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Innovations, Applications, And Current Research Trends In Spirulina Based Value Added Products- A Review

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Abstract: A Blue-green microalga Spirulina is well known for its dense nutritional profile and functional properties. This makes it an ideal candidate for developing value added products. As global demand for sustainable and health-promoting foods rises, spirulina has moved beyond traditional uses. It leads to the innovations in food, cosmetics, pharmaceuticals, and bio-based materials. This paper presents a comprehensive review of the nutritional values of spirulina, spectrum of spirulina-based products, current research innovations, and future opportunities in value addition. This paper also addresses the limitations and technological challenges which are preventing the commercialization of the product.

***Index Terms* -** Spirulina, Super foods, microalgae, value-added products, biopolymer, and sustainability

I. INTRODUCTION

Spirulina, primarily including species Arthrospira platensis and Arthrospira maxima, is a filamentous cyano bacterium which grows well in alkaline and saline waters. It is emerging as one of the most nutrient-dense microalgae, containing approximately 60–70% protein by dry weight, along with an abundance of vitamins (B1, B2, B12, E), minerals (iron, calcium, and magnesium), essential fatty acids, and bioactive pigments such as phycocyanin and β-carotene [Belay et al., 1993; Habib et al., 2008] .

Spirulina was consumed as a main part of diet by ancient civilizations as per historical records. It was used to make cakes, sause, broth etc as it is very rich in nutrients [Ciferri, 1983, Konishi et al, 1985] . The traditional practices reflect an early recognition of spirulina's nutritional value. Spirulina cultivation has expanded now a days, due to its potential to address food insecurity and malnutrition. Its rapid growth rate, minimal land use, and high yield per unit area make it an ideal candidate for sustainable agriculture and space-based food systems. Spirulina has been now incorporated into nutrition programs for mal nutrient populations. The Food and Agriculture Organization (FAO) recognizes spirulina as a sustainable and efficient source of nutrition, particularly in developing regions where micronutrient deficiencies are prevalent [FAO, 2008] . Today, spirulina is used in a wide range of value-added products, including dietary supplements (capsules, tablets, powders), functional foods (spirulina-fortified snacks, juices, pasta), and cosmetics (anti-aging creams, face masks, shampoos). It is also gaining attention in pharmaceuticals for its antiviral, anticancer, and anti-inflammatory effects, primarily attributed to phycocyanin and polysaccharide content [Singh & Dhar, 2011].

Current research focuses on enhancing spirulina's bioactive compound yield, improving sensory properties for food applications, and developing microencapsulation and nano-delivery systems to enhance bioavailability [Ronga et al., 2020] . Circular economy goals are aligned with spirulina cultivation, which is being optimized through photo bioreactors and wastewater-based systems to reduce cost and environmental impact. Innovations in spirulina-based biodegradable plastics and animal feed further broaden its commercial potential.

II. Nutritional and Functional Properties of Spirulina

Spirulina is broadly acknowledged for its dense nutritional profile and is often referred to as a "superfood" due to its very high concentration of macro and micronutrients. Its biomass contains 60–70% protein by dry weight, making it one of the richest natural protein sources available [Belay et al., 1993]. Spirulina contains all essential amino acids, generally not seen in plant proteins, though some are present in slightly lower concentrations compared to animal-based proteins [Habib et al., 2008].

In terms of vitamin content, spirulina is particularly rich in B-complex vitamins, including thiamine (B1), riboflavin (B2), pyridoxine (B6), cobalamin (B12) but the bioavailability of B12 vitamin E (α-tocopherol) from spirulina is not yet confirm [Ciferri, 1983]. It is also an excellent source of β-carotene, a precursor of vitamin A, which supports immune health and vision.

Spirulina is a good source of minerals, mostly iron, which make it superior due to bioavailability of it, to that of common iron supplements. It also contains magnesium, calcium, potassium, and zinc, which are essential for cellular metabolism, bone health, and cardiovascular function [Gershwin & Belay, 2008].
A distinguishing feature of spirulina is its high content of bioactive pigments, including phycocyanin, which gives it a characteristic blue-green color and contributes antioxidant, anti-inflammatory, and neuroprotective effects [Romay et al., 2003]. Chlorophyll and carotenoids (e.g., lutein, zeaxanthin) also contribute to detoxification and free radical scavenging.

Spirulina provides essential fatty acids, especially gamma-linolenic acid (GLA), which is rarely found in common foods. GLA has anti-inflammatory properties and is beneficial in managing conditions like arthritis and cardiovascular disease [Hirahashi et al., 2002].
Spirulina also exhibits several functional properties like,

- Antimicrobial activity against bacteria and viruses
- Antioxidant effects via radical scavenging and enzymatic modulation
- Antidiabetic effects by improving insulin sensitivity
- Immunomodulatory actions, enhancing both innate and adaptive immune responses [Karkos et al., 2011].

These combined properties make spirulina a promising candidate for use in functional foods, nutraceuticals, and beneficial interventions.

III. Value-Added Products Derived from Spirulina:

Functional Foods and Beverages

Spirulina's exceptional nutritional content makes it a potent ingredient in the development of functional foods and beverages products that offer health benefits beyond basic nutrition.

- Bakery Items: Spirulina has been successfully incorporated into bread, pasta, and cookies to enhance protein, iron, and antioxidant content without significantly altering texture when used in appropriate proportions [Piornos et al., 2020, Prakash et.al., 2023].
- Dairy Alternatives: Spirulina is added to plant-based yogurts and cheeses for its natural pigments and bioactivity. Its phycocyanin contributes color, while protein enhances nutritional value [Batista et al., 2017].
- Health Beverages: Juices and smoothies added with spirulina have gained popularity due to their energy boosting and detoxifying claims. The high chlorophyll and antioxidant content supports liver function and immunity [Kumar et al., 2018].
- Protein Bars: Spirulina improves the amino acid profile, micronutrient density, and antioxidant activity of snacks which are mainly used in sports and meal-replacement bars [Guldas & Irkin, 2010].

Nutraceuticals and Supplements

Spirulina is widely consumed as a nutraceutical, offering concentrated bioactive compounds for disease prevention and health optimization.

- Powdered and Encapsulated Supplements: Commercially available in tablets, capsules, and powder, spirulina is used globally for boosting immunity, managing anemia, and enhancing energy levels [Gershwin & Belay, 2008].
- Phycocyanin Extracts: This blue pigment is extracted and sold as an antioxidant supplement. It has shown anti-inflammatory, neuroprotective, and hepatoprotective effects in preclinical studies [Romay et al., 2003] .

Cosmetics and Personal Care

Spirulina's antioxidants and amino acids have led to its adoption in the cosmetic industry.

- Skin Care: Creams and masks formulated with spirulina improve skin hydration, reduce inflammation, and protect against free radicals [Vargas-Sánchez et al., 2021].
- Hair Care: Spirulina shampoos and conditioners claim to enhance scalp health and hair strength due to its rich protein and mineral content [Dutta et al., 2019].
- Sunscreens: Phycocyanin and β-carotene have UV-absorbing properties, making spirulina an effective natural additive in eco-friendly sun protection products [Chacón-Lee & González-Mariño, 2010].

Bioplastics and Sustainable Packaging

Spirulina has emerged as a biomaterial for sustainable packaging solutions. Biodegradable plastics made from spirulina and starch composites reduce dependence on petroleum-based polymers. These films are used for edible packaging, wrapping, and agricultural mulch. Spirulina's cellulose-free cell wall makes it ideal for binding and forming biodegradable structures [Sharma & Dhuldhaj, 2020].

Animal Feed and Aquaculture

Spirulina is a valuable feed additive due to its high protein and pigment content. Supplementing aqua feed with spirulina enhances fish pigmentation, immunity, and growth. In poultry, it improves egg yolk color and weight gain without harmful residues [Nandeesha et al., 2001; Holman & Malau-Aduli, 2013, Khalil et.al., 2023] .

Pharmaceutical and Therapeutic Products

Spirulina-derived compounds are being studied for their role in disease prevention and therapy. Pharmaceutical and Therapeutic Products [Gonga S. Et.al, 2022].

Spirulina-derived compounds are being studied for their role in disease prevention and therapy.

- **Antiviral Agents:** Sulfated polysaccharides from spirulina, such as calcium spirulan, have demonstrated inhibitory effects against viruses like HIV-1, HSV, and influenza in vitro [Hayashi et al., 1996].
- **Drug Delivery Systems:** Spirulina nanoparticles are being developed as biocompatible drug carriers. Their antioxidant-rich matrix offers promise for targeted delivery in cancer and inflammatory disease therapies [Rajasekaran et al., 2021].

IV. Recent Advances and Research Innovations:

Clinical and Functional Health Studies:

Immune Modulation: Spirulina has demonstrated potent immune modulatory effects due to its rich content of phycocyanin and polysaccharides. These compounds enhance the activity of macrophages, natural killer cells, and T-cells [Belay et al., 1993]. Clinical studies have shown improved immune responses in malnourished children and HIV patients supplemented with Spirulina [Azabji-Kenfack et al., 2011].

Metabolic Syndrome Control: Several clinical trials have confirmed Spirulina’s role in managing components of metabolic syndrome, including hyperglycemia, dyslipidemia, and hypertension. Supplementation with Spirulina (2–8 g/day) has shown significant reductions in total cholesterol, LDL, triglycerides, and fasting blood glucose, while increasing HDL levels [Lu et al., 2010].

Gut Microbiome Support: Prebiotic effects of Spirulina are gaining attention. Its fibers and polysaccharides modulate gut flora by promoting beneficial bacteria such as Lactobacillus and Bifidobacterium, while reducing pathogenic strains, supporting gut health and systemic immunity [Chamorro-Cevallos et al., 2008].

Processing Technologies:

Microencapsulation: To enhance stability and bioavailability, microencapsulation techniques such as spray-drying, freeze-drying, and ionic gelation are used to entrap Spirulina bio actives, including phycocyanin and carotenoids [Da Silva et al., 2019]. These methods protect sensitive compounds from degradation and mask undesirable flavors in food products.

Nano formulations: Spirulina-derived nano carriers are an emerging innovation in functional foods and pharmaceuticals. Phycocyanin-loaded nanoparticles have shown improved antioxidant activity and potential for drug delivery in cancer therapy [Rajasekaran et al., 2021]. Nano liposomes and nano emulsions help in controlled release and targeted delivery.
Drying Methods: Quality of Spirulina and its nutritional profile are significantly affected by drying methods. Low-temperature drying techniques like solar drying and freeze drying retain protein integrity and pigment content better than hot air drying, making them preferable for producing high-quality powder [Ramos-Romero et al., 2020].

Cultivation and Bioprocess Optimization:
Photobioreactors: Closed photobioreactor systems allow controlled Spirulina cultivation, optimizing parameters like light, pH, and CO_2 concentration for higher productivity. They reduce contamination risks and support continuous harvesting [Richmond, 2004].
Wastewater Use: Spirulina cultivation using nutrient-rich agro-industrial and municipal wastewater is gaining traction. It recycles nitrogen and phosphorus while producing biomass, offering a dual benefit of waste treatment and resource recovery [Olguín, 2012].
Carbon Sequestration: Spirulina fixes CO_2 through photosynthesis, contributing to climate change mitigation. Cultivation integrated with carbon capture from flue gases shows promise in bioremediation and sustainable production [Markou et al., 2014].

Genetic and Omics-Based Approaches:
Gene Editing: CRISPR-Cas and other genome editing techniques are being explored to enhance Spirulina's productivity, stress tolerance, and metabolite profiles. Though in early stages, successful transformation protocols are under development for improving strain characteristics [Jeamton et al., 2017].

Transcriptomics: Omics approaches, including transcriptomics and proteomics, are unlocking gene expression patterns in Spirulina under different stress and nutrient conditions. This aids in optimizing cultivation and enhancing the biosynthesis of high-value compounds [Kaur et al., 2022].

Biorefinery:
Spirulina-based biorefineries are being designed to valorize every component of its biomass. After pigment extraction (e.g., phycocyanin), the residual biomass is used for bioethanol production, animal feed, or fertilizer, ensuring zero-waste processing [Molino et al., 2021]. These integrated systems align with the principles of circular economy, promoting resource efficiency and environmental sustainability.

V. Challenges and Future Outlook
Sensory Properties: Spirulina’s strong odor, earthy taste, and dark green color is the major issue with algae-based products [Becker, 2007] . These sensory challenges restrict its incorporation into mainstream food items as algal consumption is uncommon in most of the societies. Masking the flavor using encapsulation, flavor additives, or mixing with milder ingredients has been explored but remains a technical challenge.
Cost-Intensive Production: The production of Spirulina, particularly under controlled conditions such as photo bioreactors, requires high capital investment, energy inputs, and skilled labor. While open pond systems offer lower costs, they are prone to contamination and seasonal productivity fluctuations. The drying process, necessary for shelf stability, further contributes to production costs due to energy requirements and nutrient degradation risks [Richmond & Becker, 1986, Villaró Cos et al., 2024].
Lack of Consumer Awareness: Spirulina has been used traditionally and is recognized by health authorities such as the FDA and FAO, consumer awareness remains low, especially in developing countries. Misconceptions about algae, concerns about toxicity, and unfamiliarity with its benefits limit market penetration. Effective public education campaigns and transparent labeling are essential to build trust and drive adoption [Habib et al., 2008].

Future advances in cultivation technologies, including vertical photo bioreactors, strain selection, and nutrient recycling, can significantly enhance productivity. Innovations in wastewater fed cultivation and CO_2 bio fixation also make Spirulina more sustainable and aligned with circular economy principles [Chew et al., 2017].

Emerging fields like synthetic biology and genetic engineering are opening new avenues for Spirulina optimization. Through targeted gene editing, researchers aim to boost pigment production, enhance protein quality, and develop strains with tailored bioactive compounds. This could transform Spirulina into a platform organism for pharmaceuticals, vaccines, and biofactories [Jiang et al., 2023].

One promising future application is the fortification of staple foods such as rice, wheat flour, and bread with Spirulina to fight malnutrition and micronutrient deficiencies in vulnerable populations. Pilot studies in Africa and Asia have shown success in improving iron, vitamin A, and protein intake through such strategies [FAO, 2016]

Wider adoption of Spirulina based products requires strong policy frameworks and regulatory incentives. Governments can support Spirulina cultivation through subsidies, integration into public nutrition programs (e.g., school meals), and research funding. Regulatory standardization on purity, labeling, and safety can also boost market confidence and facilitate international trade [Pulz & Gross, 2004].

Conclusion:

Spirulina (Arthrospira platensis and Arthrospira maxima) has emerged as a promising micro algal resource with immense potential for addressing global nutritional, environmental, and health challenges. Its rich profile of proteins, essential fatty acids, vitamins, minerals, and unique bioactive compounds has propelled it into the spotlight as a sustainable "super food" and a functional ingredient in a range of value-added products. The integration of Spirulina into functional foods, nutraceuticals, cosmetics, bio plastics, pharmaceuticals, and animal feed reflects its versatility and growing commercial relevance. Recent scientific advances underscore the multifaceted applications of Spirulina beyond conventional dietary supplements. Innovations in clinical nutrition, such as immune modulation, metabolic regulation, and gut microbiota modulation, suggest promising therapeutic potentials that are now being validated through rigorous clinical trials. Parallel advancements in processing technologies including microencapsulation, nano formulations, and optimized drying methods have enabled better bioavailability, sensory masking, and longer shelf life of Spirulina enriched products. The emergence of Spirulina-based biorefineries under circular economy models also showcases its alignment with sustainability goals and zero-waste principles. Despite its potential, Spirulina faces persistent challenges including high production costs, limited consumer awareness, and undesirable sensory attributes. Addressing these challenges through policy support, public education, and technical innovation is critical for its broader societal uptake. Spirulina will become transformative in future food systems, personalized medicine, and green economy initiatives. Strategic investments in R&D, regulatory frameworks, and global collaborations will be essential to unlock its full potential.

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