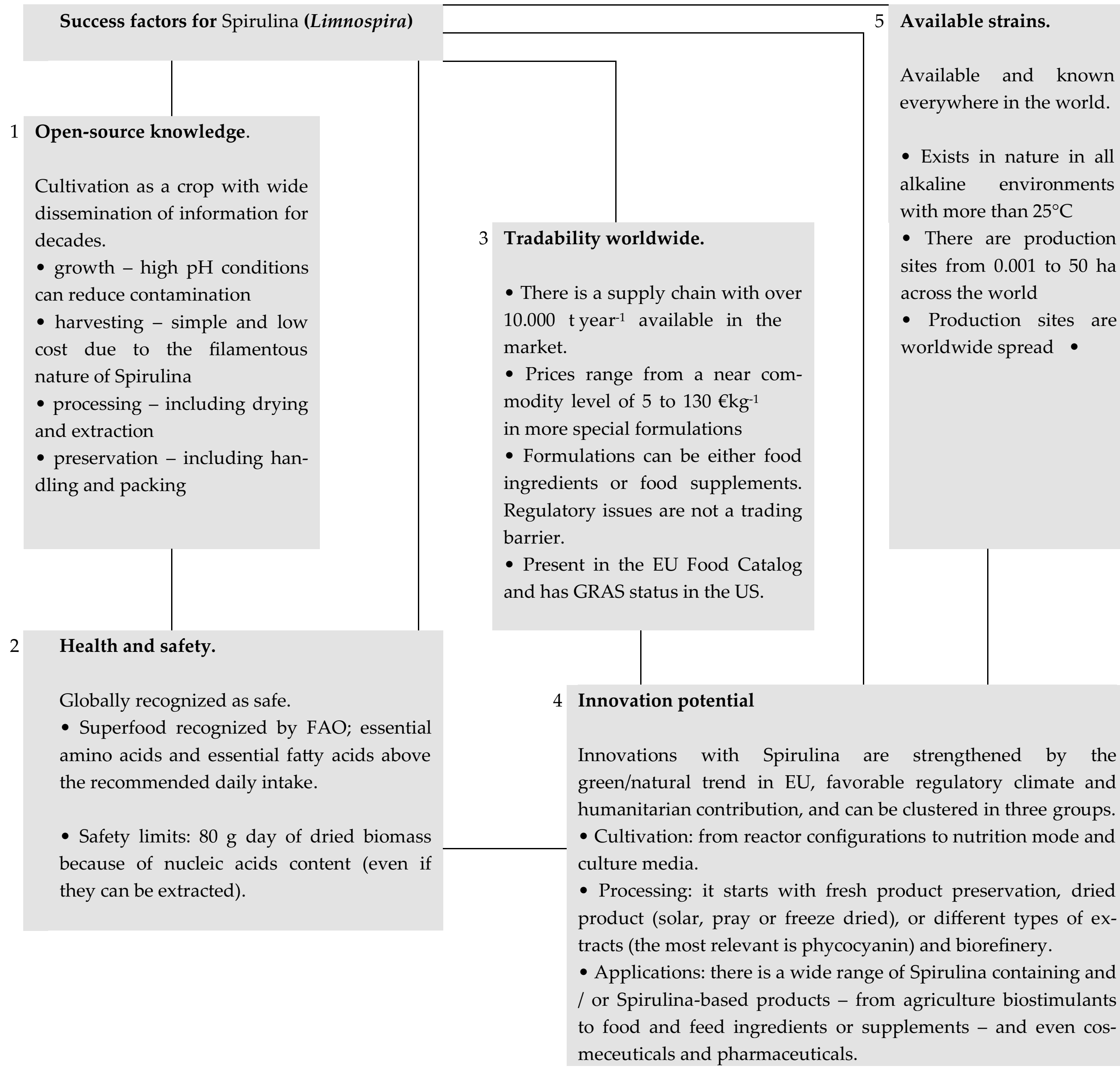

Fig. 5 Success factors for Spirulina (*Limnospira*) production and market growth

can occur occasionally in freshwater bodies or even in soils or marshes. Primary production rates as high as 10 g m^{-2} d^{-1} have been recorded in these soda lakes, which are about one order of magnitude more than most of the lakes in the world, making them the most productive natural aquatic environments.

Three species (or subspecies) isolated from these extreme environments are now cultivated worldwide: *Limnospira platensis*, *L. fusiformis* and *L. maxima*.

Conclusions

Spirulina is a known and widely accepted "crop" produced with mastered cultivation, harvesting and preservation technologies. The consumption of Spirulina is recognized safe and healthy, and it can be traded at high value worldwide. Although the main producers of Spirulina for food are found in Asia and in the US, Europe has acquired historical knowhow on *Limnospira* production, developed science-based knowledge and has invested in numerous innovative projects in order to tackle new markets. The global challenge of reaching these new markets is mainly economical, however opportunities are arising with recently approved strains.

The conclusions about *Spirulina* success framework can be described through the following Mindmap (Fig. 5).

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Declarations

Competing interests The authors declare no competing interests.

References

Agustina S, Aidha NN, Oktarina E (2019) Effect of maltodextrin concentration on the characteristic of phycocyanin powder as a functional food. AIP Conf Proc 2175:1

Amin M, ul Haq A, Shahid A, Boopathy R, Syafiuddin A (2024) Spirulina as a food of the future. In: Mehmood MA, Verma P, Shah MP, Betenbaugh MJ (eds) Pharmaceutical and nutraceutical potential of cyanobacteria. Springer, Cham, pp 53–83

Ang PO Jr (ed) (2012) Asian Pacific phycology in the 21st century: prospects and challenges. Springer, Hong Kong

Baraldi L, Usai L, Torre S, Fais G, Casula M, Dessi D, Nieri P, Concas A, Lutzu GA (2025) Dairy wastewaters to promote mixotrophic metabolism in *Limnospira (Spirulina) platensis*: effect on biomass composition, phycocyanin content, and fatty acid methyl ester profile. Life 15:184

Barsanti L, Vismara R, Passarelli V, Gualtieri P (2001) Paramylon (β-1,3-glucan) content in wild type and WZSL mutant of *Euglena gracilis*. Effects of growth conditions. J Appl Phycol 13:59–65

Belay A (2013) Biology and industrial production of *Arthrospira* (*Spirulina*). In: Richmond A, Hu Q (eds) Handbook of microalgal culture: applied phycology and biotechnology. Blackwell, Oxford, pp 339–358

Birot R, de Jouvencel D, Raginel L, Rouillé G (2012) From malnutrition to HIV: *Spirulina* is an effective solution which continues to reveal its secrets. Field Actions Science Reports (Special Issue 5). https://journals.openedition.org/factsreports/1847

Borowitzka MA, Borowitzka LJ (eds) (1986) Micro-algal Biotechnology. Cambridge University Press, Cambridge

Borowitzka MA, Beardall J, Raven JA (eds) (2016) The Physiology of Microalgae. Springer, Dordrecht, p 681

Burlew JS (1953) Algae culture. From laboratory to pilot plant. Carnegie Institution of Washington, Washington, D.C

Calderon V, Sanchez Lopez (2022) An overview of the algae industry in Europe. In: Guillen Garcia J, Avraamides M (eds) The European Commission's Knowledge Center for Bioeconomy. Joint Research Center, Luxembourg

Castenholz RW, Waterbury JB (1989) Oxygenic photosynthetic bacteria. In: Staley JT, Bryant MP, Pfenning N, Holt JG (eds) Bergey's Manual of Systematic Bacteriology. Williams and Wilkins Co; Baltimore, pp 1710–1806

Champenois J, Marfaing H, Pierre R (2015) Review of the taxonomic revision of *Chlorella* and consequences for its food uses in Europe. J Appl Phycol 27:1845–1851

Charpy L, Langlade MJ, Alliod R (2008) La Spiruline peut-elle être un atout pour la santé et le développement en Afrique? Rapport d'expertise pour le ministère de l'Agriculture et de la Pêche. IRD, Marseille, p 49

Chen TF, Zheng WJ, Wong YS, Yang F (2008) Selenium-induced changes in activities of antioxidant enzymes and content of photosynthetic pigments in *Spirulina platensis*. J Integr Plant Biol 50:40–48

Chen J, Wang Y, Benemann JR, Zhang X, Hu H, Qin S (2016) Microalgal industry in China: challenges and prospects. J Appl Phycol 28:715–725

Ciferri O (1983) *Spirulina*, the edible microorganism. Microbiol Rev 47:551–578

Clement G, Rebeller M, Zarrouk C (1965) Method of culturing algae in an artificial medium. US Patent 3403471A

Cohen Z, Vonshak A (1991) Fatty acid composition of *Spirulina* and *Spirulina*-like cyanobacteria in relation to their chemotaxonomy. Phytochemistry 30:205–206

Colla LM, Bertolin TE, Costa JA (2004) Fatty acids profile of *Spirulina platensis* grown under different temperatures and nitrogen concentrations. Z Naturforsch C 59:55–59

Craggs RJ, Lundquist TJ, Benemann JR (2013) Wastewater treatment and algal biofuel production. In: Borowitzka MA, Moheimani NR (eds) Algae for Biofuels and Energy. Springer, Dordrecht, pp 153–164

Da Silva SC, Fernandes IP, Barros L, Fernandes Â, Alves MJ, Calhelha RC, Barreiro MF (2019) Spray-dried *Spirulina platensis* as an effective ingredient to improve yogurt formulations: testing different encapsulating solutions. J Funct Foods 60:103427

Dadheech PK, Ballot A, Casper P, Kotut K, Novelo E, Lemma B, Pröschold T, Krienitz L (2010) Phylogenetic relationship and divergence among planktonic strains of Arthrospira (Oscillatoriales, Cyanobacteria) of African, Asian and American origin deduced by 16S–23S ITS and phycocyanin operon sequences. Phycologia 49:361–372

Dagnelie PC, van Staveren WA, van den Berg H (1991) Vitamin B-12 from algae appears not to be bioavailable. Am J Clin Nutr 53:695–697

Damessa F (2021) Nutritional and functional values of microalgae (*Spirulina*) naturally found in East Africa. PhD Thesis, NM-AIST, Tanzania

De Obeso Fernandez Del Valle A, Scheckhuber CQ (2021) From past to present: biotechnology in Mexico using algae and fungi. Plants 10:2530

Delrue F, Alaux É, Moudjaoui L, Gaignard C, Fleury G, Perilhou T, Richaud P, Petitjean M, Sassi JF (2017) Optimization of *Arthrospira platensis* (*Spirulina*) growth: from laboratory scale to pilot scale. Fermentation 3:59

Durand-Chastel H (1997) Production of *Spirulina* rich in GLA and sulpholipids. Sénateur des Français établis hors de France, Palais du Luxembourg, Paris

Fernandes R, Campos J, Serra M, Fidalgo J, Almeida H, Casas A, Barros AI (2023) Exploring the benefits of phycocyanin: from *Spirulina* cultivation to its widespread applications. Pharmaceuticals 16:592

Fox RD (1986) Algoculture : la *Spirulina*, un espoir pour le monde de la faim (in French). Edisud, France

Fox RD (1996) *Spirulina* – production & potential. Editions Edisud, La Calade, Aix-en-Provence

Garcia AC, Bargu S, Dash P, Rabalais NN, Sutor M, Morrison W, Walker ND (2010) Evaluating the potential risk of microcystins to blue crab (*Callinectes sapidus*) fisheries and human health in a eutrophic estuary. Harmful Algae 9:134–143

Geitler L (1932) Cyanophyceae. In: Rabenhorst L (ed) Kryptogamen-Flora von Deutschland, 2nd, vol. 14 edn. Schweiz G.U.D, Leipzig, pp 673–1196

Gershwin ME, Belay A (eds) (2007) *Spirulina* in human nutrition and health. CRC Press, Boca Raton

Godlewska K, Michalak I, Pacyga P, Baśladyńska S, Chojnacka K (2019) Potential applications of cyanobacteria: *Spirulina platensis* filtrates and homogenates in agriculture. World J Microbiol Biotechnol 35:80

Grewe CB, Griehl C (2012) The carotenoid astaxanthin from *Haematococcus pluvialis*. In: Posten C, Walter C (eds) Microalgal biotechnology: integration and economy. De Gruyter, Berlin, pp 129–144

Grosshagauer S, Kraemer K, Somoza V (2020) The true value of *Spirulina*. J Agric Food Chem 68:4109–4115

Guglielmi G, Rippka R, Tandeau de Marsac N (1993) Main properties that justify the different taxonomic position of *Spirulina* spp. and *Arthrospira* spp. among cyanobacteria. Bull Inst Océanogr 12:13–23

Gutiérrez-Salmeán G, Fabila-Castillo L, Chamorro-Cevallos G (2015) Nutritional and toxicological aspects of *Spirulina* (*Arthrospira*). Nutr Hosp 32:34–40

Habib AB, Parvin M (2008) Review on culture, production and use of *Spirulina* as food for humans and feeds for domestic animals and fish. FAO Fisheries and Aquaculture Circular, Rome No. 1034 FIMA/C1034

Hammer UT (1981) Saline Lake Ecosystems of the World. Kluwer, Dordrecht

Henrikson R (1997) Earth food *Spirulina*: how this remarkable blue-green algae can transform your health and our planet. Ronore Enterprises Inc, Laguna Beach

Henrikson R (2021) *Spirulina* world food: how this microalga can transform your health and our planet, updated and revised. Ronore Enterprises Inc, Laguna Beach

Herbert V, Drivas G (1982) *Spirulina* and vitamin B12. JAMA 248:3096–3097

Herdman M, Janvier M, Rippka R, Stanier RY (1979) Genome size of cyanobacteria. J Gen Microbiol 111:73–85

Hills C (1980) The secrets of Spirulina. University of the Trees Press, Boulder

Hutadilok-Towatana N, Reanmongkol W, Panichayupakaranant P (2010) Evaluation of the toxicity of *Arthrospira (Spirulina) platensis* extract. J Appl Phycol 22:599–605

Jenkin PM (1936) XIV.—Reports on the Percy Sladen expedition to some Rift Valley lakes in Kenya in 1929.—VII. summary of the ecological results, with special reference to the alkaline lakes. Ann Mag Nat Hist 18:133–160

Jourdan JP (1996) Cultivez votre Spiruline – Manuel de culture artisanale de la Spirulina (in French). Antenna Technologies, Mialot

Jung F, Krüger-Genge A, Waldeck P, Küpper JH (2019) *Spirulina platensis*, a super food? J Cell Biotech 5:43–54

Karssa TH, Papini A, Kasan NA (2018) Cultivation of *Arthrospira* strains in tropical conditions, with particular reference to Ethiopia. Int J Food Sci Nutr Eng 8:107–118

Kim T, Choi WS, Ye BR, Heo SJ, Oh DE, Kim S, Choi KS, Kang DH (2018) Cultivating *Spirulina maxima*: innovative approaches. In: Tiwari A (ed) Cyanobacteria. InTechOpen, Riejeka, pp 61–83

Koli DK, Rudra SG, Bhowmik A, Pabbi S (2022) Nutritional, functional, textural and sensory evaluation of Spirulina-enriched green pasta: a potential dietary and health supplement. Foods 11:70979

Koru E (2012) Earth food *Spirulina (Arthrospira)*: production and quality standards. Food Addit 10:31848

Kumar RSP (2020) Spirulina as poultry feed supplement to enhance nutritional value of chicken meat and eggs: a review. Int J Microbiol Res 11:67–71

Kumudha A, Sarada R (2015) Effect of different extraction methods on vitamin B12 from blue-green algae, *Spirulina platensis*. Pharm Anal Acta 6:1–6

Kumudha A, Kumar SS, Thakur MS, Ravishankar GA, Sarada R (2010) Purification, identification, and characterization of methylcobalamin from *Spirulina platensis*. J Agric Food Chem 58:9925–9930

Laurens LML, Olstad JL, Templeton DW (2020) Total protein content determination of microalgal biomass by elemental nitrogen analysis and a dedicated nitrogen-to-protein conversion factor. Meth Mol Biol 1980:233–242

Liestianty D, Rodiana I, Arfah RA, Assa A, Sundari Muliadi (2019) Nutritional analysis of *Spirulina* sp to promote as superfood candidate. IOP Conf Ser Mater Sci Eng 509:012031

Lu YM, Xiang WZ, Wen YH (2011) *Spirulina* (*Arthrospira*) industry in Inner Mongolia of China: current status and prospects. J Appl Phycol 23:265–269

Manen JF, Falquet J (2002) The *cpcB–cpcA* locus as a tool for the genetic characterization of the genus *Arthrospira* (Cyanobacteria): evidence for horizontal transfer. Int J Syst Evol Microbiol 52:861–867

Marcel AK, Ekali LG, Eugene S, Arnold OE, Sandrine ED, von der Weid D, Gbaguidi E, Ngogang J, Mbanya JC (2011) The effect of *Spirulina platensis* versus soybean on insulin resistance in HIV-infected patients: a randomized pilot study. Nutrients 3:712–724

Marles RJ, Barrett ML, Barnes J, Chavez ML, Gardiner P, Ko R, Griffiths J (2011) United States pharmacopeia safety evaluation of *Spirulina*. Crit Rev Food Sci Nutr 51:593–604

Maza LR, Acosta MAG, Mago C (2019) Chemical analysis of the biomass of a native strain of *Spirulina subsalsa* Oersted ex Gomont 1892 (Spirulinaceae) cultivated in low-cost saline medium. Afr J Microbiol Res 13:438–445

Moorhead K, Capelli B, Cysewski G (1993) *SPIRULINA* nature's superfood. Cyanotech Corporation, Hawaii, pp 1–63

Nelissen B, Wilmotte A, Neefs JM, De Wachter R (1994) Phylogenetic relationships among filamentous helical cyanobacteria investigated on the basis of 16S ribosomal RNA gene sequence analysis. Syst Appl Microbiol 17:206–210

Norsker NH, Barbosa M, Wijffels R (2010) Microalgal biotechnology. In: Bagchi D, Lau FC, Ghosh DK (eds) Biotechnology in functional foods and nutraceuticals. CRC Press, Boca Raton, pp 279–300

Nowicka-Krawczyk P, Muhlsteinova R, Hauer T (2019) Detailed characterization of the *Arthrospira* type species separating

commercially grown taxa into the new genus *Limnospira* (Cyanobacteria). Sci Rep 9:694
Piccolo A, Short C (2014) *Spirulina* production in the ESA-IO region: the way forward. Regional report, India
Pineda-Rodríguez YY, Herazo-Cárdenas DS, Vallejo-Isaza A, Pompelli MF, Jarma-Orozco A, Jaraba-Navas JDD, Rodríguez-Páez LA (2023) Optimal laboratory cultivation conditions of *Limnospira maxima* for large-scale production. Biology 12:1462
Plaza BM, Gómez-Serrano C, Acién-Fernández FG, Jiménez-Becker S (2018) Effect of microalgae hydrolysate foliar application (*Arthrospira platensis* and *Scenedesmus* sp.) on *Petunia* × *hybrida* growth. J Appl Phycol 30:2359–2365
Priya Sethu KM (1996) Studies on important phytochemicals and genetic transformation of the cyanobacterium *Spirulina*. PhD Thesis, University of Mysore, India
Ragaza JA, Hossain MS, Meiler KA, Velasquez SF, Kumar V (2020) A review on *Spirulina*: alternative media for cultivation and nutritive value as an aquafeed. Rev Aquac 12:2371–2395
Roussel T, Halary S, Duval C, Piquet B, Cadoret JP, Vernès L, Bernard C, Marie B (2023) Monospecific renaming within the cyanobacterial genus *Limnospira* (*Spirulina*) and consequences for food authorization. J Appl Microbiol 134:lxad159
Russo NP, Ballotta M, Usai L, Torre S, Giordano M, Fais G, Concas A (2024) Mixotrophic cultivation of *Arthrospira platensis* (*Spirulina*) under salt stress: effect on biomass composition, FAME profile and phycocyanin content. Mar Drugs 22:381
Salazar M, Martínez E, Madrigal E, Ruiz LE, Chamorro GA (1998) Subchronic toxicity study in mice fed *Spirulina maxima*. J Ethnopharmacol 62:235–241
Sallam A, Steinbüchel A (2009) Cyanophycin-degrading bacteria in digestive tracts of mammals, birds and fish and consequences for possible applications of cyanophycin and its dipeptides in nutrition and therapy. J Appl Microbiol 107:474–484
Sannasimuthu A, Kumaresan V, Pasupuleti M, Paray BA, Al-Sadoon MK, Arockiaraj J (2018) Radical scavenging property of a novel peptide derived from C-terminal SOD domain of superoxide dismutase enzyme in *Arthrospira platensis*. Algal Res 35:519–529
Santos KRDS, Hentschke GS, Ferrari G, Andreote APD, Fiore MDF, Vasconcelos V, Sant' Anna CL (2023) Molecular, morphological and ecological studies of *Limnospira platensis* (Cyanobacteria), from saline and alkaline lakes, Pantanal Biome. Brazil. Front Environ Sci 11:3389
Sasson A (1997) Micro biotechnologies: recent developments and prospects for developing countries. BIOTEC Publication 1/2542. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris
Scheldeman P, Baurain D, Bouhy R, Scott M, Muhling M, Whitton BA, Belay A, Wilmotte A (1999) *Arthrospira* ('Spirulina') strains from four continents are resolved into only two clusters, based on amplified ribosomal DNA restriction analysis of the internally transcribed spacer. FEMS Microbiol Lett 172:213–222
Shelef G, Soeder C (eds) (1980) Algae biomass: production and use. Elsevier/North Holland Biomedical Press, Amsterdam
Sili C, Torzillo G, Vonshak A (2012) *Arthrospira* (*Spirulina*). In: Whitton BA, Potts M (eds) Ecology of Cyanobacteria II: Their diversity in space and time. Springer, Dordrecht, pp 677–705
Sirakov I, Velichkova K, Stoyanova S, Staykov Y (2015) The importance of microalgae for aquaculture industry. Int J Fish Aquat Stud 24:81–84
Slifka MK, Whitton JL (2000) Clinical implications of dysregulated cytokine production. J Mol Med 78:74–80
Small E (2011) *Spirulina*—Food for the universe. Biodiversity 12:255–265
Société Océanographique de Monaco (1993) *Spirulina*, algae of life. Bulletin Spécial No. 12. Institut Océanographique, Monaco
Soeder CJ, Binsack R (1978) Microalgae for food and feed. Proceedings of the German-Israeli Workshop held 17 to 18 Oct. 1977 at Neuherberg. Ergebnisse der Limnologie 11:300
Soni RA, Sudhakar K, Rana RS (2017) *Spirulina* – From growth to nutritional product: a review. Trends Food Sci Technol 69:157–171
South J, Blass B (2001) The future of modern genomics. Blackwell, London
Thomas SS, Swaminathan K, Nagaraj JB (2003) Process to produce astaxanthin from *Haematococcus* biomass. PCT Patent Application 03/027267
Thor E, Johansen S, Nilsen LS (2005) The collection of botanical letters to Mikael H. Foslie in the Gunnerus Library: a catalogue. NTNU Vitenskapsmuseet, Norway
Tomaselli L (ed) (1985) Biotecnologie per la produzione di Spirulina (in Italian). Consiglio Nazionale delle Ricerche (CNR). Monograph, Italy, p 17
Tomaselli L (1997) Morphology, ultrastructure and taxonomy of *Arthrospira* (*Spirulina*) *maxima* and *Arthrospira* (*Spirulina*) *platensis*. In: Vonshak A (ed) *Spirulina platensis* (*Arthrospira*): physiology, cell-biology and biochemistry. Taylor & Francis, London, pp 1–15
Van den Berg H, Brandsen L, Sinkeldam BJ (1991) Vitamin B-12 content and bioavailability of *Spirulina* and Nori in rats. J Nutr Biochem 2:314–318
Venkatraman LV, Becker EW (1985) Biotechnology and utilization of algae: the Indian experience. Sharada Press, Mangalore
Vonshak A (ed) (1997) *Spirulina platensis* (Arthrospira): physiology, cell biology and biotechnology. Taylor & Francis, London
Vonshak A, Tomaselli L (2022) *Arthrospira* (*Spirulina*): Systematics and ecophysiology. In: Whitton BA, Potts M (eds) The Ecology of Cyanobacteria: their Diversity in Time and Space. Springer, Dordrecht, pp 505–522
Watanabe F, Katsura H, Takenaka S, Fujita T, Abe K, Tamura Y, Nakatsuka T, Nakano Y (1999) Pseudovitamin B(12) is the predominant cobamide of an algal health food, *Spirulina* tablets. J Agric Food Chem 47:4736–4741
Waterbury JB (2006) The cyanobacteria—Isolation, purification and identification. In: Dworkin M et al (eds) The Prokaryotes. Springer, New York, pp 1053–1073
Wayama M, Ota S, Matsuura H, Nango N, Hirata A, Kawano S (2013) Three-dimensional ultrastructural study of oil and astaxanthin accumulation during encystment in the green alga *Haematococcus pluvialis*. PLoS One 8:e53618
Xue L, Pan W, Jiang G, Wang J (2003) Transgenic *Dunaliella salina* as a bioreactor. USA Patent 2003/0066107
Zarrouk C (1966) Contribution à l'étude d'une cyanophycée : influence de divers facteurs physiques et chimiques sur la croissance et la photosynthèse de *Spirulina maxima* (Setch et Gardner) Geitler. PhD Thesis, Université de Paris, France