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The Multifaceted Role of *Spirulina* in Environmental Sustainability: Applications in Aquatic Systems and Ecosystem Management

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ABSTRACT

Spirulina, a versatile microalga, has emerged as a powerful tool for promoting environmental sustainability through its diverse applications in aquatic systems and ecosystem management. This review delves into its multifaceted roles, including enhancing water quality, reducing environmental pollutants, and contributing to the sustainable management of natural resources. spirulina's nutrient-rich profile—comprising high levels of protein, essential fatty acids, vitamins, minerals, and bioactive compounds—positions it as an effective agent in bioremediation and aquaculture. Its ability to remove contaminants such as nitrate, phosphorus, ammonium, and heavy metals highlights its importance in mitigating water pollution and restoring ecosystem balance. Additionally, spirulina's biomass can be repurposed into value-added products like biochar and natural biostimulants, offering innovative solutions for carbon sequestration, soil stabilization, and supporting aquatic biodiversity. The use of spirulina also extends to addressing the challenges posed by climate change, such as increasing greenhouse gas emissions and declining water quality. By integrating spirulina into environmental management practices, including wastewater treatment, aquaculture sustainability, and ecosystem restoration, its role in enhancing ecological resilience becomes increasingly evident. This comprehensive analysis underscores the potential of spirulina as a sustainable and versatile resource for improving environmental health, advancing biodiversity conservation, and supporting the transition to greener economies. This review delves into its multifaceted roles, including enhancing water quality, reducing environmental pollutants, and contributing to the sustainable management of natural resources, with a particular focus on the emerging application of Spirulina in wastewater and soil treatment using vertical flow constructed wetlands.

INTRODUCTION

Spirulina, also known as *Arthrospira*, has captured the attention of researchers for many years, as evident from the plethora of publications spanning its diverse aspects. An increasing wealth of information continues to emerge about its biology, biotechnological applications, nutritional benefits, and health implications. Surprisingly, its utility extends to seemingly unrelated domains like biofuel production and life support systems in space exploration. This enduring fascination is likely poised to persist. Exploring these avenues promises both societal and professional dividends. Among *Spirulina* variants, *Spirulina platensis* stands out as the most prevalent and extensively studied genus, particularly in fields such as the food industry and medicine **(Abreu *et al.,* 2023)**. *Spirulina*, originating approximately 3.5 billion years ago, represents a primitive organism capable of harnessing carbon dioxide dissolved in seawater for its sustenance. Functioning as a photosynthesizing cyanophyte (blue-green algae), spirulina thrives in intense sunlight, high temperatures, and strongly alkaline conditions **(Anvar & Nowruzi, 2021)**.

Spirulina, a versatile microalga, offers numerous environmental benefits. It thrives in nutrient-rich environments, absorbing pollutants such as nitrogen and phosphorus from wastewater, thereby improving water quality and reducing eutrophication. In addition, *Spirulina* sequesters carbon dioxide from the atmosphere, contributing to climate change mitigation. Furthermore, its efficient cultivation requires minimal land and water resources, making it a sustainable alternative to traditional agriculture. Additionally, the residual biomass from spirulina production can be repurposed into biofuels or biofertilizers, further reducing environmental impact **(Gabal *et al,* 2018; Soma *et al,* 2024)**.

Spirulina is the most extensively studied species of spirulina due to its widespread availability and robust nutritional profile. This is due to: 1- its ability to thrive in diverse environmental conditions, coupled with its high protein content, essential vitamins, minerals, and antioxidants, has made it a subject of intense scientific interest; 2- decades of research have delved into its potential applications in human nutrition, animal feed, and environmental remediation, and 3- as a result, a wealth of knowledge exists on its cultivation techniques, biochemical composition, and beneficial properties, solidifying its position as the primary focus of Spirulina research **(AbouGabal, *et al,* 2015; Soma *et al,* 2024)**.

This review focused on multifaceted roles, including enhancing water quality, reducing environmental pollutants, and contributing to the sustainable management of natural resources, with a particular aim on the emerging application of spirulina in wastewater and soil treatment using vertical flow constructed wetlands

Historical background

Spirulina was first observed in 1940 by French phycologist Pierre Dangeard around Lake Chad, where the Kanembu people harvested cyanobacteria for food using clay pots. He documented this in his report on the consumption of dihé and noted similar algae in the East African Rift Valley lakes, which were a primary food source for flamingos **(Metcalf *et al.,* 2012)**. In 1964-1965, botanist Jean Léonard encountered edible green cakes sold in Fort-Lamy (now N'Djamena), made from algae near Lake Chad. He linked these cakes to algal blooms in the area. Additionally, Spanish invaders, including Hernando Cortez, observed the Aztecs collecting a blue substance called ‘tecuitlatl’ from Lake Texcoco, a discovery documented by **Sasson (1997**) and **Vonshak (1997)**. *Spirulina* is naturally found in the alkaline lakes of Mexico and Africa **(Belay *et al*., 1996; Shimamatsu, 2004; Metcalf *et al*., 2012)**.

This historical evidence highlights *Spirulina's* long-standing significance as a nutritional resource, aligning with the focus of this manuscript on its potential for sustainable applications.

Classification

In 1827, P.J. Turpin first isolated spirulina from freshwater **(Ciferri, 1983)**. Nearly two decades later, in 1844, Wittrock and Nordstedt identified a helical, septate, green-blue microalga near Montevideo, naming it *Spirulina jenneri F. platensis*. In 1852, Stizenberger introduced the name *Arthrospira*, considering its septa presence and helical form, which Gomont later confirmed in 1892.

In 1932, Geitler merged both genera under spirulina due to their helical morphology, overlooking septa **(Vonshak, 1997)**. *Spirulina* is within kingdom Monera, division Cyanophyta, order Oscillatoriales, and family Phormidiaceae, (Fig. 1), which includes 15 species across *Spirulina* and *Arthrospira*. A revised classification in 1989 separated them into two genera, which is currently accepted **(Tomaselli *et al*., 1996)**. However, species definitions remain unclear, with *Arthrospira* often marketed as spirulina **(Sanchez *et al.*, 2003**).

Spirulina, a filamentous, multicellular, blue-green microalga, is an edible cyanobacterium **(Becker, 2007)**. Key species include *Arthrospira maxima* and *A. platensis*, differing in filament structure, vacuoles, and capsule regularity **(Tomaselli, 1997)**. Differentiation methods include microscopy and biochemical testing of 16S rRNA **(Spiller *et al*., 2000)**. Approximately, 87 *Spirulina* species exist, with 47 taxonomically recognized, such as *Spirulina subsalsa* and *Spirulina labyrinthiformis* **(Habib *et al*., 2008; Guiry & Guiry, 2011)**.

Fig. 1. Spirulina taxonomy

Morphological Features

Spirulina is a multicellular, filamentous blue-green microalga that harbors symbiotic nitrogen-fixing bacteria. It contains photosynthetic pigments such as phycocyanin, chlorophyll a, and carotenoids, and sometimes phycoerythrin. *Spirulina* is autotrophic and reproduces by binary fission **(AlFadhly *et al.*, 2022; AIbrahim *et al.*, 2024)**.

In the 1970s, protoplasts were isolated from various cyanobacteria, including spirulina, using enzymatic treatments **(Abo-Shady *et al*., 1992)**. Due to its smooth surface, spirulina is easily digestible **(Larrosa *et al*., 2018)**.

Arthrospira species show significant morphological variability (Fig. 2) influenced by environmental factors. They form helical trichomes, that vary from tightly coiled to straight, with transverse cross-walls visible under light microscopy. Trichomes typically range from 50 to 500µm in length and 3 to 4µm in width, and they float due to gas-filled vacuoles **(Tomaselli, 1997; Koru, 2012)**.

Cyanobacteria have a Gram-negative-like cell wall containing peptidoglycan, aiding in osmotic stress mitigation **(Habib *et al.*, 2008; Zafilaza *et al.*, 2015)**. *Arthrospira platensis* is characterized by multicellular cylindrical trichomes arranged in an open left-hand helix **(Ali *et al*., 2012)**.

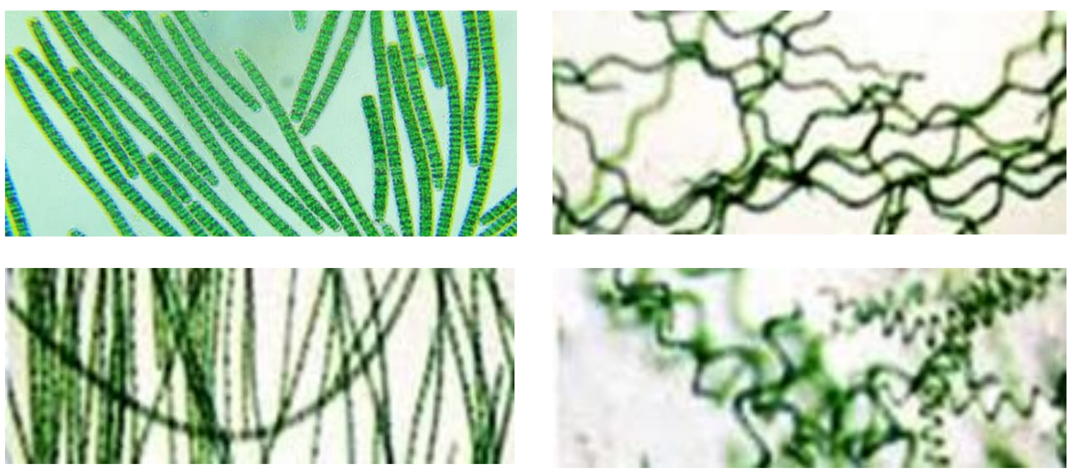

Fig. 2. *Spirulina*

Distribution in Nature

Apart from Lake Texcoco, spirulina is predominantly found in Central Africa around Lakes Chad and Niger and in East Africa along the Great Rift Valley (Table 1). Notably, lakes Bodou and Rombou in Chad maintain a stable monoculture of spirulina. It also dominates Kenya's lakes, Nakuru and Elementeita, and Ethiopia's lakes, Aranguadi and Kilotes, thriving in the alkaline conditions that are inhospitable to other microorganisms **(Kebede & Ahlgren, 1966; Ahsan *et al.*, 2008)**.

Arthrospira species, including *A. platensis* and *A. maxima*, inhabit alkaline, brackish and saline waters in tropical and subtropical regions, with *A. platensis* mainly found in Africa and Asia and *A. maxima* in California and Mexico (Table 1). Morphological and ultrastructural differences, although variable, were used for taxonomic differentiation. Recent 16S rRNA analysis has grouped species into two clusters based on geography **(Gershwin *et al*., 2008)**.

In El-Khadra Lake, Egypt, *Spirulina platensis* thrives in extreme conditions of pH 10.5 and 0.55 M salt concentration. Samples collected in summer and winter revealed various cyanobacteria and algae, including *Spirulina*, *Oscillatoria*, and *Anabaena*. These were tested for antimicrobial activity, with *Oscillatoria* filtrate inhibiting all tested microorganisms and *Anabaena* extract showing significant inhibition against *P. aeruginosa*, *B. subtilis*, and *A. niger* **(Selim *et al*., 2014)**.

Table 1. The distribution of the main populations of *Arthrospira*

Country	Location	Taxon
Chad	Natron lakes (Bodou, Mombolo, Rombou, Yoan) and pools (Latir, Iseirom, Latir, Liva), Kanem region	*A. platensis*, *A. platensis f. minor*
Chad	Lake Kailala, Lake Kossorom	*A. fusiformis*
Kenya	Natron lakes (Bogoria, Crater, Elmenteita, Nakuru)	*A. platensis*
Kenya	Rift Valley	*A. fusiformis*
Kenya	Lake Bogoria	*A. platensis*, *A. platensis f. minor*, *A. fusiformis*
Kenya	Lake Simbi	*A. platensis*, *A. fusiformis*
Kenya	Lake Sonachi	*A. fusiformis*
Kenya	Lake Oloidien	*A. fusiformis*
Ethiopia	Lake Aranguadi	*A. platensis*
Ethiopia	Lake Chiltu, Green lake	*A. platensis*, *A. fusiformis*
Egypt	Lake Maryut	*A. platensis*
Sudan	Lake Dariba, Jebel Marra	*A. geitleri*
Algeria	Pond Tamanrasset	*A. platensis*
Zambia	Lake Bangweolou	*Arthrospira* sp.
Tunisia	Lake Korba	*Arthrospira* sp.
Mozambique	Wastewater ponds	*A. fusiformis*
South Africa	Lake Tswaing	*A. fusiformis*
India	Ponds	*A. maxima*
India	Lonar Lake; ponds; tank (Madurai, MCRC isolate)	*A. indica*
Myanmar	Crater lake	*Arthrospira* sp.
Pakistan	Fish pond, Lahore	*Arthrospira* sp.
Sri Lanka	Lake Beria	*Arthrospira* sp.
China	Fish ponds, Nanking	*A. platensis*

China	Lake Bayannur	*A. platensis*
Thailand	Tapioca factory effluent lakes, Bangkok	*Arthrospira* sp.
Russia	Tunatan lake, Siberian steppe	*A. fusiformis*
Azerbaijan	Water basin, Khumbasha	*Arthrospira* sp.
Pakistan	Pond, Lahore	*Arthrospira* sp.
Mexico	Lake Texcoco solar evaporator	*A. maxima*
Brazil	Mangueira Lagoon	*Arthrospira* sp.
California	Pond, Oakland	*A. maxima*
California	Coastal lagoon, Del Mar	*A. platensis*
Peru	Lake Huachachina	*A. platensis*, *A. maxima*
Uruguay	Montevideo	*A. platensis*
Spain	Lake Santa Olalla	*Arthrospira* sp.
France	Tiny lake, Camargue	*Arthrospira* sp.
Hungary	Adasztevel-Oroshaz	*Arthrospira* sp.
Romania	Alkaline pond near Cluj-Napoca	*A. fusiformis*
Serbia	Salty puddles near River Tamiš	*A. fusiformis*

Data from **Sili *et al.* (2012)**

The chemical composition of *Spirulina*

Analysis of *Spirulina's* chemical composition reveals it as an outstanding source of proteins, lipids, carbohydrates, vitamins, dietary minerals, and pigments (Fig. 3). The exact biochemical makeup depends on the specific *Arthrospira* source, culture conditions, and production season **(Cohen, 1996; Habib *et al*., 2008; Henrikson, 2009; Falquet, 2012)**. The biochemical composition of *Spirulina* can be summarized as follows:

Protein

Spirulina contains 50-70% protein by dried weight, surpassing meat, eggs, and plant proteins. It includes all essential amino acids but is slightly deficient in methionine, cysteine, and lysine compared to animal proteins **(Gershwin *et al.*, 2008)**. *Spirulina's* protein is highly digestible (83-90%) and does not require cooking. Its protein efficiency ratio (PER) is 1.8-2.6 and net protein utilization (NPU) is 53-92%.

Spirulina's primary proteins, phycocyanin C and allophycocyanin, are notable for their health benefits and safe use as natural food colorants. These phycobiliproteins constitute 15-25% of *Spirulina's* dry weight **(Romay *et al.*, 2003)**. The chromophore phycocyanobilin (PCB), which makes up 4.7% of dried phycocyanin, inhibits NADPH oxidase activity, potentially preventing diseases like cardiovascular issues, diabetes, and neurodegenerative disorders. PCB can be consumed through whole *Spirulina*, phycocyanin protein, or isolated chromophore **(McCarty, 2007)**.

Lipids

Spirulina contains 5-7% lipids, divided into a saponifiable fraction (83%) and a non-saponifiable fraction (17%), which include essential pigments, paraffin, sterols, and terpene alcohol. Both *S. maxima* and *S. platensis* are rich in ω-linolenic acid (GLA), comprising 10-20% and 49% of their fatty acids, respectively, making *Spirulina* a significant source of GLA comparable to human milk and certain vegetable oils. *S. maxima* also contains unsaturated oleic and linoleic acids and saturated palmitic acid, which together make up over 60% of its lipid composition. Key lipids include monogalactosyl- and sulfoquinovosyl-diacylglycerol and phosphatidyl glycerol, each constituting around 20-25% of total lipids. *Spirulina's* lipid profile is predominantly ω-6 fatty acids, with minimal cholesterol content (typically <0.1mg/ 100g of dry mass) **(AbouGaba *et al*., 2015**; **Bohórquez-Medina *et al*., 2021)**.

Polysaccharides

Spirulina platensis contains significant polysaccharides, including a sulfated fraction called calcium spirulan, composed of rhamnose, methylrhamnose, xylose, uronic acids, and sulfate. Calcium spirulan has shown promise in inhibiting various viruses like HIV-1, herpes simplex 1, and influenza, with selective action against virus penetration into cells. *Spirulina* polysaccharides also activate monocytes and macrophages, boosting interleukin-1b and tumor necrosis factor alpha levels and exhibiting potent immunostimulatory effects potentially useful in therapies like cancer immunotherapy **(Pugh *et al.*, 2001; Parages *et al*., 2012)**.

Vitamins

Spirulina is acclaimed as the most abundant whole-food source of vitamin B12, including its corrinoid forms, analogs, and pseudo-vitamin B12, as well as pro-vitamin A (β-carotene). Through a highly sensitive microbiological test, it has been revealed that 36% of the vitamin B12 molecules found in *Spirulina* spp. are bioactive in humans **(Lorenz, 1999)**. Specifically, *S. platensis* contains the biologically active form of vitamin B12, methylcobalamin, at a concentration of 35-38μg/ 100g of dry *Spirulina* biomass **(Kumudha *et al*., 2010)**. Remarkably, just 20g of these microalgae is enough to meet the body's requirements for vitamins B1 (thiamine), B2 (riboflavin), and B3 (niacin) **(Sharma *et al.*, 2011; Falquet, 2012)**.

Minerals

Spirulina is rich in essential minerals such as iron (0.58-1.8 g/kg), calcium (1.3-14g/ kg), phosphorus (6.7-9.0g/ kg), and potassium (6.4-15.4g/ kg), making it a valuable nutritional supplement, especially for vegetarians. Its mineral content varies with its source and cultivation conditions, comparable to milk in calcium, phosphorus, and magnesium levels. *Spirulina* is notably high in iron, with absorption rates 60% better than ferrous sulfate. Additionally, it contains a diverse range of pigments, including chlorophyll a, beta-carotene, and various phycobiliproteins, as noted by the FAO in 2008 **(Falquet, 2012)**.

Carotenoids

Beta-carotene in *Spirulina* highlights the importance of natural vitamin sources. Natural forms, including both cis and trans types, differ from synthetic versions in absorption efficiency and health benefits. Studies link natural beta-carotene to reduced cancer risk and improved light tolerance in conditions like erythropoietic protoporphyria. It may also protect against skin cancer and enhance immune function while contributing to cardiovascular health by reducing LDL cholesterol oxidation. Beta-carotene's diverse benefits extend to influencing cellular communication in cancerous cells, potentially halting their growth. *Spirulina*, rich in various beta-carotene forms, exemplifies the nutritional advantages of natural sources over synthetic supplements **(Lafarga *et al*., 2020)**.

Zeaxanthin

Zeaxanthin, a prominent carotenoid in *Spirulina*, stands out for its antioxidant properties. It uniquely penetrates the blood-brain barrier, safeguarding vital organs like the eyes and brain without ever becoming pro-oxidative. Research highlights zeaxanthin's efficacy in combating inflammation-induced conditions such as atherosclerosis. Together with lutein, zeaxanthin plays a crucial role in eye health by filtering blue light and protecting against oxidative damage. These carotenoids also offer potential benefits against cardiovascular disease, stroke, and certain cancers, while also providing defense against UV-induced skin conditions **(Grosshagauer *et al*., 2020)**.

Phycocyanin

Phycocyanin, a blue pigment in *Spirulina*, stands out for its health benefits, distinguishing it from other green foods like chlorella, wheatgrass, and barley. As a potent antioxidant, it helps prevent renal failure from certain drug therapies and shows promise in cancer treatment and immune enhancement **(Finamore *et al.*, 2017)**. Phycocyanin also exhibits anti-inflammatory properties **(Reddy *et al*., 2000)**, scavenges free radicals, and inhibits lipid peroxidation **(Castro-Gerónimo, *et al.*, 2023)**. Animal studies reveal its ability to inhibit prostaglandin E-2, reduce allergic responses, and suppress histamine release. Further research confirms its antioxidant, anti-inflammatory, neuroprotective, and hepatoprotective effects, showing dose-dependent benefits and neuroprotection in rats **(Romay *et al*., 2003)**.

Phycocyanin, as a Cox-2 inhibitor, supports liver function, protects the liver and kidneys during detoxification, and enhances immune function, potentially suppressing cancer and viral infections. *Spirulina* extracts rich in phycocyanin show significant antiviral properties, inhibiting herpes simplex virus and cytomegalovirus **(Grover *et al*., 2021)**. Comparative studies highlight *Spirulina's* stronger impact on liver cancer cells and health compared to chlorella. Additionally, it mitigates radiation damage in rats **(Citi *et al*., 2024)**.

Gamma linolenic acid (GLA)

Linoleic acid, essential for the body and obtained through diet, converts to gamma-linolenic acid (GLA), which forms the anti-inflammatory compound prostaglandin E1 (PGE1). PGE1 is vital for joint health, heart attack and stroke prevention, fluid removal, circulation enhancement, cholesterol inhibition, nerve function improvement, and cell division regulation. GLA supplementation alleviates arthritis symptoms and premenstrual syndrome (PMS) and prevents skin disorders like psoriasis. Factors like stress, aging, alcohol, and poor diet can impair the conversion of linoleic acid to GLA. GLA dietary sources include *Spirulina*, black currant seed oil, evening primrose oil, and borage seed oil, with *Spirulina* offering a whole food form that is highly usable by the body. *Spirulina* and mother's milk are notable for their high GLA concentrations. Five grams of *Spirulina* provides 50mg of GLA, comparable to a 500mg evening primrose oil capsule **(Choopani *et al*., 2016; Xiong *et al*., 2023)**.

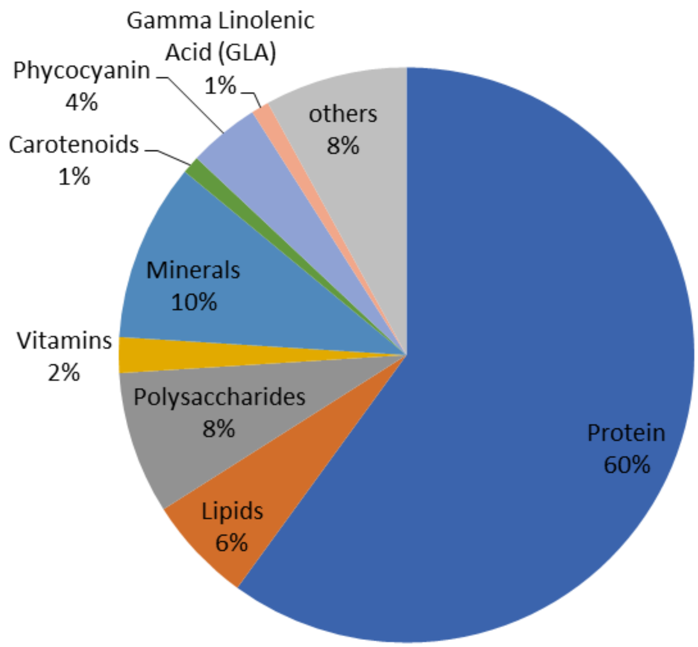

Fig. 3. The chemical composition of *Spirulina*

Factors affecting spirulina growth

Various factors influence the growth of microalgae, including light, temperature, salinity and pH, which can either facilitate or inhibit their growth (Fig. 4). Therefore, selecting appropriate growth conditions is crucial for successful *Spirulina* cultivation (**Chee Kuan Kwei, 2012; Wan *et al*., 2016**).

Light

Different microalgae species have specific light intensity preferences; some thrive under low light (<60 µmol photons m-2 s-1), while others need higher light levels (>100 µmol photons m-2 s-1). *Spirulina* reaches saturation at light intensities from 15 to 69µmol photons m^{-2} s^{-1}, in mineral medium **(Danesiet *et al.*, 2011)**.

Temperature

Temperature is a crucial factor in *Spirulina* growth. Studies show that *Spirulina maxima* and *Spirulina platensis* grow best at 30°C **(Tri-Panji & Suharyanto, 2001)**. Temperature also affects cell concentration, while growth is optimal at 30°C, harmful effects were observed at 34.5°C, likely due to thermal inactivation (**Sánchez-Luna *et al.*, 2007**).

Salinity

Salinity affects the osmotic pressure of water; higher salinity results in higher osmotic pressure **(Melati *et al.*, 2021)**. *Spirulina* species that grow optimally at a salinity of 20ppt are often found in estuarine environments, where salinities range from 20 to 30ppt **(Diana *et al.*, 2021)**.

pH

pH is a crucial environmental factor affecting the physiological growth, metabolic activities, and biomass production of *S. platensis*. Studies have shown that *S. platensis* can adapt to variable pH conditions **(Çelekli *et al.*, 2009)**. *Spirulina* thrives in alkaline, saline water with a pH range of 8.5 to 11.0, particularly in tropical high-altitude regions **(Al-Jabali *et al.*, 2024)**.

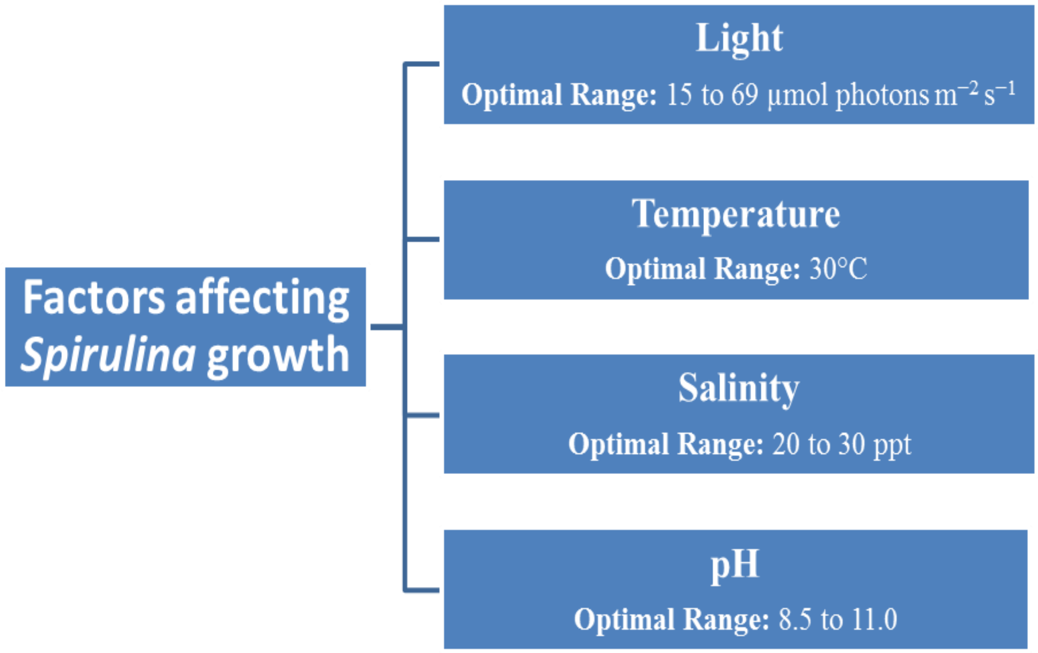

Fig. 4. Factors affecting *Spirulina* growth

Application of *Spirulina*

Spirulina has emerged as a prominent candidate in biotechnological endeavors. Numerous investigations have been published detailing the diverse array of biotechnological applications **(Mittal *et al*., 2024)**.

Use of *Spirulina* in waste-water treatment

Algae have emerged as a promising and eco-friendly solution for removing heavy metals from wastewater. These photosynthetic organisms possess the ability to absorb and accumulate heavy metals within their cellular structures **(AbouGabal *et al.*, 2022; Ashgan *el at.*, 2024)**. This bioremediation process offers several advantages over traditional methods, including low cost, high efficiency, and minimal chemical usage. By harnessing the natural capabilities of algae, we can effectively mitigate water pollution and promote sustainable environmental practices **(AbouGabal *et al.*, 2021; AbouGabal *et al.*, 2023)**. In wastewater technology, microorganisms as bioabsorbents have become prominent due to their high selectivity, ease of operation, and effectiveness compared to conventional methods. Untreated wastewater typically contains inorganic phosphorus and nitrogen from swine farming and municipal sources, chromium (VI) from textile dyeing, leather tanning, electroplating, and metal finishing industries, vinasse from alcohol production, and various other heavy metals **(Barroca *et al.* 2010)**.

Researchers have found that *Spirulina* is a suitable candidate for wastewater treatment systems. This is because the high metal content in wastewater serves as a nutrient source for *Spirulina* growth. However, excessive metal levels can be harmful when converted into biomass, which is used to produce various valuable products such as pigments, carotenes, sterols, vitamins, and polyunsaturated fatty acids. Studies have focused on the removal of nitrate, phosphorus, ammonium, urea, and chromium (VI) from wastewater **(Finocchio *et al.*, 2010)**.

Spirulina **in sustainable agriculture: Enhancing soil fertility and plant growth**

Nutrient content and biofertilizer role

Spirulina platensis, a microalga from the Cyanophyceae class, is recognized for its substantial potential in enhancing soil fertility and promoting sustainable agriculture. Its rich biochemical composition, including proteins, essential fatty acids, vitamins, minerals, and phytohormones, plays a crucial role in plant growth and development **(Anvar & Nowruzi, 2021)**. The biomass of *Spirulina platensis* is particularly noted for its high protein content (approximately 47%), essential fatty acids such as gamma-linolenic acid, and significant quantities of iron, calcium, and potassium. This nutrient richness makes *Spirulina* an effective biofertilizer, capable of enhancing the nutrient profile of the soil and preventing malnourishment of macro- and micronutrients in cultivated plants. For instance, the application of *Spirulina* to the soil has been shown to improve the agronomic bio-fortification of *Amaranthus dubius* (red spinach) by increasing its carbohydrate, protein, and vitamin A content **(Metcalf *et al*., 2021; Elsayed *et al.*, 2024)**.

Soil physicochemical improvement

Incorporating *Spirulina* into the soil improves several physicochemical properties, such as water-holding capacity, which is crucial for maintaining soil moisture and supporting plant growth. Additionally, *Spirulina* enhances the soil's mineral status, ensuring a steady supply of essential nutrients to plants. The nitrogen-fixing capabilities of *Spirulina* also reduce dependence on synthetic fertilizers, promoting more sustainable agricultural practices **(Elsayed *et al*., 2022; Shedeed *et al.*, 2022)**.

Plant growth promotion

Spirulina extracts significantly enhance the growth parameters of various crops. In a study conducted on *Lupinus luteus*, the application of different concentrations of *Spirulina platensis* extracts improved growth metrics, photosynthetic pigment content, and photosynthetic capacity. Specifically, a lower concentration (0.25%) was most effective in enhancing these parameters, suggesting an optimal dosage for maximizing plant growth without adverse effects **(Godlewska *et al.*, 2019)**.

Hormonal effects

Spirulina influences plant hormone levels, including auxins, gibberellins, and cytokinins, which are vital for regulating plant growth and development. These phytohormones contribute to improved seed germination, enhanced root and shoot growth, better flowering and fruiting, and overall increased biomass productivity. For example, the use of *Spirulina* extract in onion cultivation resulted in increased growth and yield, highlighting its effectiveness as a biostimulant **(Geries & Elsadany, 2021)**.

Stress tolerance and quality traits

The application of *Spirulina* formulations has been associated with improved nutrient use efficiency and greater tolerance to abiotic stressors such as drought and salinity. This is particularly beneficial in enhancing crop quality traits and ensuring consistent yield under varying environmental conditions. The bioactive compounds in *Spirulina*, including phenolics, proteins, and polysaccharides, contribute to these protective effects by modulating stress-responsive pathways in plants **(Sanchez *et al.*, 2003)**.

***Spirulina* biochar**

The pyrolysis of nutrient-rich *Spirulina* yields significant amounts of biochar, making it a potential soil amendment with multifaceted benefits for agriculture. *Spirulina*-derived biochar has been shown to possess high levels of nutrients, including minerals, due to its composition and pyrolysis process. When incorporated into soil, *Spirulina* biochar can improve soil properties, enhance nutrient availability, and promote plant growth. Additionally, biochar from *Spirulina* may contribute to carbon sequestration in the soil, thereby mitigating climate change effects **(Silva *et al*., 2020)**.

***Spirulina* extracts**

Utilizing *Spirulina* extract (SPE) as a natural biostimulant is pivotal for enhancing soil health and productivity, especially in regions contending with the dual burdens of salinity and heavy metal (HM) contamination. Studies have demonstrated that treating pea plants with either 10 or 15% algae extract significantly boosts yield and vegetative development compared to untreated controls **(Nawar & Ibraheim, 2014)**. SPE's efficacy lies in its ability to enhance plant chlorophyll content, metabolic processes, and antioxidant activities, thereby mitigating the detrimental effects of environmental stresses like salinity and heavy metals **(Rady *et al*., 2023)**.

Environmental benefits

Spirulina biomass, derived from the treatment of aquaculture wastewater, serves as a potent agricultural fertilizer. Its cultivation in aquatic environments aids in the removal of harmful ammonia and nitrate concentrations, offering a sustainable solution for nutrient management in intensive aquaculture systems. When integrated into soil as a fertilizer, *Spirulina* demonstrates remarkable efficacy in promoting plant growth and vitality across various leafy vegetables **(Wuang *et al*., 2016)**.

CONCLUSION

Spirulina, a versatile microalga, offers a promising solution for sustainable agriculture and environmental management. Its nutrient-rich composition and biofertilizer capabilities enhance soil fertility and plant growth, reducing reliance on synthetic fertilizers. Moreover, *Spirulina*'s ability to thrive in extreme conditions and its effectiveness in wastewater treatment demonstrate its potential to address pressing environmental challenges. The historical significance and extensive research on *Spirulina* underscore its diverse applications in biotechnology, health, and industry. To fully realize the potential of *Spirulina*, future research should focus on optimizing cultivation techniques, exploring novel applications, and assessing its long-term environmental impact. By addressing these key areas, we can unlock the full potential of *Spirulina* and contribute to a more sustainable future.

Competing interests

The authors declare that they have no conflict of interest

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