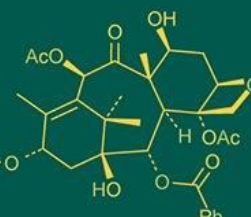
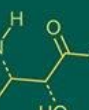
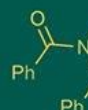


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; SP-8(11): 87-93
www.biochemjournal.com
Received: 05-08-2024
Accepted: 11-09-2024

Dr. Hafeef Roshan KT
Department of Aquaculture,
ICAR- Krishi Vigyan Kendra,
Kerala Agricultural
University, Kottayam, Kerala,
India

Exploring the versatile applications of Spirulina: A comprehensive research review

Dr. Hafeef Roshan KT

DOI: <https://doi.org/10.33545/26174693.2024.v8.i11Sb.2799>

Abstract

Spirulina, a type of blue-green algae, has garnered significant attention due to its rich nutritional profile and bioactive compounds that contribute to numerous health benefits. This review provides an extensive analysis of the various applications of Spirulina, covering its roles in nutrition, pharmaceuticals, cosmetics, agriculture, and environmental sustainability. With its high protein content, essential amino acids, vitamins, minerals, and antioxidants, Spirulina is an exceptional dietary supplement and functional food ingredient. In the pharmaceutical industry, it is explored for its potential in immune enhancement, cholesterol reduction, and cancer prevention. Spirulina's antioxidant and anti-inflammatory properties make it a valuable component in cosmetics, aiding in skin care and anti-ageing formulations. In agriculture, Spirulina is used as a biofertilizer and livestock feed supplement, contributing to sustainable practices by enhancing soil quality and improving livestock health. Furthermore, its ability to absorb heavy metals and pollutants enables its use in environmental applications, such as water purification and waste management. However, large-scale production faces challenges, including quality control, standardisation, and regulatory requirements, which must be addressed to ensure safe and effective use.

Keywords: Spirulina, nutrition, pharmaceuticals, cosmetics, agriculture, environmental sustainability

1. Introduction

Spirulina, a cyanobacterium and one of Earth's oldest life forms, has its origins dating back over 3.5 billion years. Species such as *Arthrospira platensis* and *Arthrospira maxima* thrive in alkaline, nutrient-rich freshwater environments. Its exceptional nutritional and bioactive properties have earned Spirulina the title of a "superfood." Historically consumed by ancient civilizations, including the Aztecs and Kanembu people, it has regained popularity for its applications in nutrition, health, and environmental sustainability.

Spirulina's nutritional profile is impressive, comprising 60-70% high-quality protein by dry weight, including all essential amino acids. It is rich in vitamins such as B-complex (B1, B2, B3, B6, and B12), vitamin E, and beta-carotene, and contains essential minerals like iron, calcium, magnesium, and potassium. Spirulina also provides fatty acids, such as gamma-linolenic acid, and unique bioactive compounds like phycocyanin, polysaccharides, and phenolic acids, which exhibit antioxidant, anti-inflammatory, and immune-boosting properties. This well-rounded nutritional profile makes Spirulina valuable for functional foods, dietary supplements, and even pharmaceutical applications (Becker, 2003; Gershwin & Belay, 2007) [7, 8, 14].

The bioactive compounds in Spirulina have shown potential in managing chronic diseases, including diabetes and cardiovascular disorders. Studies have demonstrated benefits in reducing oxidative stress and inflammation, key factors in these conditions. For instance, a clinical trial highlighted Spirulina's positive effects on lipid profiles and blood sugar control in diabetic patients. Furthermore, emerging evidence suggests that it may help manage conditions like arthritis, skin disorders, and hyperactivity in children by enhancing recovery and reducing inflammation (Kakos *et al.*, 2011) [25].

In agriculture, Spirulina serves as a sustainable protein source for animal feed, including aquaculture, poultry, and livestock. Its production requires significantly less land and water compared to traditional crops like soybeans. Additionally, Spirulina acts as a biofertilizer, enhancing soil fertility due to its high nitrogen content (Habib *et al.*, 2008; Bashan *et al.*, 2004) [20, 5, 6].

Corresponding Author:
Dr. Hafeef Roshan KT
Department of Aquaculture,
ICAR- Krishi Vigyan Kendra,
Kerala Agricultural
University, Kottayam, Kerala,
India

Spirulina's role extends to environmental management, particularly in wastewater treatment. A study by Olguín (2003) [36] demonstrated its effectiveness in reducing nitrogen, phosphorus, and heavy metals in wastewater, thus improving water quality. Recognized as a "food of the future," Spirulina is celebrated for its minimal resource requirements and adaptability to diverse environments, contributing to food security. However, it faces challenges related to production costs, quality control, and regulatory requirements (Belay, 2013) [10]. Its high nutritional density also makes it suitable for space missions, as organizations like NASA have explored its use in closed-loop life support systems for long-term space travel.

1.1 Nutritional and Dietary Applications of Spirulina

Spirulina's protein content, ranging from 55% to 70% by dry weight, ranks among the highest of any natural food source, comparable to animal proteins like eggs, dairy, and meat. Its amino acid composition meets the World Health Organization's recommendations for protein needs, supporting its use as a high-quality protein supplement. Studies indicate a net protein utilization (NPU) of approximately 60% to 70% (Wang *et al.*, 2021; Belay, 2002) [47, 48, 9], highlighting its efficiency for athletes, bodybuilders, and individuals recovering from illness. Elderly individuals can benefit significantly from Spirulina's nutrient density, as it offers an easily digestible source of protein that meets daily requirements despite dietary limitations. Additionally, Spirulina has been explored as a solution for protein-energy malnutrition, particularly in low-income regions. Nuhu (2023) [35] emphasized its potential to combat malnutrition due to its nutrient density and high bioavailability.

1.2 Malnutrition Treatment

Spirulina's efficacy in treating malnutrition has been evaluated in various humanitarian projects. A study in Bangladesh by Misbahuddin *et al.* (2022) [33] showed that children receiving Spirulina supplementation exhibited better weight gain, increased mid-upper arm circumference, and higher haemoglobin levels, demonstrating its effectiveness in addressing moderate malnutrition. Spirulina also provides substantial amounts of vitamin B12, making it valuable for vegetarian and vegan diets. A systematic review by Ahuja *et al.* (2021) [2, 3] confirmed its role in nutrition programs targeting vulnerable groups.

1.3 Weight Management

Spirulina aids in weight management due to its nutrient density and high protein content. A randomized controlled trial by Kim *et al.* (2023) [23] reported improvements in lipid profiles and reductions in body mass index (BMI) among overweight adults supplemented with Spirulina. Its low glycemic index also stabilizes blood glucose levels, beneficial for individuals with type 2 diabetes (Patel *et al.*, 2022) [38, 39].

2. Pharmaceutical and Therapeutic Applications of Spirulina

Spirulina is recognized for its rich composition of bioactive compounds, offering antioxidant, anti-inflammatory, cardiovascular, immune-boosting, and antidiabetic properties. Key components like phycocyanin,

polysaccharides, and essential fatty acids make it a promising candidate in complementary and alternative medicine.

2.1 Antioxidant and Anti-Inflammatory Properties

Phycocyanin, the blue pigment unique to spirulina, serves as a potent antioxidant, scavenging free radicals and protecting against oxidative damage. Recent studies have shown that its antioxidant capabilities rival those of vitamins C and E. Spirulina also inhibits pro-inflammatory mediators like cyclooxygenase-2 (COX-2), benefiting conditions such as rheumatoid arthritis. Other compounds, including beta-carotene and vitamin E, enhance its anti-inflammatory effects, aiding tissue repair.

2.2 Cardiovascular Benefits

Spirulina improves lipid metabolism, reducing total cholesterol, low-density lipoprotein (LDL), and triglycerides while increasing high-density lipoprotein (HDL) cholesterol. A study by Patel *et al.* (2022) [38, 39] demonstrated significant improvements in these parameters, which are crucial for reducing coronary artery disease risk. Gamma-linolenic acid (GLA) in spirulina further supports cardiovascular health by enhancing blood circulation and reducing inflammation.

2.3 Immune System Modulation

Spirulina enhances or suppresses immune activity, making it useful for immune-compromised individuals. Its polysaccharides stimulate cytokine production and enhance natural killer (NK) cell activity, aiding in the fight against infections and supporting those with autoimmune disorders.

2.4 Anticancer Potential

Research indicates that spirulina can inhibit cancer cell proliferation and induce apoptosis. A study by Lee *et al.* (2023) [23, 28] suggests that it may enhance conventional cancer treatments by mitigating side effects and improving patient outcomes.

2.5 Antidiabetic Effects

Spirulina regulates blood sugar levels, improves insulin sensitivity, and enhances glucose uptake. Shanmugam *et al.* (2023) [44] confirmed that spirulina supplementation significantly lowers fasting blood glucose levels, supporting better metabolic health and potentially reducing the need for conventional antidiabetic medications.

3. Cosmetic and Skin Care Applications of Spirulina

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4. Agricultural and Environmental Applications of Spirulina

Spirulina's nutrient content and eco-friendly attributes make it valuable for sustainable agricultural and environmental applications. Its roles in animal nutrition, soil health, wastewater management, and climate change mitigation are especially noteworthy.

4.1 Animal Feed Supplement

Spirulina is an effective supplement in aquaculture and livestock feed, providing 50-70% protein, essential amino acids, vitamins, and bioactive compounds that enhance growth and immunity. Early studies (Habib *et al.*, 2008) ^[20] highlighted Spirulina's benefits in fish, with recent research confirming improved growth and feed efficiency in tilapia and carp. Spirulina also enhances livestock health and reduces antibiotic use; a 2024 study in *Journal of Animal Science and Biotechnology* found it increased muscle protein and egg yolk pigmentation in poultry. Other research (Evans *et al.*, 2005) ^[15] has shown similar benefits, reinforcing its potential in sustainable animal feed.

4.2 Biofertilizer

Spirulina's nutrient richness, particularly in nitrogen, phosphorus, and potassium, makes it an effective biofertilizer. A 2024 study in *Sustainability* demonstrated that Spirulina applications boost soil organic matter and microbial activity, enhancing plant growth and nutrient uptake. Studies support its role in sustainable farming by reducing reliance on chemical fertilizers, promoting

beneficial microbes, and improving nutrient cycling. Bashan *et al.* (2004) ^[5, 6] also noted Spirulina's ability to enhance soil fertility, aligning with modern eco-friendly practices.

4.3 Wastewater Treatment

Spirulina's capacity to remove nitrogen, phosphorus, and metals makes it valuable for wastewater treatment. Research in *Environmental Science and Pollution Research* (2024) showed Spirulina's efficacy in reducing nitrogen and phosphorus levels by over 70%, supporting Olguín's (2003) ^[36] findings on microalgae's role in bioremediation. Additionally, Spirulina's ability to absorb metals like lead and cadmium has been noted since Volesky (1990) ^[51], with recent studies (Markou *et al.*, 2023) ^[31] suggesting it can be reused as biofertilizer or animal feed, creating a circular economy (Table 2).

4.4 Soil Erosion Control and Carbon Sequestration

Spirulina biomass aids in soil cohesion and erosion prevention. *Journal of Applied Phycology* (2023) ^[12] reported that Spirulina-treated soils showed increased microbial activity and organic matter, supporting findings by Metting (1996) ^[32] on microalgae's role in soil stabilization. Furthermore, Spirulina's CO₂ absorption contributes to carbon sequestration. Large-scale cultivation for atmospheric CO₂ reduction was suggested by Richmond (1986) ^[40] and further validated by Sánchez *et al.* (2023) ^[43], emphasizing its potential in climate mitigation.

5. Space Nutrition and Future Applications

Spirulina is increasingly recognized for its role in space nutrition due to its dense nutrients, easy cultivation, and low space requirements. This edible microalga holds promise for long-term space missions, providing essential nutrients while contributing to life support through oxygen production and carbon dioxide recycling (Gitelson *et al.*, 2017; Yadav *et al.*, 2023) ^[18, 50].

5.1 Nutritional Benefits for Space Missions

Spirulina's high protein content (55-70%), vitamins, minerals, and essential fatty acids make it ideal for space missions, where nutrient-dense, compact food sources are essential. It helps maintain muscle mass and bone density, both critical in microgravity environments. Its antioxidants, such as phycocyanin and β -carotene, counter oxidative stress from space radiation, enhancing cellular protection and recovery for astronauts (Chen *et al.*, 2023) ^[13].

5.2 Oxygen Production and Carbon Dioxide Recycling

In closed-loop life support systems, Spirulina absorbs CO₂ and releases oxygen via photosynthesis, contributing to a breathable atmosphere. NASA and ESA have integrated Spirulina into bio-regenerative systems to recycle air, water, and food, which reduces dependency on resupply missions (Bubenheim *et al.*, 2019) ^[11].

5.3 Cultivation in Space

Spirulina's low resource needs make it well-suited for space cultivation. It can grow in controlled environments, such as photobioreactors, which optimize growth factors and nutrient flow even in microgravity (Kliss *et al.*, 2022) ^[27]. This efficient system minimizes resource use, aligning with sustainable practices for extended missions (Yadav *et al.*, 2023) ^[50].

5.4 Addressing Space-Induced Health Challenges

Long-term missions expose astronauts to muscle atrophy, immune suppression, and radiation. Spirulina's immune-boosting polysaccharides and anti-inflammatory compounds like phycocyanin help mitigate these risks. Its calcium, magnesium, and iron content supports bone health and red blood cell production (Gusev *et al.*, 2020) ^[19].

5.5 Future Prospects for Space Exploration

As missions reach Mars and beyond, Spirulina could evolve from a supplement to a primary food staple in closed-loop ecosystems. Research into palatable Spirulina-based foods aims to improve astronaut diets, with innovations like space-friendly recipes increasing its acceptability (Bubenheim *et al.*, 2019) ^[11].

5.6 Potential Applications on Earth

Advances in space-driven Spirulina cultivation benefit Earth, particularly in addressing food insecurity and resource scarcity. Closed-loop farming techniques developed for space can support urban and vertical farming, enhancing sustainable agriculture to meet global food needs (Kliss *et al.*, 2022; Gitelson *et al.*, 2017) ^[27, 18].

5.7 Challenges and Limitations

Despite the numerous benefits associated with Spirulina, its large-scale cultivation and widespread utilization face several challenges that must be addressed to facilitate its mainstream adoption across various industries. These challenges span economic, regulatory, safety, and environmental aspects, all of which can impact the feasibility and acceptance of Spirulina products.

5.8 High Production Costs

One of the significant limitations of Spirulina cultivation is the high cost associated with large-scale production. Spirulina requires specific conditions for optimal growth, including precise light, temperature, pH levels, and nutrient availability, which can be challenging to maintain consistently. Naturally, Spirulina grows in alkaline water bodies, which may not be readily available for large-scale farming. Controlled-environment cultivation techniques, such as photobioreactors or artificial ponds, are often necessary to achieve consistent production. However, these methods incur substantial expenses due to the infrastructure, energy consumption, and nutrient inputs required (Richmond & Hu, 2013) ^[10].

The economic feasibility of Spirulina production is particularly problematic in regions where resources such as water and energy are scarce or expensive. Furthermore, maintaining optimal cultivation conditions can be labor-intensive and technically demanding. To reduce production costs, ongoing research is exploring innovative methods, including the use of low-cost substrates, enhancing light utilization efficiency, and integrating Spirulina farming with wastewater treatment (García & Bashan, 2016) ^[16]. These approaches aim to make Spirulina cultivation more economically viable.

5.9 Quality Control

Quality control is crucial for Spirulina products, particularly those intended for human consumption. Spirulina harvested from natural water bodies can be contaminated with heavy metals, pesticides, and harmful algal toxins such as

microcystins, posing health risks and compromising product safety (Gershwin & Belay, 2007) ^[17]. Implementing stringent quality control measures is essential for commercial production, including routine monitoring of growth conditions, raw materials, and final products. Closed photobioreactors offer an advantage over open-pond systems by reducing the risk of contamination.

Another challenge lies in the variability of Spirulina's nutrient composition, which can differ based on growth conditions and harvesting methods. This variability can make it difficult to standardize Spirulina-based nutritional supplements or pharmaceuticals, posing challenges for regulatory approval and consumer trust (Becker, 2013) ^[7, 8]. Third-party certifications and compliance with food safety standards can help build consumer confidence in Spirulina products.

5.10 Regulatory Hurdles

The regulatory landscape for Spirulina-based products is complex, especially for pharmaceutical and therapeutic applications. While Spirulina is widely accepted as a dietary supplement, gaining regulatory approval for its use in pharmaceutical products or as a therapeutic agent involves extensive clinical trials and scientific evidence to support therapeutic claims. Regulatory agencies such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA) require rigorous documentation and compliance with safety standards, which can be time-consuming and costly (Spolaore *et al.*, 2006) ^[46].

In some regions, regulations restrict the use of certain algal extracts in food and supplements due to concerns about safety and contaminants. Companies must navigate these regulations by adhering to quality assurance practices, food safety laws, and comprehensive documentation.

5.11 Environmental and Sustainability Concerns

Although Spirulina is generally considered a sustainable source of nutrition, large-scale cultivation can still pose environmental challenges. The use of fertilizers or synthetic growth media to promote Spirulina growth can contribute to nutrient pollution if waste management practices are inadequate (García & Bashan, 2016) ^[16]. Additionally, the energy required for controlled-environment cultivation, such as artificial lighting and temperature regulation, can increase the carbon footprint of Spirulina production, particularly in regions where renewable energy sources are limited (Richmond & Hu, 2013) ^[10].

To enhance sustainability, it is crucial to balance the environmental benefits of Spirulina cultivation with potential ecological impacts. Approaches such as recycling nutrients from wastewater, integrating Spirulina farming with renewable energy sources, and developing more efficient cultivation systems can help reduce water and nutrient inputs, making the production process more eco-friendly.

5.12 Market Limitations and Consumer Perception

While Spirulina is often marketed as a superfood, its adoption may be restricted by factors such as taste, texture, and cost. Spirulina's natural flavor, often described as earthy or slightly bitter, may not appeal to all consumers, limiting its use in mainstream food products. The relatively high cost of Spirulina supplements compared to other protein sources,

such as soy or whey, may also limit its market reach, especially in regions with lower purchasing power. Efforts to educate consumers about the unique benefits of Spirulina and the development of cost-effective

formulations could help broaden its appeal. Innovations in food processing and product development aimed at improving palatability without compromising nutritional benefits are necessary for expanding its consumer base.

Table 1: Nutritional Composition of Spirulina

Nutrient	Amount per 100 g (Dry Weight %)	% Daily Value
Protein	55-70g	110-140%
Essential Amino Acids	3.5-5g	Varies by type
Iron	28.5mg	158%
Vitamin B12	80µg	1,333%
Omega-6 Fatty Acids	1-2g	8-16%
Carotenoids	37mg	740%
Phycocyanin	1.5g	--

* Percent Daily Values are based on a 2,000-calorie diet.

Table 2: Efficacy of Spirulina in Wastewater Treatment

Parameter	Initial Concentration	Final Concentration (after Spirulina treatment)	Reduction (%)
Nitrogen	50 mg/L	15 mg/L	70%
Phosphorus	20 mg/L	5 mg/L	75%
Lead	2.5 mg/L	0.8 mg/L	68%
Cadmium	1 mg/L	0.3 mg/L	70%

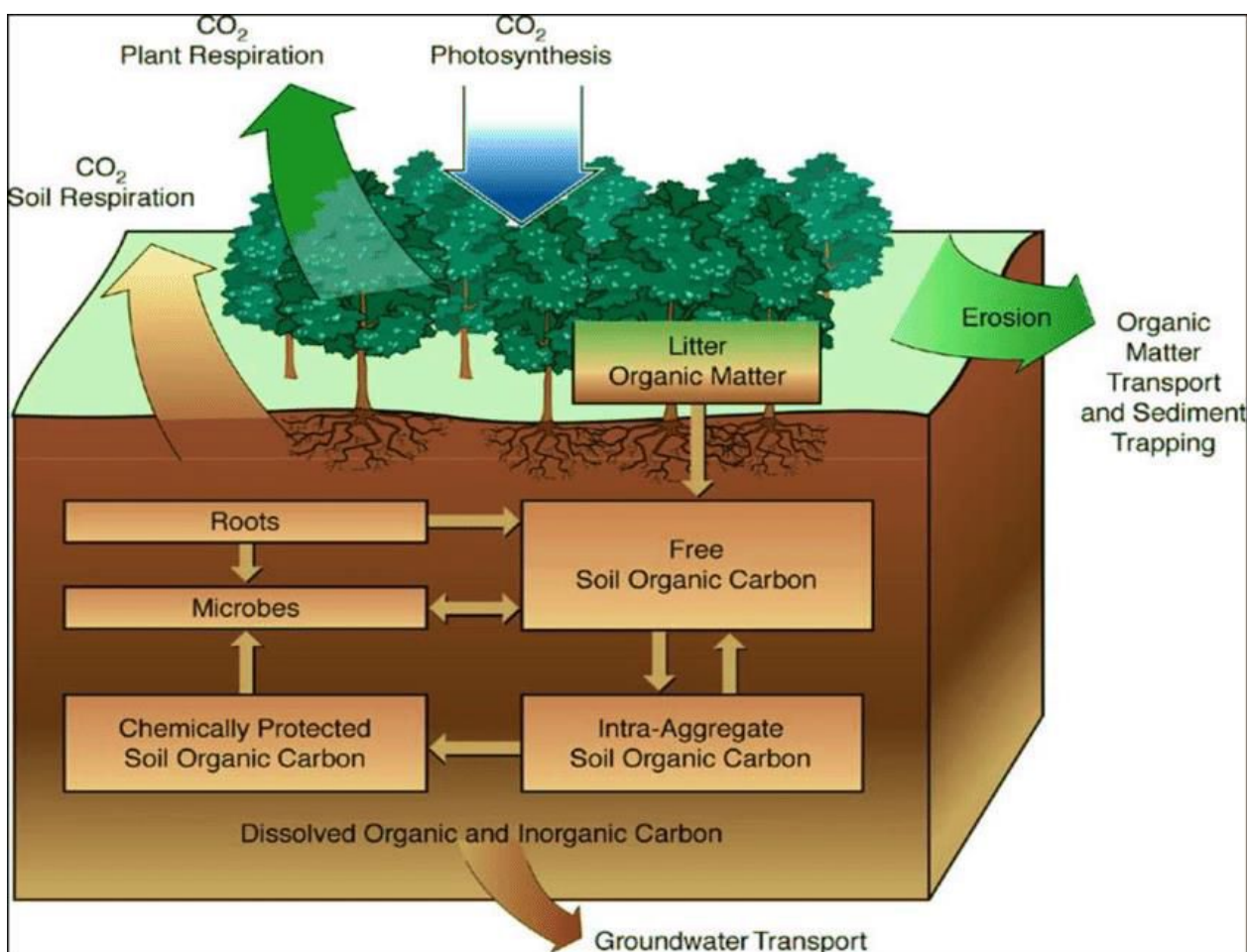


Fig 1: Soil carbon sequestration process

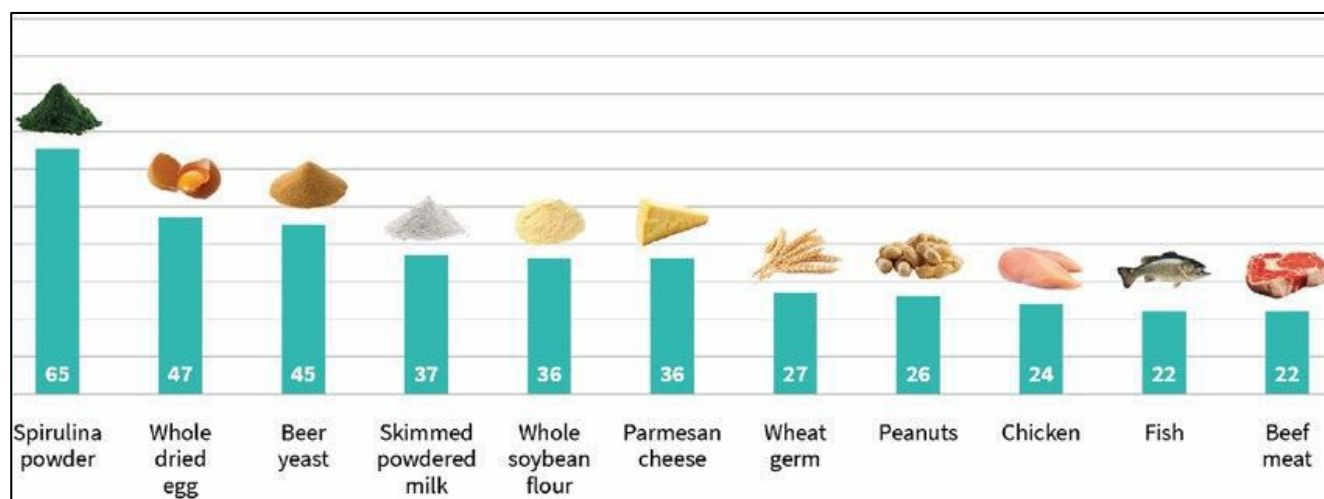


Fig 2: Quantity of Spirulina proteins and other foods (Crude protein percentage)

6. Conclusion

Spirulina presents itself as a versatile and promising resource with numerous applications across nutrition, health, cosmetics, agriculture, and environmental management. Its rich nutritional profile, bioactive compounds, and adaptability make it a valuable asset for addressing global challenges related to malnutrition, sustainable food production, and environmental sustainability. However, several challenges must be addressed to unlock Spirulina's full potential. These include optimizing production techniques to reduce costs, implementing stringent quality control measures, navigating regulatory complexities, and overcoming limitations in market acceptance and environmental impacts.

Future research should focus on improving cultivation techniques for greater efficiency and sustainability, developing advanced formulations to enhance therapeutic potential, and exploring emerging applications such as space nutrition and climate-resilient agriculture. Continued efforts can enable Spirulina to contribute significantly to sustainable development, addressing health, food security, and environmental conservation challenges globally.

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