REVIEW OF THE UTILISATION OF MICROALGAE FOR BIOENERGY AND FOOD IN A CIRCULAR ECONOMY

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ABSTRACT

Spirulina (*Arthrospira platensis*) is increasingly positioned as a dual-purpose biomass platform that can support both sustainable food production and renewable energy generation. This review evaluates *Spirulina* within a circular economy framework by linking cultivation conditions, product valorisation, and downstream conversion routes. The food pathway is motivated by *Spirulina*'s high protein density and micronutrient content, alongside its potential for low land use and net carbon uptake during growth. The biofuel pathway is assessed through cultivation strategies that modify biomass composition and improve conversion performance, including staged operation, carbon delivery control, nutrient management, and monitoring approaches that stabilise feedstock quality. An integrated facility concept is then discussed using the selected block flow diagram, which couples CO_2 utilisation, reverse osmosis water recovery, biomass separation, food processing, and bioenergy conversion. In this configuration, algae-based food processing waste is treated as a process intermediate for energy recovery, while by-products are routed to external value chains to improve overall resource efficiency. The analysis indicates that commercial feasibility depends on co-product revenue, low-carbon utilities, and tight quality assurance boundaries that protect food-grade streams while enabling robust conversion of residual biomass to energy.

Keywords: *Algae-based systems, biofuels, circular economy, CO_2 capture, sustainable energy, food security, wastewater utilisation*

INTRODUCTION

The global population is projected to reach nearly 10 billion by 2050, intensifying pressure on resource-intensive food systems responsible for up to 30% of global greenhouse gas emissions [1]. Traditional agriculture, particularly livestock farming, which occupies 80% of agricultural land [2], is a major emitter of methane and consumes vast quantities of water. In contrast, microalgae like *Spirulina* present a sustainable alternative, requiring a fraction of the land and water while sequestering significant CO_2 during growth, averaging 0.78 g CO_2 /g biomass [3] and exhibiting fixation rates 10 to 50 times higher than terrestrial plants [4]. This review examines the utilisation of algae within a circular economy framework, focusing on its dual role in bioenergy production and as a nutrient-dense food source to mitigate environmental impacts and enhance resource efficiency. The objectives of this review are to analyse the environmental benefits of algal systems, evaluate integrated pathways for bioenergy and food production, and assess the scalability and economic viability of these solutions within circular economy models.

ALGAE OVERVIEW AND POTENTIAL

Algae are simple, photosynthetic organisms fundamental to ecosystems, producing significant oxygen and forming the base of aquatic food chains. They are highly diverse, thriving in both freshwater and saltwater environments, and are classified broadly into microalgae (e.g., *Spirulina*, *Chlorella*) and macroalgae [5]-[6]. Their rapid growth and efficient conversion of sunlight into biomass make them ideal for sustainable applications. Ecologically, algae are crucial, producing approximately 50% of the Earth's oxygen and acting as primary carbon sinks through sequestration [7]. For industrial use, specific microalgae species offer distinct advantages: *Spirulina* excels with high protein content (60–70% dry weight) and superior CO_2 capture rates (1.8–2.0 g/g biomass), while others like *Dunaliella salina*, with high carbohydrate content, are suited for bioethanol. Beyond food, algae have major applications in biofuel production and wastewater treatment, utilising their ability to absorb nutrients and pollutants, thereby supporting a circular bioeconomy.

SPIRULINA: CULTIVATION AND MULTIFACETED APPLICATIONS

Spirulina (*Arthrospira platensis*) is a cyanobacterium with a centuries-old history as a food source, historically consumed by the Aztecs of Lake Texcoco and the Kanembu people of Lake Chad [8]-[9]. Recognised as a superfood, it is rich in protein, vitamins, and essential fatty acids. Today, it is cultivated commercially in controlled systems like open ponds or photobioreactors, offering a highly efficient protein source with minimal land and water requirements compared to traditional agriculture [10]. Despite this potential and

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North America's dominant market share, driven by demand for natural products and nutraceuticals, widespread adoption faces challenges, including high production costs, contamination risks in open systems, and competition from established plant-based proteins [11].

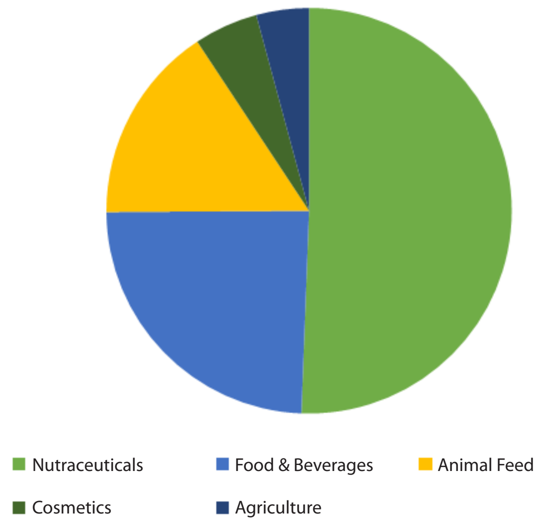

Figure 1 Global *Spirulina* market share by application (2023) [11]-[14]

Beyond direct human consumption, *Spirulina*'s value is expanded through several high-growth markets that enhance its economic viability within a circular economy. As shown in Figure 1, the global *Spirulina* market is segmented by application, with nutraceuticals, including supplements and the therapeutic extract phycocyanin, holding the largest share (50.6%) and demonstrating strong growth prospects [11]. Significant demand also exists in animal feed (15.8% share) for enhancing livestock and aquaculture nutrition [12], in cosmetics (5.1%) for skin and hair care benefits [13], and in agriculture (4.2%) as an organic fertiliser [14]. Emerging applications in biofuel production [15] and water purification [16] further illustrate its versatility. These diversified uses create valuable by-product streams, helping to offset production costs and improve the affordability of *Spirulina* as a nutrient-dense food, thereby addressing core objectives of food security and sustainable resource use.

SPIRULINA: NUTRITIONAL POWERHOUSE AND SUSTAINABLE PROTEIN

Nutritional Profile and Modern Applications

Spirulina's reputation is underpinned by an exceptional nutritional composition. It contains 60-70% protein by dry weight, providing all nine essential amino acids [17]. It is rich in micronutrients, offering higher iron content than spinach (28.5 mg vs. 2.7 mg per 100 g) and more beta-carotene than carrots (29,000 µg vs. 8,285 µg per 100 g) [18]. Its potent antioxidants, like phycocyanin, provide anti-inflammatory benefits. Classified as Generally Recognised As Safe (GRAS) by the Food and Drug Administration (FDA), typical consumption ranges from 3 to 6 g/day. Modern applications leverage this density; it is sold as powders and tablets for supplements and integrated into functional foods like pasta and energy bars, driving a market projected to grow at a compound annual growth rate (CAGR) of 10.5% [19].

Environmental and Economic Advantages

Spirulina cultivation offers profound environmental benefits, with a significantly lower resource footprint compared to conventional protein sources, as detailed in Table 1.

Table 1 Comparative environmental footprint of major protein sources [20]-[22]

Metric	*Spirulina*	Soy Protein	Beef
Water Use (L/kg protein)	2,100	1,800	15,000
Land Use (ha/ton protein)	0.02-0.05	0.4	2.5
Protein Yield (tons/ha/year)	22-44	2.5	0.4
GHG Emissions (kg CO_2-eq/ kg protein)	2-5	10-20	50-150
Carbon Sequestration Potential	High (1.8t CO_2/ t biomass)	Low	Negative

Beyond its superior environmental performance, *Spirulina* requires drastically less water and land than traditional proteins. The data in Table 1 demonstrates that *Spirulina* produces 10-100 times more protein per hectare than conventional sources while generating significantly lower greenhouse gas emissions. Furthermore, it sequesters CO_2 during growth. Economically, while current retail prices range from $8-$60/kg, technological advances and scaling aim to reduce costs to enhance accessibility [23].

Scalability and Aspirational Utilisation

Spirulina's scalability supports both niche and broad applications. The market is dominated by North America (51.3% share), with powder forms leading at 47.5% of value, while phycocyanin extracts show the highest growth (CAGR 28.1%). Beyond human consumption, *Spirulina* serves as a high-quality feed in livestock and aquaculture, improving animal health and reducing reliance on fishmeal [24]-[25]. Its most aspirational role is in combating global malnutrition. Recognised by UN bodies, it has been deployed in nutritional programs to effectively address nutrient deficiencies. Advanced cultivation systems enable scalable production on non-arable land, aiming to make this nutrient powerhouse a viable staple for food-insecure regions and a mainstream sustainable protein.

CULTIVATION STRATEGIES THAT SPECIFICALLY TARGET BIOFUEL PRODUCTION FROM SPIRULINA

Two-Stage Cultivation to Reconcile Growth and Fuel Precursor Formation

A core biofuel challenge for *Spirulina* is the trade-off between rapid biomass growth and accumulation of fuel-relevant constituents, because conditions that promote high growth often favour protein synthesis rather than energy-dense storage compounds [26]-[27]. Current studies therefore favour two-stage cultivation in which stage 1 maximises biomass under nutrient-replete, well-buffered alkaline conditions, and stage 2 applies controlled stress to shift biochemical composition toward higher carbohydrate availability for fermentation or toward conversion-friendly characteristics for thermochemical processing [28]-[29]. In practice, stage 2 can involve nitrogen reduction, altered light intensity, or modified inorganic carbon dosing to change elemental ratios, which influences downstream yields and upgrading severity in routes such as hydrothermal liquefaction (HTL) [27],[29].

Carbon Delivery Design for Biofuel Systems

For biofuel-oriented cultivation, CO_2 supply design must be treated as a unit operation that controls both productivity and downstream processing behaviour, because carbon availability affects ash formation, protein fraction, and the nitrogen content that later appears in HTL biocrude or fermentation residues [27],[30]. Large-scale work demonstrates that intermittent CO_2 addition in raceway systems can maintain alkaline pH targets while sustaining high inorganic carbon availability, which reduces carbon limitation without continuous sparging energy demand [30]. For fuel production chains that plan HTL, this is important because high moisture tolerance makes wet harvesting feasible, so the cultivation system can prioritise stable carbon delivery and productivity rather than aiming for ultra-high lipid content that would justify drying [27],[29].

Nutrient Sourcing and Process Integration for Cost Reduction

Biofuel viability depends strongly on nutrient cost and embedded emissions, so 2020–2026 work increasingly frames *Spirulina* cultivation as part of a wastewater-to-bioenergy system where nutrient removal and biomass generation occur simultaneously [26],[31]. Cultivation in anaerobically digested cattle wastewater has demonstrated substantial removals of nitrogen and phosphorus alongside high biomass concentrations, which supports a design in which wastewater treatment provides a revenue or avoided-cost credit that improves biofuel economics [26]. Related studies show that light regime and pH strongly affect pollutant removal performance and biomass formation, implying that wastewater integration requires operational optimisation rather than fixed recipes [31]. For circular systems, this approach also creates a more consistent nutrient supply profile, which helps stabilise biomass composition for downstream conversion, particularly in continuous HTL, where feed variability can alter oil quality and stability [29],[33].

Cultivation Control Metrics for Conversion Efficiency

Biofuel pathways amplify the value of process monitoring because conversion yields and product properties respond to biochemical composition and not just to total biomass harvested [27]-[28]. Early prediction models that use cultivation signals such as optical density and pH to anticipate final yield can support proactive control, reduce batch failures, and improve scheduling of harvesting and conversion equipment utilisation, which is essential for integrated fuel systems [33]. This control logic also supports tighter feed specification for HTL because nitrogen and oxygen in biocrude, and viscosity evolution during storage, can worsen when biomass composition shifts toward high protein or when conversion conditions are not matched to the feed [27],[29].

Matching Cultivation to the Most Robust Conversion Route for *Spirulina*

Recent literature indicates that cultivation strategies should be selected after choosing the primary conversion route, because the "best" biomass composition is pathway-dependent [27]-[28]. If the target route is HTL, cultivation can prioritise high areal productivity and wet harvesting readiness, because HTL processes wet biomass directly and converts proteins, carbohydrates, and lipids into a biocrude-like product [27],[29]. If the target route is bioethanol, cultivation should aim for carbohydrate-rich biomass and for operational stability that supports timely harvesting before carbohydrate is reallocated into growth, since hydrolysis and fermentation performance depend on sugar availability and process consistency [28]. If the target is biodiesel, the literature suggests that *Spirulina* generally requires either lipid enhancement strategies or conversion intensification, such as in situ transesterification, because typical lipid levels can be too low for competitive yields compared with oleaginous microalgae [34]-[35].

Comparison with Other Microalgae for Biofuel Production

From a cultivation-for-fuel standpoint, *Spirulina* competes differently from oleaginous genera. Oleaginous microalgae such as *Nannochloropsis* and *Microchloropsis* show strong lipid accumulation responses under nitrogen starvation and can achieve high lipid contents and productivities, which align directly with biodiesel-focused chains [35]. This means that biodiesel-oriented cultivation commonly favours those genera, while *Spirulina* is often favoured for HTL or fermentation routes that can valorise whole biomass and tolerate higher protein fractions [27]-[28]. In wastewater-based cultivation, comparative bench studies indicate that species respond differently to pH and photoperiod, so selection should consider local wastewater characteristics and the desired fuel pathway rather than assuming universal superiority [31]-[32]. Operationally, *Spirulina* retains a practical advantage for open systems because high alkalinity can reduce biological contamination risk, which can lower culture crash frequency and support stable feed supply for continuous conversion units [30],[33].

Comparison with Agricultural Sources in Biofuel Process Design

Compared with agricultural feedstocks, *Spirulina* cultivation can reduce dependency on arable land and can integrate CO_2 and nutrient recovery streams, but the decisive comparison for fuels is often conversion logistics and life cycle sensitivity to energy inputs [36]-[37]. Agricultural lignocellulosic routes typically face pretreatment severity, inhibitor management, and solids handling challenges that drive capital intensity and operational complexity, whereas algal biomass lacks lignin and can enter biochemical routes with different constraints focused on hydrolysis efficiency and fermentation robustness [28],[38]. For thermochemical routes, HTL provides a key advantage for algae because it processes wet biomass and can reduce energy penalties associated with drying, which is a major cost component when handling high-moisture biological feedstocks [27],[29]. However, broader life cycle assessment evidence shows that climate impacts vary widely across biofuel pathways and depend strongly on assumptions such as electricity carbon intensity, co-product allocation, and nutrient sourcing, so comparisons must be made with transparent boundaries and allocation logic [37],[39]. Studies of controlled-environment *Spirulina* production powered by low-carbon energy illustrate how system integration and energy sourcing can shift net impacts materially, which is directly relevant if biofuel cultivation uses artificial lighting or intensive pumping [36],[39].

PROPOSED CIRCULAR ECONOMY PATHWAY FOR CO-PRODUCING FOOD AND BIOFUEL FROM SPIRULINA

Figure 2 describes an integrated *Spirulina* biorefinery that couples water recovery, carbon utilisation, food processing, and energy recovery within one system boundary. The system starts with CO_2 from different sources feeding the algae input + cultivation stage, which improves carbon availability for photosynthetic biomass formation and supports carbon valorisation at the site scale [40]. A key feature is the Reverse Osmosis (RO) system that treats incoming wastewater and produces high-quality water for reuse, which reduces freshwater demand and improves process reliability for downstream separation and food processing. Similar RO-enabled reuse concepts are reported as effective for meeting reuse standards while enabling resource recovery in microalgae-linked systems [41].

After cultivation, the broth enters the biomass separation stage, which splits the process into two coordinated pathways. The primary biomass fraction is routed to the Food Processing stage to generate processed algae for food markets. This stage represents the food-quality control point, where sanitary processing and stabilisation allow the facility to supply safe products while capturing the main economic value of *Spirulina* as a nutritional ingredient [42]. The diagram also shows an explicit "algae-based food waste" stream leaving the food processing stage and returning upstream to the Bioenergy Conversion stage. This recycling is central to circularity because it converts unavoidable food-line losses and off-spec material into energy rather than disposal, which aligns with microalgae circular economy frameworks that emphasise cascading use and zero-waste designs [40].

In the bioenergy conversion stage, the system can implement wet-biomass-compatible routes so that energy recovery does not depend on full drying. A practical configuration is anaerobic digestion for wet residues and process side-streams, since digestion can convert residual organics into biogas and produce nutrient-containing by-products for external use [43]. The diagram's "by-products to be utilised by other industries" block is consistent with documented circular bioeconomy practice where recovered streams support downstream value chains, including fertiliser and biochemical applications, provided quality constraints are met [44]. Overall, the block flow diagram represents a single facility that produces food from the main biomass stream while using the food-line waste stream and residuals for bioenergy, with RO water reuse and CO_2 utilisation improving resource efficiency across the integrated pathway [40]-[41].

CHALLENGES AND POSSIBLE LIMITATIONS FOR SPIRULINA

Although *Spirulina* has strong potential as a sustainable protein and biomass source, several regulatory and quality assurance challenges limit wider adoption. Large-scale cultivation produces biomass of highly variable quality because systems range from simple open ponds to high-precision photobioreactors, leading to inconsistent

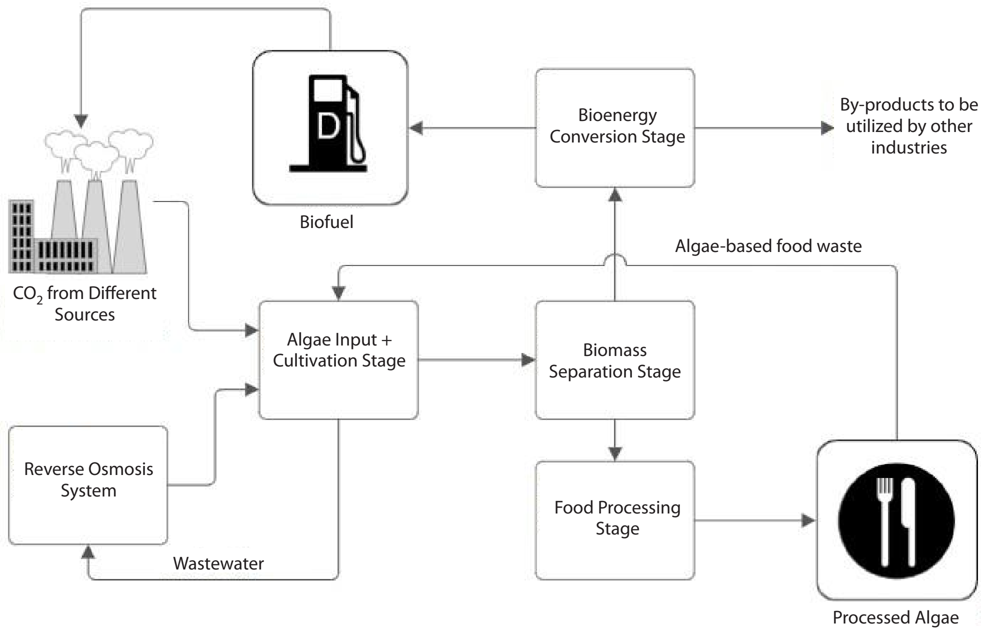

Figure 2 Stages for the proposed integrated system for algae-based bioenergy and food production [40]-[44]

purity, taste, and nutrient profiles. These inconsistencies make it difficult for producers to meet strict food safety and nutritional standards, which must be satisfied for food-grade applications [45]. Microalgae biorefineries also face regulatory uncertainty concerning the use of wastewater-derived inputs, the allowable limits for contaminants, and labelling requirements, which complicates market expansion across regions. Recent circular economy analyses stress that the absence of harmonised global regulations for microalgae restricts commercialisation and slows integration of *Spirulina* products into mainstream food and energy systems [40]. In addition, although *Spirulina* is recognised for its health benefits, pigment ingredients such as phycocyanin still suffer from stability problems during extraction and storage, increasing processing demands and limiting product diversification [42].

Production and cost limitations represent another major barrier to scaling *Spirulina*-based systems. Cultivation often requires precise control of temperature, light, mixing, and nutrient balance to prevent contamination by unwanted microorganisms, and these requirements increase energy consumption and operational costs [46]. Harvesting and dewatering also remain major cost drivers because microalgal cultures are dilute and require multi-step separation processes, which increase labour and energy demands. Technoeconomic studies indicate that even with wastewater nutrient recycling, cost reductions remain modest because the system still depends heavily on energy-intensive operations [44]. Consumer acceptance presents an additional constraint. Sensory characteristics such as strong colour and flavour, combined with limited familiarity with algae-based foods, reduce the likelihood of widespread adoption and require targeted education and product reformulation to expand acceptance beyond supplement markets [47].

CONCLUSION

This review supports a biorefinery interpretation of *Spirulina* in which food and energy outputs are co-produced through coordinated cultivation, separation, and conversion steps. *Spirulina* is well-suited to sustainable protein supply because it is protein-rich and can be produced with low land demand, but large-scale food applications require consistent quality, contamination control, and stabilisation methods that preserve nutritional and sensory attributes. For biofuel production, *Spirulina* should be matched to conversion routes that valorise whole biomass or wet residues, since its composition does not inherently favour lipid-only pathways. The proposed circular economy pathway embedded in the block flow diagram strengthens resource efficiency by coupling reverse osmosis water reuse with CO_2 utilisation, then converting algae-based food waste into bioenergy while directing other by-products to external value chains. Overall feasibility depends on value stacking from food and pigment markets, low-carbon utilities, and strict quality boundaries across unit operations.

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CONFLICT OF INTEREST

The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper.

AUTHORS' CONTRIBUTION

Ibrahim Sian Saeed and Nurul Aini Binti Amran conceptualised the study and critically reviewed and revised the manuscript for intellectual content. Ibrahim Sian Saeed drafted the manuscript, developed the methodology, and conducted the literature search, data synthesis, and analysis. Nurul Aini Binti Amran validated the methodology and supervised the study. All authors have read and approved the final version of the manuscript.

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