INTERNATIONAL JOURNAL OF PHARMACEUTICAL AND HEALTHCARE INNOVATION
journal homepage: www.ijphi.com

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Review Article

Spirulina: "A Superfood with Multifaceted Health Benefits and Commercial Applications"

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Article Info

Article history:

Manuscript ID:

IJPHI2724302025
Received: 27-December -2024
Revised :24- January -2025
Accepted: 10- March 2025
Available online: March 2025

Keywords:
Spirulina, Nutritional supplements, Bioactive compounds, Health benefits

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Abstract

Spirulina, a blue-green microalga, has emerged as a "superfood" due to its extensive nutritional composition and diverse health applications. Rich in high-quality proteins, essential amino acids, vitamins, minerals, and bioactive compounds such as phycocyanin, polysaccharides, and carotenoids, Spirulina demonstrates remarkable therapeutic potential in managing chronic conditions, including hypertension, diabetes, anemia, and liver diseases, through its antioxidant, anti-inflammatory, and immunomodulatory properties. Additionally, its ability to regulate blood lipids, enhance gut health, and combat oxidative stress underscores its importance in preventive healthcare. Beyond health benefits, Spirulina finds extensive commercial applications in the nutraceutical, pharmaceutical, and cosmetic industries. It is widely used in dietary supplements, functional foods, and skincare products due to its nutrient density and natural antioxidant properties. Its incorporation into dairy products, snacks, and beverages has been explored for both nutritional enhancement and aesthetic appeal. In the pharmaceutical domain, Spirulina shows promise as a drug carrier, leveraging its porous structure to improve drug stability and controlled release. It is a valuable ingredient in animal feed and a promising candidate for biofuel production due to its high lipid content and carbon sequestration ability. Spirulina's low ecological footprint and adaptability to extreme environments make it a sustainable and scalable resource. This paper highlights Spirulina's significant contributions to health and commercial applications, emphasizing the need for further research and innovation to maximize its benefits and establish its role as a cornerstone of sustainable development and global healthcare solutions.

Introduction

Spirulina, often called as a "superfood," is one of the most nutrient-dense and versatile whole foods known to humankind. With a rich history and an intriguing ecological and biological niche, it has been widely acknowledged for its exceptional nutritional profile and potential health benefits [1,2]. Spirulina, scientifically classified under the Oscillatoria family, belongs to a group of cyanobacteria that were among the first organisms to acquire photosynthetic capabilities. These organisms are considered ancestral forms from which higher plants evolved [3,4].This blue-green microalga derives its name from its distinctive spiral-shaped filaments and is renowned for its remarkable ability to thrive in environments that are inhospitable to most other microorganisms [5,6]. Naturally found in alkaline waters of regions such as the Pacific Ocean (near Japan and Hawaii), large freshwater lakes in Africa, North America, Mexico, and South America, Spirulina is well-adapted to extreme conditions. The two most commonly cultivated and consumed species, Spirulina platensis and Spirulina maxima, are frequently used as nutritional supplements due to their rich composition of proteins, vitamins, minerals, and bioactive compounds [7-9].Despite being referred to as algae, Spirulina is a prokaryotic organism with characteristics closely aligned to eubacteria. It exhibits a variety of structural forms, from individual cells to filamentous colonies, and displays specialized differentiation in response to environmental conditions. These adaptations, such as nitrogen fixation via heterocyst’s, enable Spirulina to sustain itself in nutrient-limited conditions while contributing significantly to ecological nitrogen cycling, particularly in rice paddy ecosystems [10,11].Among the species, Arthrosporic platensis is of particular interest due to its unique helical trichome morphology and capacity to grow under elevated alkaline pH levels. Advances in genetic and molecular studies have improved the understanding of its taxonomy and ecological adaptations, facilitating its large-scale cultivation. Its annual production has scaled to thousands of metric tons, with its use deeply rooted in traditional diets, such as by the Kanembu tribe of Chad and the Aztecs of Mexico, as well as modern applications in nutraceuticals, pharmaceuticals, and functional foods [12,13].The morphological stability of Spirulina's helical structure has been an area of active research. Environmental factors, including temperature and media conditions, influence its helical geometry, leading to reversible transitions between helical and straight trichome forms [14]. These transitions have been linked to mutations, with straight trichomes often becoming dominant in certain culture conditions. As a robust organism with a diverse range of applications, Spirulina continues to captivate scientific and industrial interest. Its cultivation under various trophic modes, ability to yield high-value compounds like phycocyanin, and potential for use in cosmetics, health supplements, and biofuels position Spirulina as a sustainable solution to several global challenges, including malnutrition, energy production, and environmental conservation [15,16]. Further research and technological advancements in Spirulina cultivation and processing promise to unlock its full potential, establishing it as a cornerstone of future health and sustainability efforts. This paper provides an overview of Spirulina's nutritional composition, therapeutic properties, and diverse applications in health, medicine, and environmental sustainability. It examines its role in managing various health conditions, including hypertension, diabetes, and inflammation, while exploring its potential in biofuels, cosmetics, and agriculture. The paper also highlights current research advancements, challenges in cultivation and extraction, and the future prospects for Spirulina as a sustainable resource [17-19].

Life cycle and processing of spirulina

Spirulina undergoes a unique life cycle characterized by three key stages: trichome fragmentation, hormogonia cell enlargement and maturation, and trichome elongation. The reproduction of Spirulina primarily occurs through the fragmentation of its long, filamentous trichomes, which consist of individual cells [20,21]. This fragmentation results in the formation of smaller segments known as hormogonia, which can grow and survive independently under favorable conditions. Hormogonia are crucial for the organism's adaptability, as they actively seek optimal environments, such as specific pH levels, temperature, and nutrient concentrations, to facilitate growth [22-24].

Once optimal conditions are met, the hormogonia undergo binary fission, leading to rapid cell division and the elongation of the trichomes [25,26]. Over time, these trichomes develop into the mature, helical structure that is characteristic of Spirulina species like Spirulina platensis and Spirulina maxima. This mature form is vital for efficient photosynthesis, nutrient assimilation, and the production of bioactive compounds, such as phycocyanin, proteins, and polysaccharides, which contribute to Spirulina's high nutritional and therapeutic value [27].

Spirulina's ability to survive in harsh environments, such as alkaline lakes and brackish waters, is a testament to its resilience. Under adverse conditions, including nutrient depletion or extreme temperatures, Spirulina can enter a dormant state, halting growth until more favorable conditions resume. This remarkable adaptability allows Spirulina to thrive in environments where other organisms struggle, further enhancing its potential as a sustainable resource [28-30].

United nations and nasa interest

Due to its wealth of nutrients and health benefits reported by consumers, Spirulina has been subjected to research throughout the world. In 1974, the United Nations named Spirulina one of the best foods for the future [31]. The UN continues to study Spirulina's potential; in 2008 the UN Food and Agriculture Organization (FAO) report on Spirulina proclaimed that there is a need for both national governments and inter-governmental organizations to reevaluate the potential of Spirulina to fulfill both their own food security needs as well as a tool for their overseas development emergency response efforts [32]. It is interesting to also note that scientists from the US Space Program at NASA have studied Spirulina as a potential food source for space travel and settlement of space stations due to its remarkable nutrient profile [33].

Composition of spirulina

Spirulina is a nutrient-rich microalga known for its comprehensive and digestible nutritional profile. It consists of approximately 60% protein by dry weight and contains all essential amino acids. Additionally, Spirulina is a rich source of vitamins, minerals, and phytonutrients. These include beta-carotene, gamma-linolenic acid (GLA), chlorophyll, phycocyanin, sulfolipids, glycolipids, superoxide dismutase (SOD), RNA, and DNA. The following sections detail the primary components of Spirulina, their molecular characteristics, and their physiological functions [34, 35].

Nutritional Components of Spirulina

Proteins

The primary protein in Spirulina is phycobilin, comprising three major proteins: phycocyanin, allophycocyanin, and phycoglobin. Phycocyanin, the most abundant, accounts for a significant portion of Spirulina's protein content (approximately 50% of its dry weight). Structurally, phycocyanin is composed of α and β subunits, which polymerize into trimers and hexamers. Each subunit comprises 160–180 amino acids with distinct molecular weights (α: 12–19 kDa, β: 14–21 kDa). Phycocyanin also contains three chromophore groups responsible for its light absorption properties, with a maximum wavelength of 620 nm. It exhibits diverse physiological activities, including antioxidant, anti-inflammatory, and anti-tumor properties, and promotes efficient protein absorption [36,37].

Polysaccharides

Spirulina contains complex heteropolysaccharides with approximately 6% sulfate content. These polysaccharides include D-mannose, D-glucose, D-galactose, L-rhamnose, and glucuronic acid, comprising 14–16% of its dry weight. Minor monosaccharides such as xylose, arabinose, and fucose are also present. These polysaccharides enhance the antioxidant system, eliminate free radicals, reduce malondialdehyde (MDA) levels, and increase serum insulin, thus mitigating oxidative stress and improving blood sugar regulation [38,39].

Lipids

Spirulina has a low-fat content (6–9%) and is a rich source of essential unsaturated fatty acids such as gamma-linolenic acid (GLA), docosahexaenoic acid (DHA), and eicosapentaenoic acid (EPA). It is the only known autotrophic organism with significant GLA levels. GLA contributes to reducing blood lipids, regulating blood pressure, and lowering cholesterol

levels, making it valuable in managing cardiovascular diseases. Furthermore, its antioxidant properties offer applications in cosmetics, including skin whitening and anti-aging formulations [40,41].

Chlorophyll

Spirulina contains high levels of chlorophyll, surpassing terrestrial plants. Chlorophyll is a natural bioactive pigment with deodorizing, therapeutic, and anti-inflammatory properties. Structurally, chlorophyll consists of a porphyrin ring with a magnesium core, making it similar to heme. Chlorophyll is lipid-soluble and utilized in various industries, including medicine, food, and cosmetics. Its presence in Spirulina (approximately 1–2% of dry weight) is a valuable marker for algal biomass evaluation [42,43].

Other constituents

Spirulina offers a broad spectrum of essential nutrients and bioactive compounds, which makes it one of the most nutrient-dense natural foods. It contains high levels of B-complex vitamins, vitamin E, vitamin K, calcium (180% more than whole milk), and iron (5100% more than spinach). Spirulina also rich in phytochemicals like beta-carotene (3100% more than carrots), phycocyanin, and SOD. The anti inflammatory and antioxidant compounds of spirulina contribute significantly to its health benefits, with just 3 g of Spirulina surpassing the antioxidant activity of five servings of fruits and vegetables [44,45].These attributes make Spirulina a potent functional food, addressing nutritional deficiencies and promoting overall health. Its diverse composition underlines its value as a dietary supplement and its therapeutic potential across a range of applications.

Table 1: Typical analysis per 100 grams for Spirulina Pacifica

Item	Amount
General	
Total Calories (Kcal)	33
Calories from Fat (Kcal)	50
Total Fat (g)	5
Saturated Fat (g)	2.2
Cholesterol (mg)	0
Total Carbohydrates (g)	16
Dietary Fiber (g)	7
Sugars (g)	0
Protein (g)	67
Vitamins	
Vit A (as Beta carotene) (IU)	375000
Vitamin E (IU)	7
Vitamin K1 (µg)	2000
Vitamin K2(µg)	500
Vitamin K2(µg)	117
Riboflavin (B2) (µg)	4667
Niacin (B3) (µg)	13333
Vitamin B6 (µg)	1000
Folate (µg)	200
Vitamin B12 (µg)	300
Biotin (µg)	<33
Pantothenic acid (µg)	150
Minerals	
Calcium (mg)	333
Iron (mg)	217
Phosphorous (mg)	1100
Iodine (µg)	500
Magnesium (mg)	500
Zinc (mg)	3
Selenium (µg)	30
Copper (mg)	0.7
Manganese (mg)	13
Chromium (µg)	1333
Sodium (mg)	1000
Potassium (mg)	2000
Carotenoids & Phytonutrients	
Gamma Linolenic Acid (GLA) (mg)	1067
Zeaxanthin (mg)	300
Total carotenoids (mg)	500
Chlorophyll (mg)	1000
C-Phycocyanin (mg)	8000
Superoxide dismutase (units)	36000

Mechanism of action of spirulina in various disease/ disorders

Spirulina has demonstrated diverse therapeutic potential through its multifaceted mechanisms of action, making it a valuable candidate for managing various diseases [46]. Its immunomodulatory properties are primarily attributed to its ability to enhance cytokine production, including tumor necrosis factor-alpha (TNF-α), interleukin-2 (IL-2), and interferon, while promoting CD4+ T-helper cell proliferation and natural killer (NK) cell activity. These effects strengthen both innate and adaptive immunity, providing protection against infections and enhancing immune surveillance. Spirulina also exerts significant chemo-protective effects, mitigating the toxicities of cytotoxic agents such as doxorubicin and cisplatin by scavenging free radicals and modulating mitochondrial function. This protective mechanism is crucial in preventing cardiotoxicity, nephrotoxicity, and hepatotoxicity during chemotherapy [47,48].

The phycocyanobilin (PCB) in Spirulina mimics bilirubin by inhibiting NADPH oxidase, reducing oxidative stress and inflammation. This property underpins its efficacy in chronic inflammatory diseases, such as arthritis and allergic rhinitis, and its potential role in autoimmune disorders. Spirulina's robust antioxidant activity, driven by its bioactive components like phycocyanin and carotenoids, protects cells from oxidative damage, which is pivotal in managing cardiovascular diseases, neurodegenerative disorders, and diabetes. It also enhances glucose homeostasis by promoting insulin sensitivity, modulating glycogen metabolism, and reducing intestinal glucose absorption [49,50].

Spirulina's anti-cancer effects involve DNA repair enhancement, apoptosis induction in tumor cells, and activation of immune surveillance mechanisms. Furthermore, its hypolipidemic action, mediated by the inhibition of lipogenesis and enhancement of fatty acid oxidation, reduces LDL cholesterol, triglycerides, and total cholesterol, while increasing HDL cholesterol. These effects contribute to the prevention of atherosclerosis [51,52]. Spirulina also displays potent antiviral activity by inhibiting viral entry, suppressing replication, and enhancing the immune response against pathogens such as HIV, HSV, and influenza. Additionally, its appetite-regulating properties, coupled with its ability to improve fat metabolism and oxidative balance, make it effective for weight management. Collectively, these mechanisms highlight Spirulina's potential as a therapeutic agent across a wide spectrum of diseases, warranting further investigation to optimize its clinical applications [53,54].

Therapeutic benefits of spirulina

Research on Spirulina's health benefits has been far-ranging. Spirulina offers a wide array of therapeutic benefits, including potent antioxidant, anti-inflammatory, and immunomodulatory properties. It has been shown to support the management of conditions such as hypertension, diabetes, hyperlipidemia, and anemia, promoting overall health and well-being and they are describing as below [55].

Hypolipidemic and Hepatoprotective Effects

Spirulina exhibits significant lipid-lowering properties by decreasing the levels of triacylglycerols, low-density lipoprotein cholesterol (LDL-C), and total cholesterol. Simultaneously, it exerts a positive effect on high-density lipoprotein cholesterol (HDL-C). The bioactive compound C-phycocyanin plays a key role in these effects by inhibiting lipid peroxidation and enhancing antioxidant activity [56]. Additionally, the high potassium and low sodium content of Spirulina contributes to reducing systolic and diastolic blood pressure. Oral supplementation (4.5 g/day for six weeks) has shown marked improvements in hypertension and lipid profiles. Furthermore, Spirulina's hepatoprotective properties are evidenced by its ability to decrease liver lipid accumulation and enhance the regeneration of hepatocytes, restoring liver integrity [57,58].

Immune-Modulatory and Anti-Viral Effects

Spirulina enhances both mucosal and systemic immunity by activating components of the innate immune system, such as macrophages, T cells, and B cells [59]. It stimulates cytokine production, including interferon-gamma, interleukins, and tumor necrosis factor-alpha (TNF-α). Spirulina-derived sulfolipids have demonstrated effectiveness against viruses such as HIV, herpes simplex virus (HSV), cytomegalovirus, and influenza. Its immunomodulatory action includes inhibition of histamine

release, contributing to reduced allergic inflammation. These properties make Spirulina a promising agent in enhancing resistance to infections and mitigating allergic conditions such as hay fever and allergic rhinitis [60,61].

Anti-Cancer Potential

Spirulina and its extracts possess anti-cancer properties, primarily through mechanisms such as enhancing DNA repair synthesis and increasing cell nucleus enzyme activity. Polysaccharides and phycocyanin derived from Spirulina have demonstrated inhibitory effects on carcinogenesis in both in vitro and in vivo studies [62,63].

Anti-Inflammatory Effects

Phycocyanobilin (PCB), a chromophore in Spirulina, inhibits NADPH oxidase, reducing oxidative stress and inflammation [64]. This mechanism contributes to the mitigation of various chronic inflammatory conditions. Studies suggest that oral administration of Spirulina or PCB-enriched extracts exerts potent anti-inflammatory effects, making it a viable therapeutic agent for conditions like arthritis [65,66].

Hematopoietic and Anti-Anemia Effects

Spirulina supplementation enhances red blood cell production and function. Clinical studies have shown steady increases in mean corpuscular hemoglobin and reductions in anemia levels in children and older adults after Spirulina intake. These effects are attributed to its rich nutrient profile, which supports hematopoiesis [67,68].

Anti-Diabetic and Hypoglycemic Activity

Spirulina has demonstrated significant hypoglycemic effects by promoting liver glycogen synthesis, inhibiting glucose absorption in the intestine, and enhancing insulin sensitivity. Phycocyanin has been shown to activate insulin signaling pathways and reduce blood glucose levels. Additionally, Spirulina polysaccharides alleviate hyperglycemia symptoms and improve glucose metabolism, making it a potential functional food for diabetes management [69,70].

Weight Management

The phenylalanine content in Spirulina influences the hypothalamus to regulate appetite, promoting satiety and reducing caloric intake. Spirulina supplementation decreases visceral fat infiltration, liver fat accumulation, and oxidative stress, while improving insulin sensitivity. Clinical studies have shown reductions in body mass index (BMI) and improvements in lipid profiles, further supporting its role in weight management [71,72].

Probiotic and Gut Health Benefits

Spirulina enhances the growth of beneficial lactic acid bacteria, thereby improving gut microbial balance. Its antibacterial activity against pathogenic bacteria and its role in maintaining intestinal epithelium integrity contribute to better gastrointestinal health and immunity [73,74].

Anti-Nephrotoxicity Effects

Spirulina protects against nephrotoxicity induced by toxins such as galactosamine by promoting hepatocyte regeneration. The hepatoprotective and nephroprotective properties of Spirulina are attributed to its rich antioxidant compounds, which reduce oxidative damage in kidney and liver tissues [75,76].

Antioxidant and Anti-Fatigue Properties

Spirulina is rich in antioxidants such as phycocyanin, carotenoids, and polysaccharides, which neutralize free radicals and reduce oxidative stress. These properties enhance the body's resistance to fatigue, making Spirulina a beneficial supplement for athletes and individuals experiencing chronic fatigue [77,78].

Anti-Allergic and Anti-Inflammatory Effects

In allergic rhinitis patients, Spirulina has been shown to reduce pro-inflammatory cytokines such as IL-4. It also inhibits the release of histamine, alleviating symptoms of allergic inflammatory responses. These effects extend to other inflammatory conditions, including arthritis [79,80].

Utilization prospects of spirulina

Human Consumption

Spirulina has been extensively studied for its role in human health and nutrition. Clinical trials have demonstrated its efficacy as a supplementary treatment for various diseases. For instance, Spirulina capsules have been shown to lower blood lipid levels, mitigate leukocyte reduction following

radiotherapy and chemotherapy, and enhance immune function. Since the 1980s, Spirulina has been widely incorporated into health foods, feed, and biochemical products [81,82].

Use as Feed and Feed Additives

The use of Spirulina as a feed or feed additive necessitates careful species identification to avoid contamination or substitution with toxic cyanobacteria, such as those producing microcystins. Spirulina's transformation into powdered form enables its incorporation into diverse food products, including soups, sauces, pasta, snack foods, instant beverages, and baked goods. Research highlights its application in food formulations like oil-in-water emulsions, vegetable puddings, biscuits, and pastas, emphasizing its stability under processing and storage conditions. Studies also reveal its enrichment potential in wheat flour-based pasta, improving green coloration, nutritional profile, and functional properties due to bioactive compounds [83, 84].

Application in Dairy Products

The addition of Spirulina during yogurt production enhances water retention, firmness, and nutrient content, resulting in a curd-like texture and a vibrant green hue. Incorporating 1% Spirulina powder into soft cheese formulations increases beta-carotene and protein content, reduces moisture, and extends shelf life. These applications demonstrate Spirulina's potential for innovation in dairy products [85,86].

Applications in Medicine

Spirulina's porous cell structure and surface composition, rich in proteins, polysaccharides, amino acids, and fatty acids, make it a promising candidate for drug carrier systems. Its high drug adsorption capacity allows for controlled drug release, stabilization of active ingredients, prolonged bioavailability, and enhanced therapeutic efficacy. Spirulina's antioxidant and anti-inflammatory nutrients, including lutein and beta-carotene, provide hepatoprotective effects. These compounds mitigate oxidative damage, prevent complications such as hepatitis and cirrhosis, and inhibit the replication of the hepatitis C virus, suggesting potential applications in treating liver diseases [87,88].

Applications in Cosmetics

Spirulina contains antioxidants such as carotenoids and vitamin E, which protect the skin from oxidative damage and environmental stressors. It also promotes skin hydration, firmness, and elasticity through peptides that stimulate collagen synthesis. Polysaccharides and sulfides contribute to anti-inflammatory effects and moisture retention. Additionally, lutein and carotenoids inhibit melanin synthesis, reducing dark spots and enhancing skin radiance. Spirulina polysaccharides also demonstrate UV protection, with sun protection factors (SPF) ranging from 10 to 15 [89,90].

Applications in Health Care Products

Spirulina's diverse nutritional and antioxidant profile strengthens the immune system, enhancing the body's resistance to infections and diseases. The bioactive compounds in Spirulina reduce blood lipid and sugar levels, offering preventive benefits against cardiovascular diseases and diabetes. Spirulina promotes digestive health through its dietary fiber and probiotics, enhancing intestinal motility and facilitating regular bowel movements. The vitamins and antioxidants in Spirulina provide energy and reduce fatigue and stress, improving overall vitality. Spirulina's bioactive compounds support healthy skin, hair, and nails, enhancing their appearance and overall health [91,92].

Applications in Biofuels

Spirulina biomass contains approximately 25% oil, which is rich in unsaturated fatty acids. These oils can be extracted and converted into biodiesel, making Spirulina a viable raw material for renewable energy [93,94]. Through photosynthesis, Spirulina generates oxygen and hydrogen, which can be utilized in clean energy technologies like fuel cells. Anaerobic digestion of Spirulina biomass also produces biogas, offering an alternative to natural gas. Spirulina efficiently absorbs carbon dioxide during growth, serving as a carbon sink. Biofuels derived from Spirulina exhibit lower carbon emissions, contributing to environmental sustainability [95,96].

Products available in indian market

Spirulina, often referred to as a "superfood," is available in various forms in the Indian market, addressing diverse

consumer needs. Dietary supplements, including tablets, capsules, and powders, are the most common forms of Spirulina [97]. Notable brands such as Organic India, Neuherbs, and Vruksha Vitals offer Spirulina products rich in essential nutrients like proteins, vitamins, and antioxidants, aimed at improving immunity, energy, and overall well-being [98,99].In addition to supplements, Spirulina has made its way into functional foods such as energy bars, smoothies, and fortified dairy products [100]. Spirulina-enriched fermented milks are also gaining popularity, demonstrating enhanced probiotics viability and improved sensory characteristics.[108] Furthermore, Spirulina's use as a natural pigment in foods like beverages and desserts highlights its utility in both nutrition and aesthetics [101,102].The cosmetic industry in India also incorporates Spirulina into face masks and creams for its anti-aging and antioxidant properties. Additionally, Spirulina is utilized in animal feed, particularly in poultry and aquaculture, to boost growth, improve egg yolk pigmentation, and enhance disease resistance in livestock [103,104].

Future prospective

Spirulina, often referred to as a "superfood," has a long history of safe consumption and extensive applications as a natural dietary supplement. Its high nutritional density, safety profile, and functional properties position it as a valuable resource in health, food, and cosmetic industries [105].Despite its potential, challenges such as low extraction yields and high production costs limit the scalability of Spirulina-derived products. Future research should focus on improving extraction methods, enhancing active compound yields, and conducting comprehensive clinical trials to validate its health benefits. Genetic engineering offers promising avenues for Spirulina modification, enabling optimized growth, nutrient composition, and novel applications [106].Ongoing research into Spirulina's antioxidant capabilities highlights its utility beyond healthcare, including food preservation and environmental applications. However, rigorous safety evaluations are necessary to address potential sensitization and interactions with other substances. With its multifaceted applications and potential for innovation, Spirulina is poised to become a pivotal component in the development of functional foods, health products, and sustainable technologies [107].

Conclusion

Spirulina emerges as a highly versatile and sustainable superfood with substantial potential in diverse fields, including health, nutrition, medicine, and environmental sustainability. Its exceptional nutritional composition, rich in proteins, essential amino acids, vitamins, and bioactive compounds such as phycocyanin and polysaccharides, positions it as a key player in promoting overall health and well-being. The bioactive properties of Spirulina, including its antioxidant, anti-inflammatory, and immunomodulatory effects, alongside its therapeutic roles in managing conditions such as hypertension, diabetes, and anemia, underscore its value as a functional food with wide-reaching health benefits. Beyond its health applications, Spirulina's contributions extend to cosmetics, agriculture, and biofuel production, highlighting its adaptability and potential to address critical global challenges, such as food security, environmental conservation, and sustainable energy solutions. However, despite its promising benefits, there remains a need for further research to optimize its cultivation, enhance the extraction of bioactive compounds, and comprehensively evaluate its long-term safety and efficacy.As global interest in Spirulina continues to grow, with endorsements from renowned institutions like NASA and the United Nations, its role in shaping the future of sustainable nutrition and healthcare becomes increasingly significant. Continued investigation into its molecular mechanisms, clinical applications, and potential for large-scale production will ensure its broader utilization and contribute to its potential as a cornerstone in global health and environmental sustainability.

Ethical approval

NA

Informed consent

Not Applicable.

Funding

No funding was received for conducting this study.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare no conflict of interest among themselves. The authors alone are responsible for the content and writing of this article.

Financial interests

The authors declare they have no financial interests

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