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Microalgae *Spirulina* Supercharging Aquaculture: Harnessing *Spirulina's* Role in Combating Abiotic and Biotic Stressors in Aquaculture

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Abstract

Spirulina is a filamentous multicellular naturally occurring blue-green algae, having a high nutritional value. It has been declared as 'super food' of 21st century by the World health Organization (WHO). It is widely used in pharmaceutical, cosmetics, nutrition and in aquaculture as feed, growth enhancers and immunostimulants. In the field of aquaculture *Spirulina platensis* is well known for its a rich source of protein. It possesses biologically active compounds like phycocyanin and carotenoids because of which the immunity and overall health status of fish and other vertebrates can be enhanced during stressful condition. *Spirulina* supplementation in diet of fish and shrimp, can improve their growth and survival rates. *Spirulina* is also used for water management practices in aquaculture systems across the globe.

Keywords: Antioxidant, Microalgae, Phycocyanin, *Spirulina*

Introduction

Microalgae are tiny organisms that are found in aquatic environments and visible only under a microscope. They occur singly or often form colonies or blooms, visible as coloured patches in aquatic water bodies. They are autotrophic organisms and play a crucial role in ecosystem, serving as primary producer and providing food for various organisms in the next trophic level. Their ability to grow rapidly and thrive in various conditions makes them a subject of extensive research and innovation. Additionally, microalgae are renowned for their potential in biotechnological application, biofuel production, wastewater treatment and source of nutrition supplement. Microalgae serve as a source of macromolecules such as protein or carbohydrates and also provide important nutrients such as essential poly unsaturated fatty acids, vitamins and biologically active pigments. *Spirulina*, is a cyanobacterial microalga, that is extensively used in aquaculture for various purposes like as a protein source in feed, a growth enhancer and immunostimulant for sustaining health of aquaculture organisms.

Spirulina is also a source of essential lipids, polyunsaturated fatty acids, carbohydrates, steroids, vitamins and some very valuable biologically active pigments. *Spirulina* is not only known of its rich protein content, but also is an exceptional source of an immunologically important pigment phycocyanin, which is a compound that makes up about 10-15% of its biomass, depending upon the specific culture conditions. Through its antioxidant properties *Spirulina* possess the ability to neutralize oxygen free radicals and the anti-inflammatory capability leads to it inhibit the enzymes involved in the production of inflammatory prostaglandins. Carotenoids, are another category of pigments, that *Spirulina* possess, particularly β-carotene and astaxanthin, that plays a very important role in shielding living cells from oxidative harm. This microalgae can be directly consumed by organisms dwelling in aquatic bodies or may be included in fish diets in culture systems It can have a significant positive effect on the immune responses of fish and other vertebrates to stressful conditions and can encompass both non-specific and specific immunity. It can not only enhance growth performance but also regulate the swimming and

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locomotory activities of these organisms. It improvises the antioxidant defense capability of the cells against lipid peroxidation and the creation of free radicals.

General Features of *Spirulina platensis*

S. platensis, belongs to the order Oscillatoriales. It can be identified under the microscope because of its helical and filamentous characteristics. *S. platensis* is widely distributed and are distinguished by their loosely coiled trichomes. Their fully developed trichomes typically measure several millimeters in length and are composed of cylindrical cells ranging from 3 to 12 micrometers in diameter. The layers that make up the gram-negative cell wall of *Spirulina* include a large peptidoglycan structural layer. The structural features are composed of two regions: a central nucleoplasmic region and a periphery made up of thylakoid membranes linked to gas-filled vacuoles, phycobilisomes and many additional subcellular elements, like aggregates of polyglucan and polyphosphate. The existence of cross-walls, or septa, between the trichome's cells that may be seen under a light microscope, is the primary classical taxonomic characteristic of this species. *Spirulina* species are photoautotrophic organisms that possess the ability to perform oxygenic photosynthesis.

Nutritional and Bioactive Compounds of *Spirulina*

S. platensis has a nutritionally rich profile having 55 to 70% protein, 12 to 25% carbohydrates, 6 to 8% lipids, 7 to 13% minerals and 8 to 10% dietary fibres (Jung *et al.*, 2019) (Figure 1). It is a highly valued edible microorganism which has been declared as a 'super food' of 21st century by WHO and categorized as single celled protein by food industries.

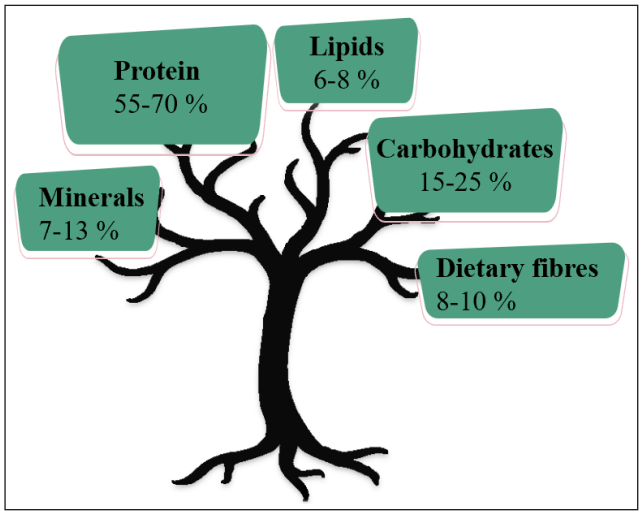

Figure 1: The general composition of *Spirulina platensis*

It is a significant source of protein, phycocyanin, chlorophyll a, carotenoids, vital amino acids, vitamin B and minerals like, calcium, potassium, manganese, iron, magnesium and zinc. *Spirulina* protein is considered to have the finest amino acid composition among plants. Additionally, its biomass consists of significant quantity of vitamin B_{12} in it. *Spirulina* has been globally recognized, commercially accepted as ingredient in feed, cultivated extensively and processed on industrial scale to create range of value added products.

The specific biologically active compounds that make Spirulina of such importance includes pigments like phycocyanin, chlorophyll, total carotenoids, β-carotene, zeaxanthin, polysaccharides, mostly ribose and rhamnose and gamma linolenic acid (GLA). C-phycocyanin, allophycocyanin, chlorophyll, xanthophyll and beta-carotene are the main components that hold considerable value in both biological and commercial terms (Figure 2). Amongst these, the pigments of substantial importance that also hold high market value are phycocyanin, chlorophyll and beta-carotene. Amongst the phycobiliproteins pigments which are phycocyanins, phycoerythrins and allophycocyanins, the pigment that gives *Spirulina* its bluish hue/colour is phycocyanin. It is because of this, that these organisms are commonly known as blue-green algae. Phycocyanin is soluble in water and possesses strong antioxidant properties. Carotenoids are another class of naturally occurring pigments with added value that are derived from microalga and involved in light harvesting and cell defense against damage caused by singlet oxygen.

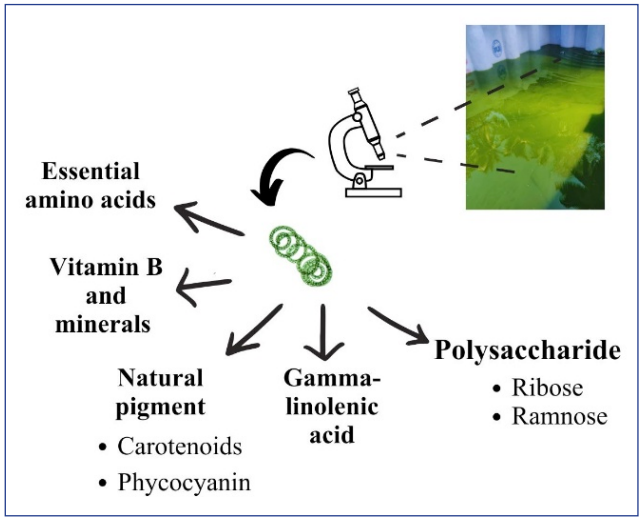

Figure 2: Bioactive compounds found in microalgae *Spirulina*

Open Culture of Microalgae *Spirulina*

Mass culture of *Spirulina* includes four main steps. These are culturing, harvesting, drying, packaging. Culturing involves outdoor culture of *Spirulina* usually in open raceways or ponds. After calculating the volume of total medium required for the pond (area × depth of the culture), add mother culture @ 1 g $litre^{-1}$ (Figure 3). Once good amount of biomass is obtained, harvesting is done by means of filtration (usually after 10 days). Drying is done either by spray drying or drum-drying methods. It yields dry *Spirulina* powder, usually having a moisture content of less than 3 to 4%. Packaging, if required, involves the use of oxygen-barrier bags.

Therapeutic Benefits of Bioactive Compounds of *Spirulina*

The substantial amount of phytonutrient content and bioactive pigments present in *Spirulina* is acknowledged for their nutraceutical and potential pharmaceutical benefits. Its anti-inflammatory and antioxidant properties are well documented for its capacity to safeguard the physiological

Figure 3: Open culture of *Spirulina platensis* in crates

systems of the body of host from oxidative damage, caused by any biotic or abiotic pollutants (Figure 4). Because of its remarkable antioxidant, anti-inflammatory, radical scavenging and hepatoprotective capabilities phycocyanin can scavenge a range of free radical species, which include hydroxyl, superoxide and alkoxy radicals. Phycocyanin hampers the enzymes responsible for the production of inflammatory prostaglandins and efficiently counteracts the synthesis and action of oxygen-producing free radicals. Phycocyanin contains an open chain chromophore known as phycocyanobilin (PCB), a form of tetrapyrrole. PCB exhibits a chemical structure that looks like that of a bile pigment, bilirubin, recognized for its ability to scrounge multiple *in vivo* reactive oxygen species. Bilirubin is known for its capacity to obstruct oxidative responses that are facilitated by the action of peroxynitrite (ONOO-).

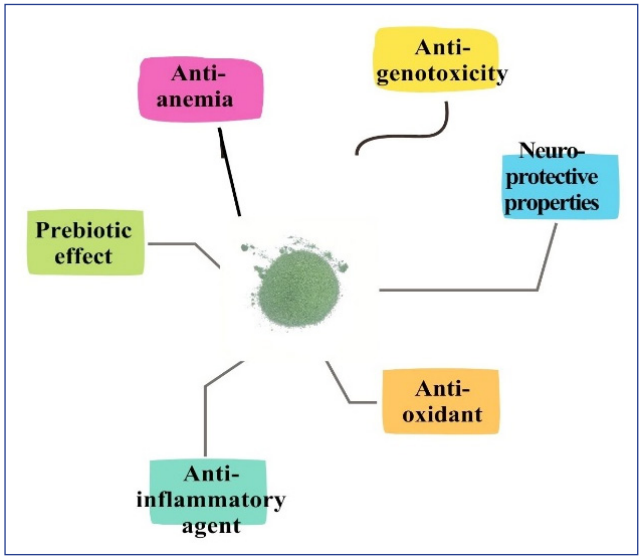

Figure 4: Therapeutic effects of *Spirulina*

Carotenoids, predominantly astaxanthin or β-carotene, are also identified to protect living cells from oxidative damage. Carotenoids have scavenging properties against free radicals that stops and halts the chain reactions during inflammation. It quenches singlet oxygen species and release energy as heat. Carotenoids contribute to a rise in the circulating lymphocyte count, particularly T-helper cells, stimulate the proliferation of T and B lymphocytes, enhance the rejection of foreign tissues and prevent the loss of macrophage receptors.

It has been demonstrated that carotenoids improve the non-specific and specific immune systems and guard against mutations in cellular DNA. Xanthophylls and carotenes, derived from *S. platensis*, have been demonstrated to participate in various metabolic pathways within the body, significantly influencing the function of vitamins and minerals in the organism. A diet rich in carotene is regarded as significant for public health because of its ability to reduce the risk of disease. Various carotenoids have been linked to bioactivities that may help prevent cancer, cardiovascular diseases and macular degeneration. Biomass of *Spirulina* has received certification as GRAS (Generally Recognized as Safe) and is widely available within the marketplace in various forms, including tablets, capsules and dry powder.

Successful Applications of *Spirulina* in Aquaculture

Spirulina (*Arthrospira*) *platensis* serves as a valuable resource in aquaculture, functioning as a feed source, promoting growth and acting as an immunostimulant (Nag *et al.*, 2025). Aquaculture uses of *Spirulina* with respect to its nutritional properties, could take two pathways. First as a replacement of fishmeal in fish diets and second as a source of functional feed that could enhance immune system of the fish by improving the immune biochemical parameters of the body (Figure 5). The cost of fishmeal in the aquaculture commerce is extremely high because of it being rich in protein and other nutrients. It is a comprehensive element for the fish feed formulations. However, the prices of fishmeal have been increasing as fisheries are becoming overexploited, over years.

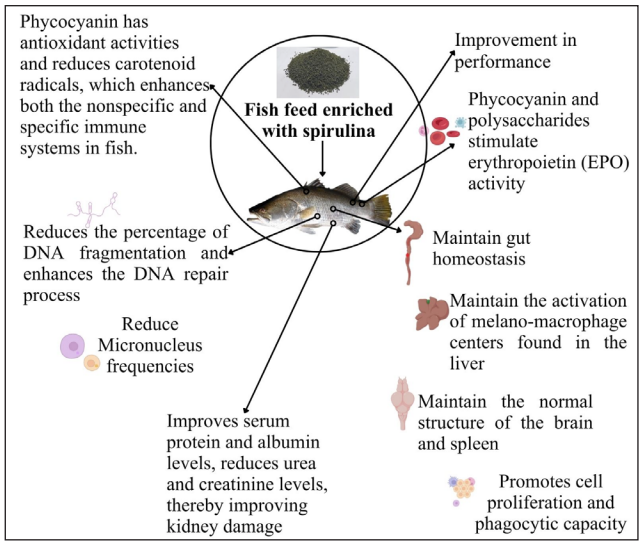

Figure 5: The role of *Spirulina* in improving the health of fish

Numerous studies have been done to validate the efficiency of *Spirulina* in enhancing immunity and health status, along with improving the water quality to benefit the production of cultured organism in aquaculture systems. It has already been demonstrated in various studies that *Spirulina* supplementation in diet of fish and shrimp, can enhance

their growth and survival rates. The shrimp farms in Vietnam, observed a momentous decrease in death rates along with an upsurge in growth performance, when *Spirulina* incorporated diets were given to the indigenously cultured shrimp. Healthier shrimp populations could be received because of the antimicrobial properties of *Spirulina* that helped in controlling bacterial infections. Another research conducted on *Nile tilapia* in Egypt explored that fish fed with *Spirulina*-supplemented feed displayed greater immune responses and better resistance to common pathogens. This led to healthier production of cultured tilapia species and reduced dependence on antibiotics. Carp culture has also been recognized to be benefited from the inclusion of *Spirulina* in the water management practices in Chinese aquaculture systems. In addition to its potential benefits in aquaculture, *Spirulina* have also been reported to remediate the polluted aquatic environment providing relief to organism inhabiting it. It can be used to bioremediate organic and inorganic pollutants; reduce nitrate, ammonia and phosphate levels and consequently regulate conditions of eutrophication. This leads to improvement in water quality parameters, provide favourable habitat and results in better growth performances of various fish species inhabiting there.

Spirulina's Use in Aquaculture as a Practical Feed

Spirulina can significantly enhance the growth performance of fish. It possesses properties that are antioxidant, anti-inflammatory and anti-allergic in nature. Bioactive peptides of *Spirulina* could act as hormones, antibiotics, or neurotransmitters and favourably impact physiological processes by engaging with target cells and binding to particular receptors. Polysaccharides especially oligosaccharides, protect against pathogens also support the growth of beneficial microorganisms; preserve intestinal homeostasis and support immunoregulation and gastrointestinal function. Bioactive compounds of *Spirulina* can activate the melano-macrophage centres (MMCs) in liver tissue and diffuse the tubular epithelial, degeneration in kidney. It encourages cell division and phagocytes while triggering the release of TNF-α and IL-1β. Phycocyanin has scavenging activities against superoxide, hydroxyl and alkoxy radicals. Carotenoids reduce free radicals, enhances both non-specific and specific immune system. Astaxanthin induce "CYP1A" and "CYP1A2" detoxification enzymes. Additionally, it boosts the quantity of cells that secrete IgM antibodies, decrease the MDA levels, enhance SOD & CAT activity, elevate GSH and GPx level. The bioactive compounds also activate leucocyte activities in fish. GLA precursors of prostaglandins (E_2 and F_2), possess potent vasodilator, anti-inflammatory and anti-aggregatory properties. *Spirulina* is reported to exhibit an antigenotoxic effect. It decreases DNA fragmentation percentage and elevates the DNA restoration. *Spirulina* improves serum protein and albumin levels, lowers urea and creatinine levels, manages cholesterol and triglyceride and enhances insulin resistance. Several investigations have proven the incorporation of *Spirulina* in fish diets to be an effective solution for combating biotic or abiotic stressors that are usually encountered during various aquaculture practices (Table 1).

Table 1: Spirulina's role in mitigating biotic and abiotic stress (fed pelleted feed incorporated with Spirulina crude extract) (Nag *et al*., 2025; Watanuki *et al*., 2006; Toughan *et al*., 2018; Abdelkhalek *et al*., 2015)

Species	Challenged by	Results
Common carp (*Cyprinus carpio*)	*Aeromonas hydrophila*	Increase in phagocytosis in liver and leucocytes, increased tumor necrosis factor (TNF)-α and interleukin (IL)-1β genes expression, resistance to *Aeromonas hydrophila*.
	Atrazine	Decrease in the levels of MDA, ALT, AST and ALP, enhance SOD activity, elevates GSH level.
African catfish	Chlorpyrifos (CPF)	Improve RBCs, Hb and PCV without effect on MCV, MCH and MCHC, elevated the count of lymphocytes and monocytes, enhance ALT, AST, TC, TGs, vLDL, LDL,HDL, glucose, urea and creatinine levels, enhance PA and PI, activity of GSH in the liver, brain, gills and intestine, GPx and CAT activity.
Nile tilapia (*Oreochromis niloticus*)	*Aeromonas hydrophila*	Enhance the response of natural killers cells and macrophages, increase in resistance to *Aeromonas hydrophila* infection.
	Subacute exposure deltamethrin (DLM) intoxication	Decreases lipid peroxidation.
	Pseudomonas fluorescens	Increase in the hematocrit level, lysozyme activity, neutrophil adherence.
	Intoxicated with aflatoxin B1 (AFB1)	Reduce levels of ALP, ALT and AST, MDA, urea and creatinine, improved the blood protein and albumin levels, activities of SOD and GSH.

Table 1: Continue...

Species	Challenged by	Results
	Chlorpyrifos (CPF)	Reduce AST, ALT and ALP activities, lower urea and creatinine levels, reduce MDA levels in liver, kidneys and gills, improves sTP and albumin levels.
Rohu (*Labeo rohita*)	Copper toxicity	Improve feeding and growth parameters in copper-exposed fish, enhance phosphatase activities.
	Mercuric chloride toxicity	Reduce mercuric chloride accumulation in tissues and increased mercuric chloride elimination through faeces, lessening the metal burden and its toxicity to fish.
	Aeromonas hydrophila	Increase sTP, albumin and globulin, MPO and eruloplasmin activity in serum, Hb, RBC, WBC and lyosozyme activity in blood.
	Triclosan	Improved Hb, RBC, MCH in blood, sTP, albumin in serum, reduced GST, ALT, AST, ALP and creatinine levels in serum, reduced histological lesions in vital organs, micronuclease in blood and % tail DNA damage in blood, liver and gill.

[Hb: Hemoglobin; RBC: Red blood cells; WBC: White blood cells; MCH: Mean corpuscular hemoglobin; MCV: Mean cell volume; MCHC: Mean corpuscular hemoglobin concentration; PCV: Packed cell volume; Ig: Immunoglobulin; sTP: Total serum protein; MDA: Malondialdehyde; ALT: Alanine transaminase; AST: Aspartate transaminase ; ALP: Alkaline phosphatase; GST: Glutathione transferase; GPx: Glutathione peroxidase; SOD: Superoxide dismutase; CAT: Catalase; GSH: Glutathione-S-transferase; MPO: Myeloperoxidase; PA: Phagocytic activity; PI: Phagocytic index; TGs: Triglcerides; vLDL: Very Low density lipids; LDL: Low density lipids; HDL: High density lipids]

Conclusion

Spirulina, aids as a valuable resource in aquaculture, functioning as a feed source, acting as an immunostimulant and promoting growth. It has been demonstrated to participate in various metabolic pathways within the body, significantly influencing the function of necessary macro as well as micro-molecules in the organism. *Spirulina* when incorporated in fish diets, it delivers resistance to several pathogens and combats stressful conditions created by other pollutants in the body of host. It offers antioxidative and an immunostimulant effect, decreases oxidative damage, improves haemato-physiological parameters and recovers growth. Several researches have been done to explore the full potential of *Spirulina* in aquaculture, with potential outcomes indicating towards its acceptance in aquaculture as well as pharmaceutical industries. Further studies are needed to focus on its synergistic effects with other aquaculture components and practices emphasising on sustainable production and development.

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