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A Review on the Potential Benefits and Future Prospects of Spirulina

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ABSTRACT: Spirulina is a cyanobacterium that has substantial nutritional and medicinal value due to its high protein, vitamin, mineral, and bioactive compound content. Its lipid-lowering, immunomodulatory, neuroprotective, anti-inflammatory, and antioxidant qualities support its use in the treatment of diabetes, cancer, cardiovascular, and neurodegenerative illnesses. Its biomass yield and production of bioactive metabolites are intended to be increased by recent developments in cultivation, genetic engineering, and bioprocess optimization. **Spirulina** has a wide range of uses in food, medicine, biofuels, and environmental biotechnology. As such, it has enormous potential for advancements in biotechnology and industry in the future.

KEYWORDS: Spirulina, immunomodulatory, anti-diabetic, anti-cancer, cardiovascular effects, neuroprotective properties, bioplastics, wastewater treatment.

I. INTRODUCTION

The rise of lifestyle-related diseases, including non communicable diseases (NCDs), is largely due to environmental factors, stress, poor diet, sedentary behaviour, and urbanization. These changes have led to an increase in conditions like heart disease, type 2 diabetes, obesity, and cancer.[1]

Neurological and brain disorders are also on the rise, with neurodegenerative diseases like Alzheimer's, Parkinson's, and ALS causing cognitive and motor impairments. To prevent these diseases, preventive measures like a balanced diet, regular exercise, stress management, and abstaining from toxins are crucial.[2]

Example for natural drugs which prevent these diseases are: **Ginkgo biloba, Bacopa monnieri, Spirulina** (microalgae).

SPIRULINA

Spirulina, a marine or freshwater microalgae with spiral filaments, is a photosynthesis capable cyanobacterium. It thrives in high-salt, alkaline water reservoirs in subtropical and tropical regions. **Spirulina** algae are highly nutritious, including 60-70% protein, vitamins, minerals, and vital fatty acids. The FDA considers them the perfect nourishment for humanity and a "super food," while the nourishment and Agriculture Organization (FAO) and the United States Space Agency employ them as a nutritional supplement.[3,4,5]

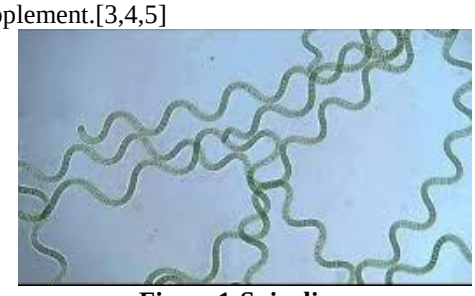

Fig no.1:Spirulina

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SYNONYMS
Arthrospira maxima / Spirulina maxima
Arthrospira platensis / Spirulina platensis
Arthrospira fusiformis / Spirulina fusiformis

VERNACULAR NAMES
1. **Kanembu(Chad)- Dihe**
2. **Aztecs(Mexico)- Tecuitlatl**

SCIENTIFIC CLASSIFICATION
Arthrospira maxima/ Arthrospira platensis
- **Domain : Bacteria**
- **Kingdom : Eubacteria**
- **Phylum : Cyanobacteria**
- **Class :Cyanophyceae**
- **Sub-class :Oscillatoriophycideae**
- **Order :Oscillatorlales**
- **Family :Oscillatoriaceae / Microcoleaceae**
- **Genus :Arthrospira**
- **Species: Arthrospira platensis/ Arthrospira maxima** [6]

TAXONOMY

Spirulina, was first isolated in 1827. Helical, septal, green-blue microalgae known as **Spirulina jenneri f. platensis** was discovered in 1844. In 1852, published first taxonomic description, naming the new genus **Arthrospira** after septa, helical shape, and multicellular structure. In 1892, attributed the aseptate and septal forms. In 1932, reunified the two genera and named them **Spirulina**. In 1989, microorganisms were divided into two genera: **Spirulina** and **Arthrospira**, with the most significant species being **Arthrospira maxima** and **A. platensis.** The term "**Spirulina**" has been widely used in research on microalgae, making it challenging to modify.

NATURAL HABITAT

Spirulina may be found in several environments, including soil, marshlands, freshwater, brackish water, ocean, and thermal springs. **Spirulina** thrives in alkaline, saline water (>30 g/l) with a high pH (8.5-11.0), particularly at high altitudes in the tropics with abundant sun radiation.

Spirulina platensis and **Spirulina maxima** flourish in very alkaline lakes in Africa and Mexico, where the cyanobacteria population is mostly monospecific. **Spirulina** species are more likely to thrive in water with higher pH and conductivity levels. The Rift Valley lakes in eastern Africa have a pH close to 11 and a high concentration of sodium carbonate. **Spirulina platensis** was isolated from waters containing 85-270 g of salt per litre, with optimal growth occurring at 20-70 g of salt per liter. This micro-organism's capacity to use ammonia as a nitrogen source at high alkaline pH levels may be attributed to its comparatively high cytoplasmic pH (4.2-8.5).[7].

MORPHOLOGY AND MICROSCOPY

Feature	Arthrospira maxima	Arthrospira platensis
Trichome constriction	Not or slightly constricted at cross walls	Clearly constricted
Trichome diameter	Wider	Narrower
Trichome ends	Attenuated with 6-7 cells; terminal cell capitate and sometimes calyptrate	Less attenuated; terminal cell less specialized
Coil diameter	Slight attenuation toward apices	Constant coil diameter
Granulation at cross walls	Densely granulated with regular distribution of gas vacuoles	Densely granulated but less regular
Sheath (SEM)	Thicker; deep ribs on trichome surface	Thinner; shallow, anastomosed ribs
Trichome length	Longer	Shorter(5-7) coils
Motility	Higher gliding motility	Lower gliding motility [8].

Table no.1:Morphology and microscopy

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Fig no.2:Arthrospira maxima

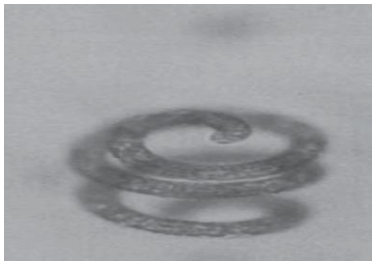
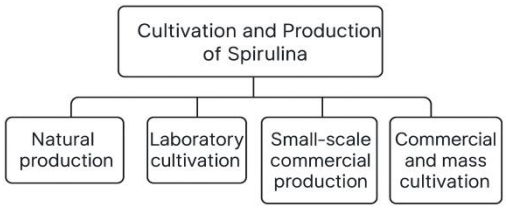


Fig.3:Arthrospira platensis

ULTRA STRUCTURE

Electron microscopy displays the cell structure of **A. maxima** and **A. platensis,** two common prokaryotic species. They lack a nucleus and plastids and have a thin, multilayered cell wall with a readily identifiable electron-dense layer. The cell wall is composed of four layers: L I, L II, L III, and L IV. The cytoplasm in the periphery area is low in electron density and contains polyglucan granules, gas vacuoles, fibrils, and lipid droplets. Thylakoid membranes are oriented parallel and contain electron-opaque phycobilisomes.[9].

CULTIVATION AND PRODUCTION OF SPIRULINA



Natural production

Spirulina is used in various industries, including commercial production. In Mexico, Sosa-Texcoco Ltd has been harvesting **Spirulina maxima** from Lake Texcoco since 1936, using a semi-natural cultivation process that doubles algal biomass in three to four days.

Laboratory cultivation

Spirulina productivity is influenced by eight major environmental factors, including luminosity, temperature, inoculation size, stirring speed, dissolved solids, pH, water quality, and macro and micronutrient presence. Light regimes, such as average irradiance and specific light energy utilization rate, play a crucial role in **Spirulina** growth. Maximal mixing enhances cell concentration and productivity of biomass at the highest light intensity.

Small-scale commercial production

Spirulina can be grown in unlined ditches with low flow, stirred by wind energy or humans, and harvested using a suitable cloth. This simple technology allows for small-scale farming and aquaculture, making **Spirulina** a valuable resource for local communities.

Commercial and mass cultivation

Commercial and mass cultivation of microalgae began in Japan in the early 1960s with the **Chlorella** culture and **Spirulina** in the early 1970s at Lake Texcoco, Mexico. **Spirulina** is typically grown in shallow ponds with paddle wheels for mixing, with two types of open raceway ponds used.

Harvesting and processing

Harvesting, processing, and packing involve eight stages, reducing salt content, removing interstitial water, neutralizing biomass, breaking down trichomes, and ensuring a 20-30% reduction in production costs. [7].

CULTIVATION SYSTEMS

Cyanobacteria may be grown in both open and closed systems, each with its own set of needs for culture type, temperature, pH, light, nutrients, and CO2.

1. Open system

Open systems are cost-effective, durable, and suitable for growing cyanobacteria under various environments such as alkaline or acidic, precise temperatures, and nutritional needs. However, they have drawbacks such as contamination susceptibility, poor CO_2 solubility, and limited control over ambient conditions.

2. Closed system

Closed cultivation methods provide more control over growing conditions and lower the danger of contamination. In photo bioreactors, they optimize biomass growth factors including CO_2 supply and illumination, leading to increased

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biomass growth and synthesis of desired metabolites. Establishing growth conditions for cyanobacteria is crucial for optimizing growth and output.[10]

CHEMICAL CONSTITUENTS OF SPIRULINA

Spirulina is a nutrient-dense microalgae with several uses in food, pharmaceuticals, nutraceuticals, and animal feed.[11]

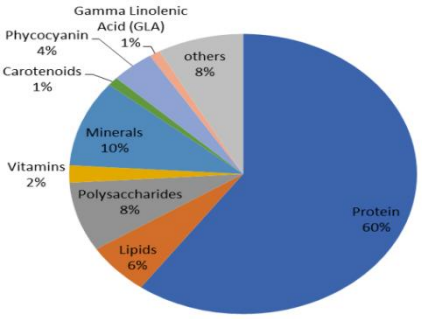
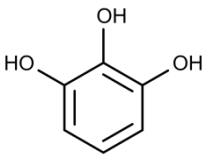


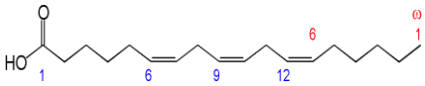
Fig no.4:Chemical constituents

Proteins (50-70% of its dry weight)	**Essential amino acids:** leucine (7.67%), lysine (4.37%), methionine (2.39%), phenylalanine (4.42%), threonine (4.88%), tryptophan (1.93%), and valine (6.37%). **Non-essential amino acids :**alanine, arginine, glycine, and serine.
Lipids	**Polyunsaturated fatty acids** (PUFAs) (5-10%). **γ-linolenic acid** (GLA) (most prominent). Other important fatty acids : **linoleic acid, oleic acid, and palmitic acid.** **Omega-3 fatty acids:** α-linolenic acid (ALA)
Carbohydrates (15-20%)	**Monosaccharides:** glucose, rhamnose, xylose, mannose, galactose. **Sulphated polysaccharide:** calcium spirulan (Ca-SP).
Pigments	**Phycocyanin**: (47% of dry weight). Other pigments: **chlorophyll A, xanthophyll,-carotene, echinenone, myxoxanthophyll, phycobiliprotein, lutein, zeaxanthin, and cryptoxanthin.**
Vitamins and Minerals	**B-complex vitamins:** thiamine, riboflavin, niacin, and folate. **Fat-soluble vitamins:** vitamin E **Minerals**: iron, calcium, magnesium, zinc, and potassium.
Secondary metabolites	**Phenolic compounds :**pyrogallol, gallic, chlorogenic caffeine, vanillic, p-coumaric, naringin, naringenin, and catechin. **Polyphenolic compounds:** ferulic acid, caffeic acid. **Flavonoids:** kaempferol, quercetin, myricetin, rutin, procyanidins, isoquercetin, genistein, hesperidin.

Table no.2:Chemical constituents



Gamma linoleic acid



Pyrogallol

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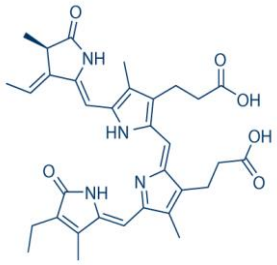

Phycocyanin (pigment)

PHARMACOLOGICAL ACTIVITY

PHARMA-COLOGICAL ACTIVITY	DESCRIPTION
Antioxidant activity	**Phycocyanin-** a blue pigment in spirulina, has antioxidant properties that help mitigate oxidative stress. **Carotenoids-** including β-carotene, zeaxanthin, and lutein, neutralize reactive oxygen species. **Chlorophyll-** supports detoxification and tissue protection.
Anti-inflammatory activity	**Phycocyanin** inhibits pro-inflammatory cytokines and reduces inflammatory enzyme activity
Anti-viral activity	**Phycocyanin –** act by reducing viral replication rates and inhibiting influenza hemagglutination in early infection stages.
Anti-diabetic activity	**Spirulina** supplementation act by reducing fasting blood glucose and HbA1c levels, largely due to its ability to modulate glucose metabolism and enhance insulin resistance
Lipid lowering and cardiovascular activity	**Phycocyanin** and **GLA** - regulate lipid metabolism, prevent fat accumulation in blood vessels, and **Spirulina's** antioxidant and anti-inflammatory properties prevent atherosclerosis and other cardiovascular diseases.
Neuro - protective activity	Neuroprotection against neurotoxic stressors, including oxygen/glucose deprivation, hydrogen peroxide, glutamate, amyloid and making them promising therapeutic products for brain disorders. [11]
Importance in weight control	**Spirulina** act by inhibiting macrophage migration, preventing liver fat accumulation, reducing oxidative stress, and increasing insulin sensitivity. [3]
Antibacterial activity	**Spirulina** contains compounds with chromophore groups and bonds, which may contribute to its antibacterial activity

Table no.3: Pharmacological activity

UNLOCKING THE POTENTIAL BENEFITS OF SPIRULINA

Spirulina has several health benefits, making it an excellent nutritional supplement. It enhances immune function and has several antioxidant qualities, including anti-inflammatory, anticancer, lipid elimination, and antiviral effects. Including **Spirulina** in one's diet can improve immunity, well-being, and anti-aging.[12]

1. IMMUNOMODULATORY ACTIVITY

Phycocyanin : plays a central role in modulating immune functions by enhancing the activity of natural killer (NK) cells, macrophages, and T cells, while also promoting the production of antibodies.

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Polysaccharides : enhance immune responses. They stimulate the production of cytokines such as interferon-gamma (IFN-γ) and IL-2 which are crucial for activating immune cells and coordinating the immune response. [13]

2. ANTIDIABETIC EFFECT

Phycocyanin, polysaccharides, and GLA: Control blood glucose levels and improve insulin resistance. According to studies, **Spirulina** supplementation can lower fasting blood glucose and HbA1c levels, helping to manage type 2 diabetes better. [14]

3. ANTICANCER EFFECT

Phycocyanin promotes apoptosis, inhibits tumor cell growth, and reduces angiogenesis. Carotenoids and polysaccharides protect DNA and reduce the risk of cancer.[15]

4. CARDIOVASCULAR EFFECTS

Phycocyanin has an important role in reducing oxidative stress and inflammation, both of which contribute to cardiovascular disease. It has been shown to minimize oxidative damage and protect the endothelial cells that line the blood arteries, enabling improved circulation and heart function. [14]

5. NEUROPROTECTIVE PROPERTIES OF SPIRULINA

Spirulina contains neuroprotective characteristics that protect against brain illnesses such as Alzheimer's, Multiple Sclerosis, and Parkinson's Disease. Its antioxidant, anti-inflammatory, and anti-amyloid properties may help reduce oxidative stress and inflammation in the brain, hence preserving cognitive function.

EFFECT OF SPIRULINA ON NEURODEGENERATIVE DISEASES

a) MULTIPLE SCLEROSIS

Acute inflammatory demyelination and axonal injury are the two pathogenic processes that produce neurological problems in MS patients.

C Phycocyanin (C-PC) promotes the expression of genes involved in remyelination, axon-glia processes, and gliogenesis while significantly decreasing the expression of demyelination genes such as PPAR and CD44. C-PC also decreases MDA while increasing SOD, CAT, and GPx levels.[16]

b) PARKINSON'S DISEASE

Parkinson's disease (PD) is a chronic, progressive, neurological condition with several causes. Parkinson's disease primarily affects the elderly, with a 1-2% incidence rate after age 60-65.

Phycocyanin prevents or delays oxidative stress damage by lowering free radical accumulation and boosting the antioxidant enzyme systems catalase (CAT), superoxide dismutase (SOD), and glutathione peroxidase (GPx).

Pre-treatment with marine green **Spirulina** polysaccharide in the brains of MPTP-treated mice significantly increased immunoreactive staining and mRNA expression of tyrosine hydroxylase and dopamine transporter (DAT). Furthermore, GPx and SOD activity in the midbrain and serum were much greater than those of monoamine oxidase B (MAOB), suggesting that this polysaccharide's capacity to combat oxidative stress may be responsible for its neuroprotective effects. One study found that adding marine green **Spirulina** to the diet significantly reduced SOD and CAT activity in DJ-193 flies, a **Drosophila melanogaster** model of Parkinson's disease. This promotes lifespan and locomotor activity.[17]

c) ALZHEIMER'S DISEASE

AD is the most prevalent age-related neurodegenerative disease, with multiple potential causes, including oxidative stress, chronic inflammation, altered insulin metabolism, and cholinergic insufficiency. Alzheimer's disease is characterized by senile plaques containing Aβ peptides, persistent neuroinflammation, and neurofibrillary tangles made up of tau proteins.

C-phycocyanin (C-PC): may inhibit the amyloid formation process of bovine serum albumin (BSA).[18]

OTHER POTENTIAL BENEFITS

Beyond its potential health benefits, Spirulina has a wide range of industrial and commercial applications, including cosmetics, biofuel production, waste water treatment, etc.

1.IN FOOD

Spirulina, a popular food component with several nutritional and health advantages, is utilized in dietary supplements and energy bars. Its high phycocyanin concentration qualifies it as a natural colorant. **Spirulina**-enriched meals increase nutrient intake, reduce cholesterol and sugar levels, and protect against chronic illnesses.[3]

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2. IN FEED

Spirulina, a high-quality, bioactive component in animal feed, is used in cattle, poultry, aquaculture, and pets to boost growth performance, immunological function, and disease resistance. It is also increasingly being utilized in pet food to promote general health and well-being.[19]

3. IN MEDICINE

Spirulina, which contains bioactive substances such as phycocyanin, sulphated polysaccharides, and PUFAs, has potential therapeutic uses in immunomodulation and cancer prevention. Its anti-inflammatory, antioxidant, antiviral, and anticancer effects boost the immune system, prevent dangerous microorganism development, and cause apoptosis in cancer cells. Its lipid-lowering and anti-inflammatory qualities make it a potential supplement for the treatment of chronic illnesses, including cardiovascular and type 2 diabetes, as well as weight control.[11]

4. IN POLLUTION CONTROL

Industrial operations pollute the environment, which has an influence on life and ecosystems. Bioremediation, which uses microorganisms to decrease trash and heavy metals, has been investigated for its cost-effectiveness and environmental impact. **Spirulina**, a cyanobacterium species, has been shown to reduce toxicity by physical and chemical adsorption.[20]

5. IN COSMETICS

Cosmetics, whether natural or synthetic, are used for body painting, religious or decorative purposes. They protect the skin against antioxidants using vitamins, nutrients, and enzymes. **Spirulina** extracts, notably phycocyanin, have been shown to promote wound healing and cell proliferation in creams, with the best impact occurring at 1.125% **Spirulina** extract. [21]

6. IN BIOPLASTICS

Plastics are popular because they are strong, lightweight, and resistant to deterioration. However, they harm the environment by generating garbage and polluting it. Biodegradable polymeric materials may be made from crops such as maize, rice, wheat, and potatoes, however land availability and competition in the food and feed markets provide obstacles. Microalgae such as **Spirulina** provide a feasible alternative since they combine well with polyethylene and have a greater tensile strength than conventional plastic bags.[22]

7. IN WASTE WATER TREATMENT

Algae and microorganisms are environmentally beneficial options for heavy metal removal from wastewater, with cheap costs, great efficiency, and minimum chemical use. **Spirulina**, a good nutrition source, is an appropriate choice for wastewater treatment since it removes nitrate, phosphate, ammonium, urea, and chromium from the water.[23]

8. IN SPACE

Spirulina, a kind of microalgae, has the potential for space missions due to its function in CO_2 fixation, oxygen generation, sustenance creation, and recycling. It thrives in bioreactors and can withstand Martian settings, making it ideal for long-duration space missions.[24]

9. MICROROBOTS

Microrobots, also known as microswimmers, are photosynthetic microorganisms that can perform microscale activities such as medication delivery, cell manipulation, and biosensing. Their size and controllability make them suitable for precise navigation in difficult to reach human cavities.

S. platensis cells were modified into helical magnetic microswimmers for targeted molecular delivery in an intestinal tract mimicking. [24]

FUTURE PROSPECTS

Spirulina, a versatile microalga, is being investigated for possible biotechnological uses in the food, cosmetics, pharmaceutical, and energy industries because to its versatility and rapid development.

1. Future Development of Spirulina Production

Current approaches are energy intensive and need particular environmental conditions. Advances in biotechnological methods can boost yields and bioactive chemicals. Future study should concentrate on sustainable, cost effective farming practices, trash recycling, and renewable energy sources.[7]

2. Potential in Food and Nutrition

This component is commonly utilized in dietary supplements and functional foods. It has the potential to improve functional meals that target particular health goals.

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Advanced food processing can enhance biofortification and bioavailability of **Spirulina,** thereby expanding its role in global food supply.[3]

3. Therapeutic potential

According to studies, **Spirulina** offer antioxidant, anti-inflammatory, antiviral, and cancer-fighting properties, which might aid immune system support, metabolic health, diabetic control, and cardiovascular health.[12]

4.Industrial and environmental biotechnology

Spirulina is a versatile organism with a wide range of industrial biotechnology uses, including use as a sustainable alternative to synthetic colors in confectionary, drinks, and cosmetics, as well as a component in nutraceuticals and functional meals. It also plays an important role in environmental biotechnology by recovering nutrients from wastewater and is being investigated as a feedstock for biofuel production, with the potential to produce biodiesel, bioethanol, and biogas.[26].

II. CONCLUSION

Spirulina, a blue-green algae with anti-inflammatory, neuroprotective, antidiabetic, antioxidant, and anticancer properties, has potential applications in wastewater treatment, biofuels, bioplastics, biofertilizers, and cosmetics. Future development in genetic engineering, cultivation technologies, and bioprocess optimization will enhance its production and applications, contributing to bio-based industries, environmental sustainability, and human health with further study and development.

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