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Editorial

From Waste to Wealth: *Spirulina* Cultivation and the Food Security towards Future of Rounded Bioeconomy

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The global community is presently facing a "Global Water Bankruptcy", with roughly 75% of the world's population living in countries classified as water-insecure or critically water-insecure as of 2026. This captious intersection of rapid urbanization, population growth, and industrialization has driven food systems and environmental stability to an end point, with about 3 billion people and over half of worldwide food production located in areas where water storage is decreasing or unstable [1,2]. Customary linear models of resource use-often summarized as "take-make-waste" or "extract-produce-dispose"- have established inadequate as they work on the hypothesis of infinite resources and planetary susceptibility to absorb waste. This model has upshot in important environmental, economic, and social crises. As wastewater generation continues to rise alongside exploding nutrient losses to the environment, the urgency to adopt sustainable, regenerative, and circular solutions has never been greater. In this developing landscape, biological systems capable of simultaneously addressing food security, environmental remediation, and resource recovery are gaining renewed attention. The negative implications of non-biodegradable plastics on environment have led to the need for eco-friendly materials that can mitigate environmental degradation. *Spirulina* algae have emerged as a promising candidate for sustainable biocomposite production due to their rapid growth rate, high protein content, and eco-friendly nature [3]. This editorial explores the unique properties of *Spirulina*, including its mechanical strength, biodegradability, and potential environmental benefits when used as a biocomposite material [3]. Comparisons with other biomaterials, such as polylactic acid (PLA) and cellulose, highlight *Spirulina*'s advantages and limitations. The editorial correspondingly discusses the challenges of Spirulina's scalability and commercial application in biocomposites. Also, characterization techniques such as SEM, FTIR, and TGA are used to identify the properties of biocomposite. Among them, *Spirulina* has emerged as a especially powerful candidate because of its extraordinary productivity, nutritional worth, and ability to diverse cultivation environments [1-3].

Spirulina is a nutrient-dense blue-green cyanobacterium containing 60-75% high-quality protein with all essential amino acids, along with polyunsaturated fatty acids (GLA), vitamins (B12, iron), and pigments like phycocyanin. As a potent "superfood" supplement, it offers antioxidant, anti-inflammatory, and immune-boosting properties as already documented in context to mushroom [4-6]. Its rapid growth rate, high photosynthetic efficiency, and comparatively low land requirement distinguish it from conventional agricultural commodities and position it as a sustainable protein alternative for a growing global population. Despite these advantages, the expansion of *Spirulina* production at industrial scale has been hindered by the economic and environmental burdens associated with traditional chemical-based culture media. The reliance on synthetic carbon, nitrogen, and phosphorus sources in *Spirulina* (*Arthrospira*) cultivation is a major bottleneck, as these inputs can account for up to 65% of total nutrient costs, whereas correspondingly contributing to a noteworthy environmental footprint, including carbon emissions from fertilizer production. While *Spirulina* is frequently measured a sustainable, high-protein substitute to conventional foods, the high economic cost of standard, chemical-based culture media (e.g. Zarrouk medium) and the environmental influence of producing these nutrients limit its broader, large-scale adoption [4].

Wastewater, often regarded solely as a pollutant and disposal challenge, represents an underutilized reservoir of nutrients essential for microalgal growth. This editorial provides a novel approach towards synthesis with recent advancements in microalgae-based wastewater treatment and biorefinery processes, emphasizing new methodologies and integrated approaches that address key challenges and highlight potential for transformative impacts in sustainable resource management and bio-product development [5]. Municipal sewage, agricultural runoff, aquaculture effluents, and agro-industrial wastewaters are rich in nitrogen, phosphorus, and micronutrients, yet their discharge into natural water bodies remains a major driver of eutrophication and ecological degradation. Redirecting nutrient-rich waste streams-such as wastewater from food processing, agricultural runoff, and flue gas-toward *Spirulina* cultivation is a highly sustainable, «waste-to-wealth» strategy that simultaneously addresses multiple environmental and economic goals. By acting as a bioremediation agent, *Spirulina* cleans water and air while generating valuable biomass, creating a circular bioeconomy [7,8]. By coupling wastewater treatment with biomass production, this strategy not only mitigates environmental pollution nonetheless also lessens dependence on synthetic fertilizers and freshwater resources.

Scientific evidence authorizes that *Spirulina* (precisely *Arthrospira* platensis and *A. maxima*) can be efficaciously cultivated in several types of wastewater, contributing a sustainable, low-cost technique for bioremediation and nutrient removal. It has confirmed high efficacy in removing nutrients (nitrogen and phosphorus) and organic pollutants (reducing COD/BOD) from diverse sources, together with municipal wastewater, aquaculture effluent, and agricultural run-off. This twin functionality highpoints the latent of *Spirulina*-based systems as nature-based explanations for wastewater management. Nevertheless, the practical implementation of wastewater-based cultivation is accompanied by significant challenges [8]. Wastewater conformation is integrally variable, frequently characterized by variations in nutrient concentrations, high turbidity, and the presence of toxic substances such as heavy metals, ammonia, and evolving contaminants. These factors can unfavorably affect *Spirulina* growth performance, biochemical profile, and product protection, predominantly once biomass is envisioned for food or nutraceutical applications [9].

To overcome these limitations, researchers have discovered a range of mitigation approaches, with controlled dilution emerging as one of the most extensively adopted strategies. Dilution lessens the concentration of inhibitory compounds and progresses light penetration, thus enhancing photosynthetic efficacy and growth constancy. Though, excessive dilution may result in nutrient constraint and abridged biomass productivity, emphasizing the importance of optimizing dilution ratios rather than accepting uniform practices. Complementary tactics such as nutrient balancing, pre-treatment and integration with wastewater treatment technologies have further heightened system performance. Practices including adsorption, membrane filtration, biochar application, and microalgae-bacteria consortia have established potential in reducing toxicity and enlightening effluent quality. Current advances in combined biotechnological systems have extended the scope of wastewater valorization beyond biomass production alone. The incorporation of *Spirulina* cultivation into microalgae-microbial fuel cells demonstrates the latent to couple wastewater treatment with renewable energy generation, even though current power outputs keep on modest. Correspondingly, the recovery and recycling of nutrients from waste-derived sources such as struvite, digestate, and vermicompost line up closely with circular economy principles by closing nutrient loops and lessening resource losses [10]. These inventions jointly indicate a move toward multifunctional bioprocesses intended to bring environmental, economic, and societal advantages. From an environmental viewpoint, replacing chemical-based culture media with wastewater-derived nutrients can considerably decrease the life cycle impacts of *Spirulina* production. Life cycle valuations reliably recognize cultivation as the most resource-intensive step in microalgal bioprocesses. Wastewater operation drops greenhouse gas emissions linked with fertilizer production, preserves freshwater resources, and lessens nutrient discharge into aquatic ecosystems. Moreover, *Spirulina* aids to climate change mitigation via carbon dioxide fixation during photosynthesis, strengthening its role in sustainable development approaches [9]. Notwithstanding its promise, the transition from laboratory-scale studies to industrial-scale wastewater-based *Spirulina* cultivation remains a multifaceted undertaking. Ensuring reliable wastewater quality, founding robust monitoring and pretreatment procedures, and safeguarding biomass quality are critical fundamentals for commercial positioning. Advances in sensor technologies, automation, and Internet of Things-enabled monitoring systems proposal opportunities for real-time control of cultivation parameters [10], hitherto their amalgamation into *Spirulina*-wastewater systems remainders restricted. Economic practicability will eventually depend on optimizing system design, minimizing treatment costs, and identifying high-value applications for *Spirulina* biomass.

Beyond technological deliberations, wastewater-based *Spirulina* cultivation conveys wider implications for water security, environmental governance, and sustainable food systems. Global assessments of water usage expose that domestic and industrial sectors cause vast quantities of wastewater, much of that remnant incompetently treated. Mixing microalgal cultivation into existing water infrastructure delivers a pathway to augment treatment efficacy whereas enlightening valuable resources [11,12]. This approach is predominantly relevant for regions facing acute water shortage, nutrient pollution, and food insecurity, where regionalized and low-input resolutions are instantly required. Eventually, the cultivation of *Spirulina* in wastewater represents more than a technical revolution; it embodies a swing in viewpoint toward reformative resource management [13]. By redefining wastewater as a treasured input rather than an inevitable by-product, this tactic brings into line of scientific novelty with ecological accountability and socio-economic flexibility. Sustained interdisciplinary research, reinforced by empowering strategies and industry engagement, will be indispensable to comprehend the bursting potential of wastewater-based *Spirulina* systems. As the global community pursues pathways toward supportable and circular bioeconomies, *Spirulina* cultivation stands out as a commanding example of how biological processes can transmute environmental tasks into prospects for long-term sustainability [13-16].

Conclusion and Future Perspectives

The transition from customary, high-cost chemical media to waste-based nutrient rootage for *Spirulina* cultivation is a challenging pathway toward a sustainable orbicular bioeconomy. It upcycles industrial, agricultural, and wastewater into high-value protein and pigments (like C-phycocyanin) whereas reducing the environmental footmark. Lastly, taken together previous studies [17] with present documentation, future research directions are proposed to overcome these challenges and fully realize *Spirulina*'s potential in sustainable materials development and food security.

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