phycology

Review

Integrated Microalgal–Aquaponic Systems for Enhanced Water Treatment and Food Security: A Critical Review of Recent Advances in Process Integration and Resource Recovery

Charith Akalanka Dodangodage [1,*], Jagath C. Kasturiarachchi [2], Induwara Arsith Wijesekara [2], Thilini A. Perera [3], Dilan Rajapakshe [4] and Rangika Halwatura [1]

[1] Department of Civil Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka; rangika@uom.lk
[2] Department of Applied Sciences, Sri Lanka Institute of Information Technology, New Kandy Road, Malabe 10115, Sri Lanka; jagath.k@sliit.lk (J.C.K.)
[3] Department of Plant Sciences, University of Colombo, Colombo 00300, Sri Lanka; thilini@pts.cmb.ac.lk
[4] KU Innovation Park, University of Kansas, Lawrence, KS 66047, USA; sandil.rs89@gmail.com
* Correspondence: dodangodageca.24@uom.lk

Abstract

The convergence of food insecurity, water scarcity, and environmental degradation has intensified the global search for sustainable agricultural models. Integrated Microalgal–Aquaponic Systems (IAMS) have emerged as a novel multi-trophic platform that unites aquaculture, hydroponics, and microalgal cultivation into a closed-loop framework for resource-efficient food production and water recovery. This critical review synthesizes empirical findings and engineering advancements published between 2008 and 2024, evaluating IAMS performance relative to traditional agriculture and recirculating aquaculture systems (RAS). Reported under controlled laboratory and pilot-scale conditions, IAMS have achieved nitrogen and phosphorus recovery efficiencies exceeding 95% while potentially reducing water consumption by up to 90% compared to conventional farming. The integration of microalgal photobioreactors enhances nutrient retention, may contribute to internal carbon capture, and enables the generation of diversified co-products, including biofertilizers and protein-rich aquafeeds. Nevertheless, significant barriers to commercial scalability persist, including the biological complexity of maintaining multi-trophic synchrony, high initial capital expenditure (CAPEX), and regulatory ambiguity regarding the safety of waste-derived algal biomass. Technical challenges such as photobioreactor upscaling, biofouling control, and energy optimization are critically discussed. Finally, the review evaluates the alignment of IAMS with UN Sustainable Development Goals 2, 6, and 13, and outlines future research priorities in techno-economic modeling, automation, and policy development to facilitate the transition of IAMS from pilot-scale innovations to viable industrial solutions.

Keywords: microalgal–aquaponic systems; food security; nutrient recovery; circular economy; resource optimization; sustainable agriculture

Check for updates

Academic Editor: Marcin Dębowski

Received: 7 November 2025
Revised: 22 December 2025
Accepted: 26 December 2025
Published: 12 January 2026

1. Introduction

Global food insecurity, environmental degradation, and climate variability are converging to exert unprecedented pressure on modern agricultural systems. With the global population projected to exceed 9.7 billion by 2050, the demand for sustainable and resource-efficient food production frameworks is more critical than ever [1,2]. This urgency is

https://doi.org/10.3390/phycology6010014

amplified by diminishing arable land, stagnating yield growth, and the intensifying effects of climate change. Agricultural productivity may decline by 3.1 to 7.4% for every 1 °C rise in global temperature, disproportionately affecting vulnerable regions such as Sub-Saharan Africa, where more than 346 million people remain undernourished [3,4]. At the same time, almost 40% of the global population is already affected by freshwater scarcity, creating severe constraints on agricultural resilience [3].

Nutrient runoff further intensifies ecological stress. Excess nitrogen and phosphorus from agriculture drive eutrophication, biodiversity loss, and freshwater degradation. In China's Taihu Lake Basin, agricultural runoff accounts for more than half of the total nitrogen and phosphorus loads, and similar patterns have been observed across Europe and North America [4,5]. Although mitigation strategies such as buffer strips and precision fertilization offer localized benefits, their scalability and long-term effectiveness remain limited. These measures primarily reduce nutrient losses rather than enabling systematic recovery and reuse, leaving substantial resource inefficiencies unresolved.

Aquaponics has emerged as a promising closed-loop strategy by integrating aquaculture with hydroponics to recirculate water and nutrients. These systems can reduce freshwater use by up to 90% relative to conventional farming [6]. Advanced designs such as Double Recirculating Aquaponic Systems (DRAPS) have demonstrated improved water and nutrient efficiency, enabling crop yields that match hydroponics but with lower input requirements [7]. Similar innovations in Recirculating Aquaculture Systems (RAS) highlight the importance of water reuse, biofiltration, and nutrient stabilization for sustainable fish production, positioning RAS as a foundational platform for systems that integrate plants and microalgae [8]. However, aquaponic performance is still limited by nutrient imbalances, particularly the restricted availability and recycling of nitrogen and phosphorus, which affects consistent productivity and limits alignment with sustainability goals such as SDG 6 (Clean Water and Sanitation) [8,9]. These constraints indicate that while aquaponics improves resource efficiency, it does not fully resolve nutrient recovery inefficiencies inherent to conventional food production systems.

To enhance nutrient recovery, microalgae have been proposed as a complementary module within aquaponic systems. Strains such as *Chlorella vulgaris* sp. can achieve nitrogen and phosphorus removal efficiencies above 90% while producing biomass suitable for biofertilizers, soil conditioners, and bioenergy feedstocks [10,11]. These high removal efficiencies are mainly reported under controlled laboratory or pilot conditions, where light, temperature, and hydraulic retention time can be tightly regulated. Aquaponic effluents typically contain low levels of heavy metals, increasing the suitability of harvested or immobilized algal biomass for agricultural reuse [12,13]. Furthermore, microalgal biomass is rich in proteins, essential fatty acids, and micronutrients, offering a nutritionally dense resource that can partially substitute conventional protein sources such as soy or fish meal [14–18].

However, microalgal performance can vary significantly under real aquaponic conditions, where pH, N:P ratios, hydraulic retention time, and organic loading fluctuate over diel cycles. These variations may reduce nutrient removal efficiency or alter biomass biochemical profiles, creating uncertainty in downstream uses [19]. Such sensitivity underscores that microalgae, when deployed as standalone treatment units, may face operational instability under the variable conditions characteristic of integrated food production systems.

This reflects a key symmetry between aquaponic limitations, which include insufficient nutrient recovery, and microalgal limitations, which include sensitivity to variable effluents. Together, these constraints highlight the need for integrated engineering solutions rather than isolated modules. Microalgae also contribute to climate resilience due to their strong carbon fixation capacity. Certain strains, including *Chlorella* spp., can fix 0.77

to 2.22 g CO_2 L^{-1} d^{-1}, even when cultivated with industrial flue gases containing NO_x and SO_x [20]. Such values have mostly been achieved in controlled laboratory or pilot photobioreactors where illumination and mixing are optimized. Under ideal conditions, annual protein yields can exceed 22 to 44 tons per hectare, considerably higher than terrestrial crops while using far less land and water [17]. Nevertheless, the reproducibility of these performances under long-term, integrated operational conditions remains an open challenge.

Integrating microalgae into aquaponics has been proposed as a multifunctional platform where water, nutrients, and carbon can potentially circulate more efficiently between fish, plants, and algae. Integrated Microalgal–Aquaponic Systems (IAMS) can operate as fully integrated loops, side-stream polishing units, or hybrid systems linking RAS with external algal modules for targeted nitrogen and phosphorus removal. Although both aquaponics and microalgae systems are well-established individually, their combined operation has been explored far less, with most evidence limited to small laboratory or pilot trials. Existing studies indicate enhanced nutrient recovery, water savings, biomass valorization, and carbon capture, but scaling remains constrained by challenges in photobioreactor design, irradiance control, hydraulic compatibility, and diel fluctuations in oxygen and pH. Moreover, integrating additional biological and engineering modules may increase system complexity, energy demand, and control requirements, introducing trade-offs that must be carefully evaluated.

To address these limitations, this review outlines a multi-module IAMS concept where fish effluent undergoes sedimentation and filtration before flowing into hydroponic plant beds for primary nutrient uptake. The effluent then enters photobioreactors for tertiary nutrient polishing, after which the treated water is returned to the fish tanks. This configuration is presented as a conceptual framework rather than a universal solution, acknowledging that alternative system architectures may be more suitable depending on scale, resource availability, and operational objectives. Despite increasing interest in integrated systems, there is still no comprehensive review that synthesizes the engineering, biological, and sustainability dimensions of IAMS. This review therefore aims to critically evaluate nutrient recycling strategies, microalgal species selection for aquaponic effluents, photobioreactor configurations that support integration, and the economic and environmental trade-offs associated with scaling. In doing so, particular emphasis is placed on assessing the robustness of reported performances, the transferability of laboratory-scale findings, and the uncertainties that emerge during long-term and large-scale operation. The review also discusses how IAMS align with the United Nations Sustainable Development Goals, particularly SDG 2, SDG 6, and SDG 12.

This work synthesizes empirical findings, engineering advancements, and sustainability assessments relevant to integrating microalgae into aquaponic and recirculating aquaculture systems. Emphasis is placed on peer-reviewed studies reporting nutrient removal performance, biomass productivity, photobioreactor configurations, and system-level resource flows. The scope focuses on research published between 2008 and 2024, covering laboratory, pilot, and semi-industrial trials that inform the engineering and operational design of feasible IAMS configurations.

2. Contextual Background: Food Security and Agricultural Constraints

2.1. Global Food Security Challenges

The global population is projected to exceed 9.8 billion by 2050, requiring a 50–100% increase in food production to meet caloric and nutritional needs [20]. However, agriculture already occupies 38% of the planet's ice-free land and consumes about 70% of global freshwater withdrawals, making it one of the most resource-intensive sectors [21].

Irrigation inefficiencies further exacerbate stress, with 30–50% of applied water lost to evaporation and runoff under conventional systems. In comparison, closed-loop systems such as aquaponics and microalgae-based cultivation can recycle up to 99% of water [12,22]. However, such high recycling efficiencies are predominantly reported under controlled or optimized operating conditions, and real-world performance may be constrained by system scale, management intensity, and infrastructure requirements. Food insecurity remains particularly critical in regions such as Sub-Saharan Africa and South Asia, where agricultural expansion cannot keep pace with population growth. Only 20% of global cropland is irrigated, yet this fraction produces 40% of the world's food, demonstrating the productivity gap between irrigated and rain-fed systems [20]. Integrated systems that reuse nutrient-rich aquaculture effluent for plant and algal cultivation offer a strategy to improve nutrient retention and reduce input dependency [23].

Climate change intensifies these vulnerabilities. Rising temperatures, erratic rainfall, and advancing soil degradation have slowed yield growth; global wheat yields are increasing at just 1.1% per year, below the 1.3% threshold needed to stabilize food prices [24]. Moreover, 33% of global soils are degraded due to erosion, nutrient depletion, and excessive agrochemical use [25]. Microalgae-based systems bypass the need for soil entirely and can generate biomass useful for soil rehabilitation or amendments. Nevertheless, the feasibility of deploying such systems at scale depends on energy availability, system integration, and long-term operational stability.

Urbanization further constrains arable land availability, particularly in Southeast Asia and West Africa, where productive land is rapidly converted for industrial expansion [26]. Microalgae bioreactors and aquaponic units can be deployed vertically or on marginal lands. Producing 1 kg of beef protein requires up to 258 m^2 of land, whereas microalgae require less than 2.5 m^2 for the same protein output [27], supporting their suitability for compact environments. Global protein demand continues to rise, yet livestock farming, currently the dominant protein source, has a substantial environmental footprint. Producing 1 kg of beef protein emits up to 60 kg CO_2-eq, whereas microalgal protein cultivated using waste CO_2 can achieve near-zero emissions [26,28]. These contrasts highlight the potential of alternative protein systems while also underscoring the importance of assessing their performance beyond idealized production scenarios.

Despite technological progress in Recirculating Aquaculture Systems (RAS), nutrient losses remain substantial, with nitrogen and phosphorus losses reaching 79% and 83%, respectively [23]. Integrating microalgae with RAS offers a pathway to convert residual nutrients into biomass, improving circularity and reducing eutrophication risks. Collectively, these trends underscore the declining sustainability of traditional food production. Integrated systems that combine aquaponics with microalgal cultivation present a promising alternative by reducing water demand, utilizing waste nutrients, and enhancing resilience in a changing climate [12,22,29], provided that system integration challenges and scale-dependent constraints are adequately addressed.

2.2. Limitations of Traditional Agriculture

Traditional agriculture faces persistent challenges related to water scarcity, soil degradation, nutrient inefficiency, greenhouse gas emissions, and climate vulnerability. Agriculture consumes nearly 70% of global freshwater, yet traditional irrigation systems, particularly surface and flood irrigation, can waste up to 60% of applied water [30,31]. Critical groundwater aquifers in regions such as Sub-Saharan Africa and western India show depletion rates of 0.5–1.5 m per year [31]. In contrast, aquaponic systems recycle 95–99% of water [12].

Land degradation further constrains productivity, with over 33% of soils affected by erosion, salinization, nutrient depletion, and structural decline [25]. Although conservation agriculture can mitigate degradation, deeper structural changes are required. Aquaponics and microalgal cultivation eliminate soil dependence and can be deployed in degraded or urban environments [26]. Nutrient inefficiency remains a major environmental issue. Global nitrogen fertilizer application averages 68.61 kg ha^{-1}, reaching 228.48 kg ha^{-1} in China, yet plant uptake efficiency often falls below 50%, resulting in nutrient losses and eutrophication [5]. Microalgae-based systems can achieve >90% nitrogen and phosphorus removal by converting waste nutrients into biomass [10,32], although these efficiencies are largely reported from laboratory or pilot-scale studies with tightly controlled operating conditions.

Traditional agriculture contributes significantly to greenhouse gas emissions (approximately 20% of global emissions) mainly due to livestock methane and nitrous oxide from fertilization [33,34]. Microalgae can sequester CO_2 and achieve carbon-neutral or carbon-negative outcomes depending on the culture conditions [23,28], yet these outcomes are highly sensitive to energy inputs for illumination, mixing, and harvesting, which may offset net climate benefits at larger scales.

Climate variability further threatens food production. For example, maize yields decline by approximately 1.7% for every 1 °C temperature increase during drought periods [35]. Integrated aquaponic systems offer resilience by operating within controlled environments that buffer external climatic fluctuations [12]. Together, these limitations underscore the need for more sustainable, resource-efficient alternatives. Integrated systems combining aquaponics with microalgal cultivation can mitigate water loss, reduce nutrient discharge, and enable cultivation in non-arable spaces while introducing new operational and economic considerations that must be critically evaluated.

2.3. Agricultural Runoff and Water Pollution

Nutrient runoff remains one of the most damaging consequences of traditional agriculture. Excess nitrogen and phosphorus escape via leaching and surface runoff, driving eutrophication, harmful algal blooms, and hypoxia [5]. Closed-loop aquaponic systems retain nutrients internally, minimizing environmental discharge [22].

Case studies highlight the severity of nutrient pollution: agriculture contributes over 50% of nitrogen and phosphorus loads in China's Taihu Lake Basin [5], while nutrient losses from U.S. Midwest croplands contribute to an annual hypoxic dead zone in the Gulf of Mexico exceeding 22,500 km^2 [36]. Integrating microalgal reactors with aquaponic systems can significantly reduce nutrient discharge, achieving near-zero losses under controlled conditions [29]. However, maintaining such low discharge levels requires precise hydraulic control, consistent biomass harvesting, and stable operating conditions, which may be difficult to sustain under long-term or large-scale deployment.

Nutrient pollution also elevates public health risks. In many low-income regions, contaminated surface water is reused for irrigation, exposing populations to pathogens such as *E. coli* and *Cryptosporidium* [37]. Aquaponic systems continuously filter water, reducing microbial contamination [12]. Microalgae-based systems further repurpose fish waste into biomass while achieving >90% nutrient removal [32]. Urbanization accelerates nutrient export. In China's Guishui River Basin, rapid urban expansion increased nitrogen export by 11.6% [38]. Intensive fertilization can elevate phosphorus losses to 3.3% [5]. Integrated microalgal aquaponic systems bypass soil pathways entirely, enabling precise nutrient management and preventing runoff, provided that system loading rates remain within the design limits.

Climate-driven extreme rainfall can trigger sudden nutrient pulses from fertilized fields [39]. Closed-loop systems avoid these vulnerabilities by retaining water and nutrients internally, enhancing climate resilience [12]. Nutrient pollution imposes substantial economic costs; across Europe and North America, billions are spent annually on mitigation. Microalgae-integrated RAS configurations can eliminate nearly all nutrient discharge under optimized conditions, converting waste into valuable biomass [23,40], although system failures or overload events can rapidly reverse these gains.

2.4. Rationale for Integrated Microalgal–Aquaponic Systems

Despite progress in aquaponic and microalgal technologies, these approaches are typically implemented independently, resulting in incomplete nutrient recovery and limited circularity. RAS configurations continue to lose substantial fractions of nitrogen and phosphorus, while stand-alone microalgal reactors depend on stable nutrient inputs and often generate biomass that is underutilized or inconsistently produced [23,32].

As highlighted in earlier sections, current systems address isolated aspects of food–water–nutrient challenges, water scarcity, nutrient inefficiency, and environmental degradation, but do not provide a fully integrated, multifunctional solution. This fragmentation underscores a critical gap: the need for platforms that simultaneously recycle water, capture and transform nutrients, generate useful biomass, and reduce ecological impacts.

Integrated Microalgal–Aquaponic Systems (IAMS) respond directly to this need. By coupling aquaculture effluents with microalgal photosynthesis and plant production, IAMS can enhance nutrient retention, stabilize water quality, diversify biomass outputs, and improve resilience. At the same time, IAMS introduce additional biological and engineering complexity, including increased energy demand, control requirements, and scale-dependent trade-offs that must be carefully assessed. The following section introduces the structure, operational principles, and functional potential of IAMS [41]. By structuring IAMS with sequential module, water and nutrients are progressively recovered and recycled, addressing the limitations of standalone aquaponics or microalgae systems highlighted above.

3. Aquaponic Systems: Promise and Limitations

3.1. Overview of Aquaponics

Aquaponics is a recirculating food-production system that couples fish culture with hydroponics, enabling the reuse of nutrient-rich aquaculture effluent for plant production [12,42–44]. As illustrated in Figure 1, water from aquaculture units passes through biofiltration components where ammonia is oxidized, after which the treated stream is directed to hydroponic beds for nutrient uptake. The closed-loop configuration minimizes discharge relative to linear agricultural or aquaculture models, where leaching and effluent losses are common [43]. However, the degree of closure achieved in practice varies substantially across system designs and operational scales, and complete nutrient containment is rarely realized under continuous production.

Water-use efficiency is one of aquaponics' strongest environmental advantages; however, reported values vary substantially by system type and operational scale. Controlled experiments have achieved water requirements of 25–50 L per kg of produce [43,45], whereas field or commercial systems generally exhibit higher consumption due to evapotranspiration, system maintenance, and climatic factors [46]. Comparable trends are observed for aquaculture performance: while intensive aquaculture may require up to 300 L kg^{-1} of fish, aquaponic configurations can reduce this to <100 L kg^{-1} under optimized recirculation [43], though such reductions are sensitive to stocking density, biofilter capacity, and operational discipline, which are difficult to maintain consistently at commercial scale.

Aquaponics also enables dual production from a single water source. Trials with basil grown in coupled systems reported approximately 20% higher yields compared to hydroponic monoculture, attributed to enhanced microbial interactions and steady nutrient supply [45]. Nevertheless, yield advantages are not universal across crops and are often diminished for fruiting species or under fluctuating nutrient regimes. Spatial adaptability, such as deploying units on rooftops, degraded land, or compact urban sites, has been demonstrated across diverse geographies [43], although long-term operational stability remains closely tied to energy availability, climate control, and system management expertise.

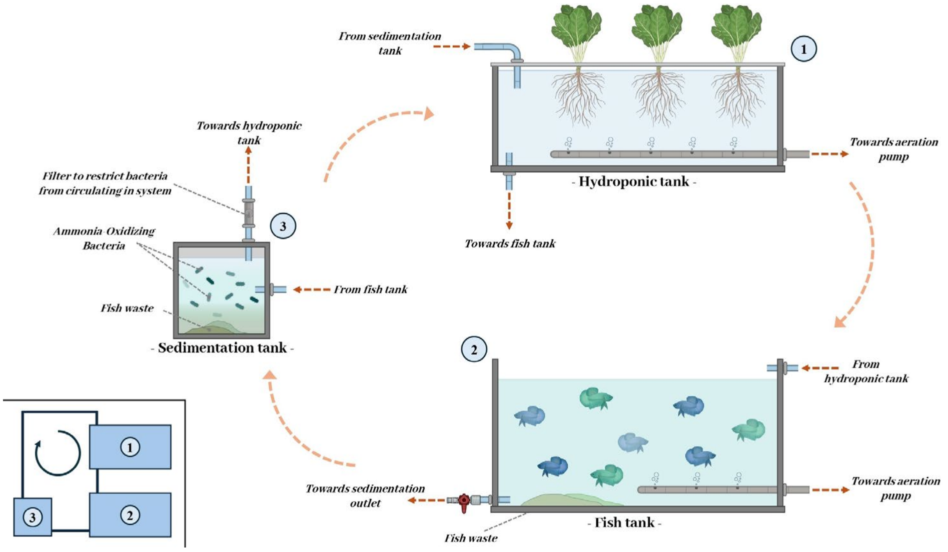

Figure 1. Schematic of Conventional Aquaponics Showing Fish, Biofiltration, and Hydroponic Plant Beds. Numbered labels represent the primary modules: (1) Hydroponic unit, (2) Aquaculture unit, and (3) Sedimentation/Biofiltration unit. Orange dashed arrows indicate the direction of recirculating water flow between modules.

Integration with renewable energy, particularly solar photovoltaics, has been shown to reduce greenhouse gas emissions by up to 70% and decrease freshwater eutrophication potential by approximately 35% relative to grid-powered systems [47]. These reductions are strongly location-dependent and influenced by regional energy mixes and system load profiles. When benchmarked against high-input vertical farming or hydroponics dependent on synthetic nutrient solutions, aquaponics offers a more decentralized and resource-efficient alternative, but it remains constrained by biological coupling, nutrient imbalance, and residual waste generation.

3.2. Nutrient Management and Systemic Constraints in Aquaponics

Despite its advantages, aquaponics faces structural limitations related to nutrient availability, nutrient imbalances, and residual discharge. Fish effluent is typically rich in nitrogen but often insufficient in phosphorus, potassium, and calcium for fruiting crops [43,48]. Consequently, 10–20% of nutrients must still be externally supplemented to achieve optimal plant performance, particularly in species with high macronutrient demand [43]. This supplementation requirement challenges claims of full nutrient circularity and reveals a fundamental mismatch between fish-driven nutrient profiles and plant physiological needs.

Nutrient availability in aquaponics is influenced by fish species, feeding rates, biofilter performance, temperature, and microbial dynamics. Leafy greens tolerate these nutrient fluctuations reasonably well, but fruiting crops often exhibit deficiencies unless phosphorus and potassium are manually corrected [43,49]. Decoupled aquaponic systems have emerged to address this issue by allowing independent nutrient control for fish and plants; however, they require additional inputs and partially compromise the biological interdependence that defines coupled systems [50]. As a result, decoupling improves agronomic control but shifts aquaponics closer to hybrid hydroponic–RAS configurations rather than fully integrated ecosystems.

Residual discharge remains another operational challenge. Even Recirculating Aquaculture Systems (RAS) integrated within aquaponics require periodic water exchange and generate sludge containing significant nitrogen and phosphorus loads [45]. While nutrient retention in aquaponics exceeds conventional aquaculture, where nitrogen and phosphorus losses can reach 79% and 83%, respectively [23], nutrient capture efficiency declines with increasing system scale, hydraulic variability, and suboptimal management. Constructed wetlands can achieve >90% nitrogen removal [5], outperforming many practical aquaponic configurations and highlighting persistent gaps in nutrient containment.

Sludge management introduces further complexity. The composition and nutrient density of aquaponic sludge are highly variable, requiring monitoring and post-treatment before reuse. Repurposing sludge as fertilizer can reduce freshwater eutrophication by approximately 23% [45,51], yet irregular sludge generation and handling requirements impose additional operational burdens. Feed composition is also a limiting factor: protein-rich feeds result in nitrogen-heavy but phosphorus-poor effluents [43], necessitating continuous nutrient balancing. Transitioning to plant-based or more balanced diets can reduce nutrient skew but may compromise feed conversion ratios and fish growth performance.

Table 1 summarizes key differences in water-use efficiency, nutrient retention, land requirement, climate resilience, and greenhouse gas emissions across conventional agriculture, aquaponics, and microalgae-integrated systems.

Table 1. Comparative Performance of Conventional Agriculture, Aquaponics, and Microalgae-Integrated Systems.

Parameter	Traditional Agriculture	Aquaponics	Microalgae-Integrated Systems	Reference
Water-use efficiency	50–70% losses	95–99% recycling	Up to 99% recycling	[12,22,30]
Nutrient retention	<50% uptake; high runoff	Internal cycling	>90% N and P removal	[5,32]
Land requirement	High; limited in urban areas	Low; vertical use possible	Very low (<2.5 m^2/kg protein)	[19,27]
Climate resilience	Highly vulnerable	Controlled environment	Controlled environment	[22,29,30]
GHG emissions	High	Lower	Potentially carbon-negative	[28,30]

These comparisons underline that while aquaponics substantially outperforms traditional agriculture in water efficiency and nutrient reuse, it does not inherently achieve the high nutrient-capture efficiencies required for near-zero discharge systems.

3.3. Opportunities and Limitations of Microalgal Integration in Aquaponic Frameworks

Persistent nutrient inefficiencies, nutrient-profile imbalances, and discharge challenges in aquaponics have driven interest in microalgal integration as a complementary biological solution. Microalgae exhibit rapid growth kinetics and high nutrient assimilation efficiencies, often exceeding 90% nitrogen and phosphorus removal from aquaculture effluents under optimized laboratory conditions [52,53]. These values exceed typical plant-based nutrient recovery, which frequently stagnates at 60–70% due to crop saturation limits and harvest cycles [52].

However, most reported microalgal performance metrics originate from laboratory-scale photobioreactors or tightly controlled pilot studies. Translation to commercial systems requires the careful consideration of light availability, contamination risks, hydraulic residence times, and operational complexity. Failure to account for these factors can lead to overestimation of real-world nutrient removal efficiencies. Nevertheless, the compact footprint and high throughput of algal systems offer advantages over land-intensive treatment approaches such as constructed wetlands [54].

Microalgae also contribute to carbon capture, a function absent in conventional aquaponics. Species such as *Chlorella* sp. can fix CO_2 at rates up to 0.12–2.22 g L^{-1} day^{-1} [20,55], enhancing system sustainability while supporting oxygenation beneficial for biofilter performance. However, maximal fixation rates are achieved under optimized light and CO_2 delivery conditions, which may increase energy demand at scale.

A key advantage of microalgal integration lies in enabling broader resource valorization. Algal biomass produced from nutrient-rich effluent can serve as fish feed, organic fertilizer, bioplastic precursor, or a source of high-value compounds such as pigments and nutraceuticals [56,57]. Compared with composting or anaerobic digestion, algae offer faster growth rates and more diverse downstream applications [58]. Economic feasibility, however, remains highly sensitive to harvesting efficiency, biomass consistency, and market access for algal products.

From an environmental perspective, microalgae-integrated systems reduce nutrient leakage by continuously scavenging residual nitrogen and phosphorus from effluent streams that would otherwise be discharged [59]. This biological integration provides a more synergistic alternative to decoupled aquaponics, which often relies on external nutrient inputs and increased energy demand [44]. At the same time, algal reactors introduce additional engineering complexity related to light delivery, fouling control, and hydraulic management.

Overall, microalgae offer a critical functional bridge that can advance aquaponics toward deeper circularity by enhancing nutrient capture, enabling carbon mitigation, and generating valuable co-products. Nevertheless, widespread adoption requires rigorous evaluation of long-term stability, system integration costs, and performance under non-ideal operating conditions. Residual nutrient discharge from conventional aquaponics—particularly nitrogen and phosphorus escaping plant uptake—motivates the inclusion of a downstream microalgal module, as illustrated in the representative IAMS flow (Fish → Sedimentation → Plants → Algae → Fish) discussed in Section 4.1. This tertiary polishing step enhances nutrient recovery and stabilizes water chemistry.

4. Microalgae: Versatile Solution for Sustainable Food and Water Systems

4.1. Concept and System Architecture

The IAMS described in this review represents an advanced closed-loop platform that integrates aquaculture, hydroponics, and microalgal photobioreactors (PBRs) into a unified circular resource-cycling architecture. Unlike conventional aquaponics—where nutrient recovery is largely constrained by plant uptake and residual nitrogen or phosphorus may accumulate—IAMS configurations reported in the literature introduce a tertiary microalgal treatment stage to enhance nutrient recovery, improve water quality, and support internal carbon cycling [44,52]. However, it is important to note that the performance metrics described in this section are largely derived from controlled environments and may not fully reflect the stochastic constraints of commercial-scale outdoor operation.

At the core of this architecture is a sequential water-flow pathway designed to enable progressive nutrient transformation and biological polishing across multiple trophic levels. As illustrated in Figure 2, effluent from the fish tanks—enriched with ammonium, organic solids, and dissolved metabolites—first passes through a sedimentation–filtration unit that removes suspended solids and supports the initiation of nitrification. This pre-treated stream then flows into the hydroponic plant beds, where crops assimilate the bulk of dissolved nitrates and micronutrients, forming the primary nutrient-removal stage within the system.

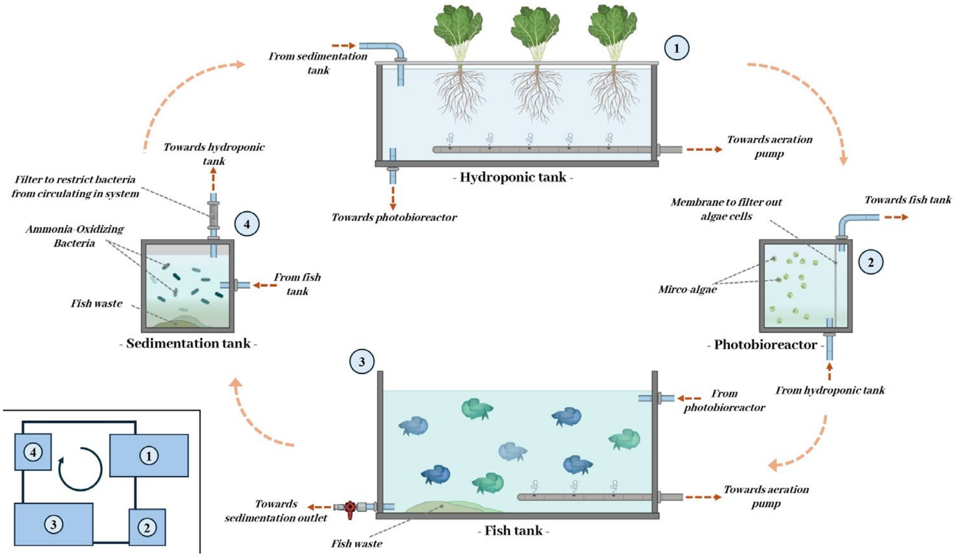

Figure 2. Conceptual Integrated Microalgal–Aquaponic System (IAMS) Architecture with Sedimentation, Hydroponics, and Tertiary Microalgal Polishing. Numbered labels indicate the system modules: (1) Hydroponic unit, (2) Aquaculture unit, (3) Sedimentation/Biofiltration unit, and (4) Tertiary microalgal photobioreactor (PBR). Orange dashed arrows denote the direction of the recirculating water flow, highlighting the sequential nutrient recovery pathway.

Following plant uptake, the partially polished effluent enters the microalgal PBR, which functions as a tertiary nutrient-polishing module. Within this unit, strains such as *Chlorella vulgaris* and *Scenedesmus obliquus* scavenge residual nitrogen and phosphorus while releasing oxygen through photosynthesis, further stabilizing water quality prior to recirculation [60–62]. This downstream placement of the algal module reflects design strategies reported for IAMS that prioritize plant productivity while using microalgae to capture nutrients that escape root-zone assimilation.

However, this sequential integration introduces fundamental hydraulic trade-offs. Fish culture units typically require short hydraulic retention times (HRTs) to prevent ammonia accumulation and maintain animal health, whereas microalgal reactors require longer HRTs to support biomass growth and effective nutrient assimilation. Operating these components within a single recirculating loop often necessitates compromise flow regimes that may reduce algal productivity or limit nutrient-removal efficiency under variable feeding or stocking conditions [52,60].

A frequently proposed mitigation strategy within IAMS architectures is the inclusion of a semi-permeable membrane interface associated with the algal PBR. This membrane permits the passage of nutrient-rich water while retaining algal cells, preventing their intrusion into downstream units and enabling controlled biomass harvesting [63,64]. Although membrane-assisted PBRs are not universally adopted, they represent an important design option discussed in the literature for improving hydraulic decoupling and operational stability. The membrane acts as a functional boundary, adapting principles from membrane bioreactor systems for algal–aquaponic integration.

After tertiary algal polishing, clarified water returns to the fish tanks, completing the recirculation loop. Under steady-state operation, such configurations can minimize external discharge, reduce nutrient accumulation, and lower freshwater demand relative to conventional aquaponics or recirculating aquaculture systems (RAS) [44,53].

Despite these advantages, achieving chemical compatibility across all biological compartments remains challenging. Fully IAMS typically operate near neutral pH (≈7.0–7.5) to balance fish health and nitrify bacterial activity. This range is suboptimal for micronutrient availability to plants and for many high-productivity microalgal strains that perform best at higher pH values. As a result, tightly coupled systems often impose compromised operating conditions that suppress yields across multiple trophic levels [44,60,62].

Microalgal integration also modifies dissolved oxygen dynamics. While photosynthetic oxygen production can reduce reliance on mechanical aeration during daylight hours, diel oxygen fluctuations remain a concern. Algae consume oxygen during dark respiration, potentially inducing nocturnal hypoxia in fish tanks if supplemental aeration or buffering capacity is insufficient [52,61]. Concurrent CO_2 uptake during photoperiods can elevate pH, further complicating system stability within fully integrated loops.

Collectively, these findings indicate that IAMS architectures establish a three-tier circular bioprocess capable of enhancing nutrient recovery and water purification. However, system performance is governed not solely by the efficiency of individual components, but by their hydraulic, chemical, and biological compatibility at the system level. Successful implementation therefore depends on the careful control of flow rates, pH buffering, oxygen management, and light availability, underscoring the importance of integrated design rather than modular optimization alone [65,66].

4.2. Microalgal Species Selection

Species selection is a cornerstone of IAMS design because it dictates nutrient-removal performance, biomass productivity, and downstream market value. Unlike conventional aquaponics—where plants provide the primary nutrient sink—IAMS assign a tertiary polishing role to microalgae, which must simultaneously deliver oxygenation, carbon capture, and vaporizable biomass. Accordingly, candidate strains are evaluated on three intersecting criteria: (1) balanced nitrogen and phosphorus assimilation, (2) tolerance to the variable physico-chemical conditions typical of recirculating water loops, and (3) capacity to accumulate protein, lipids, or specialty metabolites with commercial relevance [61,67–70]. Candidate microalgal strains are positioned in the tertiary polishing module of IAMS (Figure 2), downstream of plant uptake, to maximize residual nutrient assimilation. Because species performance is evaluated within a downstream polishing context, strain robustness to fluctuating nutrient loads and hydraulic residence times becomes more critical than peak laboratory productivity.

A consolidated categorization is presented in Tables 2 and 3, which distinguishes between species suitable for coupled freshwater integration and those requiring strict hydraulic decoupling due to salinity or pH constraints.

Table 2. Freshwater Microalgal Species with Validated Scales, Biochemical Value, and PBR–IAMS Assessment.

Species	Validated Scale	Key Biochemical Value	PBR–IAMS Strengths	IAMS Constraints & Trade-Offs	References
Tetradesmus obliquus	Lab	Balanced nutrients	Stable growth under variable nutrient loads.	Moderate lipid content limits high-value extraction; limited commercial data.	[69]
Chlorella sorokiniana	Lab	Protein > 50%	High-temperature tolerance.	Dense cultures suffer severe light limitation (self-shading) in deep PBRs.	[70]

Table 2. *Cont.*

Species	Validated Scale	Key Biochemical Value	PBR–IAMS Strengths	IAMS Constraints & Trade-Offs	References
Spirulina (Arthrospira) platensis	Commercial	Protein 60–70%	High protein yield; digestible biomass.	High pH requirement (>9.0) chemically incompatible with tilapia/lettuce (pH ≈ 7.0) unless fully decoupled.	[70,71]
Euglena gracilis	Lab	Paramylon	Metabolic flexibility (mixotrophic).	Sensitive to shear stress from pumping; requires gentle airlift mixing.	[71]
Botryococcus braunii	Lab	Hydrocarbons	Unique lipid composition for biofuel production.	Extremely slow growth; poor volumetric productivity makes it unviable for rapid nutrient polishing.	[71]
Chlorella vulgaris	Commercial	Protein 45–55%	High N/P uptake; broad pH tolerance (6.5–8.5).	Small cell size (<5 µm) creates high harvesting energy costs; prone to grazing in non-sterile effluent.	[72,73]
Haematococcus pluvialis	Lab/Pilot	Astaxanthin	High-value nutraceutical product.	Requires nutrient stress (starvation) to produce pigment, contradicting continuous nutrient removal.	[73]
Scenedesmus obliquus	Pilot	Protein 50–58%, Lipids	Strong wastewater adaptability; robust growth.	Rigid cell wall requires expensive pre-treatment for digestibility; adhesive wall promotes biofilm fouling.	[74]

Table 3. Major Marine Microalgal Species with Validated Scales, Key Biochemical Values, and Barriers to Integration with Freshwater IAMS.

Species	Validated Scale	Key Biochemical Value	Primary Barrier to Integration with Freshwater IAMS	References
Nannochloropsis sp.	Commercial	EPA-rich lipids	Salinity Mismatch: Requires brackish/seawater, lethal to standard hydroponic crops (e.g., lettuce, tomato).	[71,74]
Dunaliella salina	Commercial	β-carotene	Hypersaline Requirement: Obligate halophile; cannot grow in freshwater fish effluent.	[70]
Tetraselmis suecica	Lab	Carbohydrates	Salinity Dependence: Marine strain; restricted to mariculture-based aquaponics (e.g., seabass, samphire).	[72]
Phaeodactylum tricornutum	Pilot	EPA	Silica Requirement: Diatom species requiring silicate dosing, increasing chemical complexity.	[73]
Isochrysis galbana	Lab	DHA	Environmental Sensitivity: Requires strict temperature and salinity control; low contamination tolerance.	[72]
Chaetoceros muelleri	Lab	Protein 40–50%	Silica & Salinity: Marine diatom; incompatible with freshwater loops.	[72]

Chlorella vulgaris is the most frequently deployed strain and remains the benchmark for nutrient remediation in freshwater loops. In controlled laboratory settings under standard aquaponic effluent loads, it routinely attains 95–98% nitrogen removal and >92% phosphorus removal [75], exceeding the 55–70% uptake observed in hydroponic lettuce [76]. Its broad pH tolerance (6.5–8.5) affords operational resilience in systems subject to diel CO_2 fluctuations, a stability margin that narrower-range species such as *Scenedesmus obliquus* (optimal 6.0–8.0) cannot consistently maintain [76–78].

However, the dominance of *C. vulgaris* in laboratory and pilot studies does not guarantee monoculture stability under non-sterile aquaponic conditions. In open or semi-open recirculating loops, fast-growing indigenous microalgae, cyanobacteria, or microbial grazers (e.g., rotifers and protozoa) frequently outcompete inoculated strains, leading to "culture drift" and loss of the intended production organism [69,75]. Such competitive displacement is rarely reported in short-term trials but represents a major constraint during long-term operation.

Where nutritional enrichment is paramount, *Spirulina (Arthrospira) platensis* provides a compelling alternative. Although its phosphorus capture is modestly lower (85–90%) [79], its protein content reaches 65–70% of dry mass—surpassing *C. vulgaris* (45–55%) [80]. However, *Spirulina* obligately requires alkaline conditions ($pH > 9.0$) to maintain culture dominance, creating a chemical incompatibility with neutrophilic fish (pH 7.0–7.5) and hydroponic crops (pH 5.5–6.5). Consequently, *Spirulina* integration typically necessitates hydraulic decoupling or specialized alkaline-tolerant fish species, rather than direct insertion into standard aquaponic loops [70,81–83].

Systems targeting biofuel co-products often prioritize lipid accumulation, a niche where *Scenedesmus obliquus* excels [84]. Under nitrogen-limited regimes, it reallocates carbon into neutral lipids more efficiently than *Spirulina*. However, species such as *Scenedesmus* possess adhesive cell-wall structures that can promote biofilm formation and microbial attachment. In tightly coupled IAMS loops, this characteristic may facilitate the persistence of opportunistic bacteria, creating biosecurity risks if hydraulic separation barriers are insufficient [69,84].

In contrast to these freshwater candidates, marine species such as *Nannochloropsis* sp. and *Dunaliella salina* present fundamental integration barriers for standard IAMS. While *Nannochloropsis* offers high lipid productivity and *Dunaliella* is valued for β-carotene accumulation, both require saline or hypersaline conditions lethal to freshwater fish (e.g., tilapia, carp) and standard hydroponic crops (e.g., lettuce, tomato) [85–88]. Consequently, these species are restricted to specialized saline aquaponic configurations (e.g., seabass/samphire systems) or strictly decoupled side-stream processes, rather than integrated circular loops.

Suitability for PBR-IAMS reflects reported nutrient uptake performance, controllability under closed photobioreactor conditions, and compatibility with freshwater or low-salinity aquaponic environments, rather than intrinsic nutritional value alone. Finally, operational resilience under fluctuating field conditions is essential for decentralized deployments. Both *C. vulgaris* and *Tetradesmus obliquus* (syn. *Scenedesmus*) maintain relatively stable performance across variable light, temperature, and nutrient loads, making them reliable workhorse species in low-infrastructure settings [69]. In contrast, taxa such as *D. salina* and *Nannochloropsis* sp. demand tighter salinity, irradiance, and contamination control, restricting their viability in dynamic or resource-constrained environments. These comparative insights reinforce the need for species selection strategies that balance nutrient-removal goals, biosecurity, biomass consistency, and local environmental realities.

4.3. Photobioreactor (PBR) Designs and Integration Approaches

Photobioreactors (PBRs) form the functional backbone of tertiary nutrient recovery and biomass generation within Integrated Microalgal–Aquaponic Systems (IAMS). Unlike traditional aquaponic systems that rely primarily on plant-root zones for nutrient removal, PBRs provide a biologically driven polishing stage capable of removing residual nitrogen, phosphorus, and dissolved organics with high precision and efficiency [89,90]. Their enclosed and modular nature enables superior control over hydrodynamics, gas exchange, and illumination, supporting dense microalgal cultivation with nutrient-removal efficiencies often exceeding 90% under optimized laboratory conditions [65]. Within the staged treatment logic of IAMS, PBR performance cannot be assessed in isolation, as hydraulic and gas-exchange conditions are constrained by upstream aquaculture and downstream plant requirements.

PBR configurations vary widely in geometry, mixing strategies, and optical properties. Open systems such as raceway ponds remain the most commonly used configuration for commercial biomass production due to low capital costs, simplicity, and large surface-area-to-volume ratios [70,72]. However, their limitations are substantial: high evaporative losses, low CO_2 mass transfer efficiency due to shallow depths, susceptibility to contamination, and poor control of temperature and irradiance [70,91]. Although open ponds account for approximately 98% of global algal biomass production, their areal productivity ($\approx$15–20 t ha^{-1} yr^{-1}) remains significantly lower than that of closed PBR systems [91,92].

Closed PBRs offer controlled environments, high biomass densities, and reduced contamination risk. Common variants include flat-panel, tubular, helical, vertical column, airlift, and membrane-based PBRs [71,74]. Flat-panel reactors provide short optical paths (1–7 cm) and surface-to-volume ratios between 20 and 80 m^2 m^{-3}, enabling productivities up to 5 g L^{-1} d^{-1} under optimized conditions [71]. Tubular reactors—horizontal or helical—achieve high radiation utilization but face challenges related to oxygen accumulation and thermal regulation due to enclosed geometry [74,91]. Airlift and bubble-column designs provide effective mixing with low shear stress, making them suitable for shear-sensitive species such as Chlorella [71,73]. Membrane-based and plastic-bag PBRs expand the design space by offering sterility and low cost, albeit at the expense of mechanical durability and long-term operational robustness [74,91].

Nevertheless, high-surface-area PBR designs, particularly flat-panel and tubular reactors—are inherently prone to biofouling when operated with organic-rich aquaponic effluents. Rapid biofilm formation on illuminated surfaces reduces light penetration, accelerates photon attenuation, and necessitates frequent mechanical or chemical cleaning. These maintenance demands are rarely reflected in laboratory-scale productivity values and can significantly increase downtime and operational labor at scale [74,91,92].

Hybrid configurations seek to combine the economic advantages of open systems with the productivity of closed designs. Thin-layer cascade (TLC) PBRs maintain culture depths of 3–6 cm through baffle-controlled flow, improving light penetration while limiting contamination via semi-enclosed covers [70]. Computational fluid dynamics analyses demonstrate that incorporating mixing rods and raised inlet tubes reduces dead zones and sedimentation risks by improving velocity uniformity [70]. Other hybrid approaches integrate enclosed inoculum PBRs with open raceway ponds to maintain high-density seed cultures ($\approx$2.0 g L^{-1}) while lowering overall production costs [93]. Semi-closed polyethylene tubular hybrids have demonstrated turbulent flow regimes ($Re \approx$ 17,500–23,700), approaching plug-flow behavior with minimal axial dispersion [73].

Advanced reactor geometries have further improved mass transfer and light utilization. Tangent double-tube PBRs (TDTPs) generate internal vortices that enhance bubble breakup and mixing, achieving biomass yields of 2.81 g L^{-1}, approximately 124% higher than conventional single-tube systems—while reducing shear stress by 39% [94]. Concave spiral ribbed tubular designs increase light–dark cycling frequencies (up to 2.28 Hz) and gas holdup, improving productivity under light-limited conditions [95]. Sponge-inserted tubular PBRs function as static mixers and light diffusers, enhancing radial mixing at low flow rates [96]. Cyclic-flow PBRs equipped with buoyant pipe pigs provide automated biofilm removal, addressing a persistent operational challenge in tubular reactors [97].

Despite these innovations, oxygen inhibition remains a critical constraint in enclosed tubular and flat-panel PBRs. High photosynthetic oxygen evolution can elevate dissolved oxygen concentrations beyond algal tolerance thresholds, leading to photoinhibition and reduced growth unless degassing columns or stripping units are incorporated. These auxiliary systems increase both capital expenditure and energy demand, complicating claims of net efficiency improvements in IAMS integration [74,91,94].

Material selection further influences PBR performance and integration feasibility. While borosilicate glass offers excellent optical clarity and chemical resistance, lightweight polymers such as acrylic and polycarbonate reduce structural mass by over 60% and enable customizable geometries that optimize the optical path length [98,99]. Vertical stacked polymer modules are particularly attractive for urban or rooftop IAMS installations where spatial footprint and load-bearing capacity are constrained.

Illumination strategy is a dominant driver of PBR productivity. Red–blue LED systems achieve photosynthetic conversion efficiencies up to 22%, supporting biomass productivities of $\approx$40 g m^{-2} d^{-1} compared with 25–28 g m^{-2} d^{-1} under fluorescent lighting [100,101]. Flat-panel and airlift reactors equipped with LED arrays demonstrate strong nutrient-removal performance even under intermittent lighting regimes, improving energy efficiency in IAMS contexts [102]. However, pilot-scale flat-panel systems frequently exhibit productivity declines as reactor height increases and thermal gradients intensify, although optimized aeration and heat dissipation can partially restore laboratory-scale performance [103,104].

Scaling remains constrained by optical limitations. While thin-layer PBRs ($\leq$10 cm) maximize light availability, scaling these systems inevitably reduces surface-to-volume ratios, intensifying self-shading and sharply reducing volumetric productivity. This trade-off between footprint efficiency and photon utilization represents a fundamental barrier to translating laboratory performance to commercial-scale IAMS installations [71,91,103].

To synthesize reactor geometries, operational principles, performance metrics, and integration suitability, Table 4 presents a consolidated comparison of major PBR configurations relevant to IAMS deployment.

Table 4. Photobioreactor (PBR) Configurations, Performance Features, and Integration Considerations for IAMS.

Reactor Type	**Core Design Principle**	**Performance Strengths**	**IAMS-Relevant Limitations/Trade-Offs**	**Reference**
Open ponds/raceways	Shallow depth (30–50 cm); natural illumination	Low capital cost; simple operation; scalable footprint	High evaporation, contamination risk, poor CO_2 transfer, and unstable water quality make direct coupling with fish loops unsuitable without decoupling	[70]
Thin-Layer Cascade (TLC) semi-closed	Baffles, shallow flow (3–6 cm), partial enclosure	Enhanced light penetration; reduced evaporation; improved productivity vs. open ponds	CFD-identified dead zones if poorly designed; still sensitive to contamination under open exposure	[70]
Low-cost bottle PBR	Small-volume PET reactors with air stones	Ultra-low cost; accessible for pilot or rural IAMS	pH rise, mineral precipitation, and limited scalability restrict long-term operation	[104]
Horizontal tubular hybrid	LDPE tubes with paddle-driven flow	Near plug-flow behavior; scalable; improved light use	Biofouling and dead zones in associated open tanks increase maintenance burden	[73]
Raceway + thin-layer systems	Combined open systems overview	TLC enables higher areal productivity	Open raceways remain productivity-limited and unsuitable for nutrient polishing alone	[71]
Flat-panel/column/tubular PBRs	Short light path; high surface-to-volume ratio	High biomass density; nutrient removal > 90%	Temperature control and capital cost increase with scale	[71]
Tubular, helical, VAP systems	Tilted tubes (6–12°) for gas transfer	Improved CO_2 dissolution and mixing	Oxygen accumulation and fouling require active control	[74]

Table 4. *Cont.*

Reactor Type	**Core Design Principle**	**Performance Strengths**	**IAMS-Relevant Limitations/Trade-Offs**	**Reference**
Hybrid closed–open systems	Closed inoculum PBR feeding open ponds	High inoculum density; reduced contamination risk	Downstream open ponds remain contamination-prone	[93]
Tangent Double-Tube PBR (TDTP)	Dual-tube vortex-inducing geometry	124% productivity increase; reduced shear stress	Structural complexity and fabrication cost limit adoption	[94]
Cyclic-flow PBR	Automated pigging for biofilm removal	Sustained light path; mitigates fouling	Mechanical complexity increases maintenance demand	[97]
LED-driven PBRs	Artificial spectral control	Highly controlled growth; very high productivity	High CAPEX and energy demand restrict food-focused IAMS unless high-value products are targeted	[92]
Sponge-insert tubular PBR	Static mixers for light dilution	Improved radial mixing and photon distribution	Cleaning difficulty and fouling risk	[96]
Ribbed tubular PBR	Spiral ribs enhance light–dark cycling	Improved photosynthetic efficiency under dense cultures	Higher pumping energy requirements	[95]
Comparative synthesis (Open vs. Closed)	Energy vs. productivity trade-off	Closed PBRs enable IAMS integration	Closed systems trade energy demand for stability and control	[72,91]

Overall, the diversity of PBR designs provides flexibility for IAMS integration, enabling reactor selection tailored to nutrient loading, spatial constraints, and operational objectives. Modular flat-panel reactors suit urban nutrient-polishing applications, while tubular and hybrid PBRs offer scalable pathways for high-throughput biomass generation. Advanced geometries mitigate historic challenges in mixing and light distribution, yet their successful deployment remains contingent on effective fouling control, oxygen management, and energy optimization, reinforcing that PBR performance in IAMS is governed as much by system-level constraints as by reactor design innovation.

4.4. Cultivation Strategies for Optimized System Performance

Optimizing microalgal performance within IAMS requires the precise control of illumination, hydrodynamics, carbon supply, temperature, pH, and nutrient loading, as microalgae respond more sensitively to physicochemical fluctuations than hydroponic crops or aquaponic plants [65,66]. Appropriate cultivation management ensures stable nutrient removal, consistent biomass productivity, and resilience under fluctuating fish-driven nutrient pulses. A synthesis of key engineering and biological optimization pathways is presented in Table 5, summarizing design parameters, dominant mechanisms, and implications for nutrient recovery and cultivation stability.

Table 5. Key Optimization Strategies for Microalgal Cultivation and Nutrient Recovery within IAMS.

Optimization Strategy	**Design/ Operational Parameter**	**Scientific Mechanism**	**Implications for IAMS (Cultivation + Nutrient Recovery)**	**Scalability/Operational Trade-Offs**	**Reference**
Light path optimization	Culture depth 3–6 cm	Reduces self-shading; improves photon penetration	Stable biomass yield and consistent N/P removal	Requires precise hydraulic control at scale	[70]
Light spectral tuning	Red–blue LEDs (450–470/620–680 nm)	Matches chlorophyll absorption peaks	Higher nutrient uptake kinetics; lower energy per biomass	Increased CAPEX and system complexity	[101,102]
Light/dark cycle control	Engineered vortices; ribbed flow (2–3 Hz)	Prevents photoinhibition	Sustains productivity under high density	Hydraulic design constraints increase cost	[94,95]
Solar pattern optimization	Diurnal light modulation	Aligns photosynthesis with natural rhythms	Reduces pH drift and carbon imbalance	Less effective in high-latitude or indoor systems	[104]
Advanced mixing engineering	Sponge inserts; deflectors; marine impellers	Improves radial mixing	Enhanced nutrient uptake with low shear	Cleaning and fouling management required	[96,105,106]
Hydrodynamic control	Paddle speed 0–12 rpm	Prevents sedimentation	Uniform nutrient exposure	Energy demand rises with flow velocity	[73]
Aeration optimization	0.2–0.3 vvm CO_2–air	Stabilizes pH; improves carbon availability	Boosts N/P assimilation by 20–30%	CO_2 supply logistics needed	[103,107]

Table 5. *Cont.*

Optimization Strategy	Design/ Operational Parameter	Scientific Mechanism	Implications for IAMS (Cultivation + Nutrient Recovery)	Scalability/Operational Trade-Offs	Reference
CO_2 concentration tuning	1–5% CO_2 or flue gas	Reduces photorespiration	Enables high-rate nutrient removal	Flue gas impurities require pretreatment	[71,72,97]
Intermittent aeration	1 h ON/3 h OFF	Limits pH overshoot	Stabilizes algal–plant competition	Requires automated control systems	[94,104]
Nutrient loading control	Regulated daily feed	Maintains balanced N:P ratio	Avoids shock loading	Sensitive to fish biomass fluctuations	[73]
Two-stage cultivation	Growth → nutrient stress	Induces lipid/TAG synthesis	Enables biofuel precursor recovery	Reduces continuous nutrient removal efficiency	[71,92]
Mixotrophic supply	Organic-carbon wastewater	Dual phototrophic + heterotrophic growth	Faster ammonium removal	Increased bacterial competition and oxygen demand	[73,93]
Wastewater integration	Municipal/agro-wastewater	Provides N, P, organic C	Reduces fertilizer inputs	Pathogen and regulatory concerns	[72,93]
Biofilm management	Pigging; turbulence; brushing	Restores light path	Maintains long-term performance	Mechanical wear and downtime	[73,97]
Temperature regulation	Waste-heat reuse; greenhouse	Maintains metabolic optimum	Extends annual cultivation window	Climate-dependent feasibility	[91,97]
Cultivation mode selection	Continuous vs. batch	Controls nutrient availability	Continuous mode aligns with fish nutrient flux	Lower flexibility for product switching	[73]
Co-culture strategies	Algae–algae/algae–bacteria	Metabolic complementarity	Improved N/P removal and biomass quality	Community stability difficult to maintain	[72,92,104]
Membrane-integrated PBRs	Air-scouring; electrocoagulation	Solid and nutrient polishing	Produces cleaner recirculation water	Membrane fouling and replacement cost	[73,74]
Biorefinery integration	Biomass valorization	Converts nutrients into products	Enhances system economics	Market dependence and processing energy	[108,109]

Light management remains a principal determinant of microalgal metabolism. Red–blue LED systems tuned to 450–470 nm and 620–680 nm align with chlorophyll absorption peaks, increasing photosynthetic efficiency and improving nutrient assimilation by up to 22% relative to fluorescent lighting [101,102]. Thin-layer cascade reactors (3–6 cm depth) reduce self-shading and enhance light penetration, achieving higher biomass yields and more stable N/P removal under variable loading [70]. In tubular and hybrid PBRs, engineered light–dark cycling through induced vortices or spiral ribs improves photosynthetic conversion efficiency under dense culture conditions [94,95]. Synchronizing illumination with solar diurnal patterns—low in the morning, high at midday, and low in the afternoon—minimizes pH excursions while supporting natural carbon fixation rhythms [104]. Advanced internal mixing structures such as optical deflectors, sponge inserts, and marine impellers further reduce dark zones and improve photon distribution while avoiding shear damage [96,105,106].

However, artificial illumination represents a substantial energetic burden in IAMS. Continuous LED operation, particularly in enclosed or indoor PBR configurations, can dominate system electricity demand and, in some cases, exceed the calorific energy content of the harvested biomass. This “energy parasite” effect threatens net-energy positivity unless lighting is strategically limited to critical growth phases or supplemented by solar-driven or daylight-guided systems [71,102,103].

Hydrodynamic optimization ensures uniform residence time and stable nutrient availability across cultivation systems. Adjusting flow velocities and paddle-wheel speeds (0–12 rpm) prevents sedimentation and minimizes dead zones in raceway ponds [73]. In advanced configurations, vortex-enhanced reactors such as Tangent Double-Tube PBRs improve gas–liquid mass transfer while reducing shear stress, increasing biomass yields by up to 124% compared with conventional tubular systems [94]. Automated cyclic-flow pigging systems mitigate internal fouling and maintain optical clarity, preserving reactor performance over extended operational periods [97].

Despite these gains, active mixing relies on continuous pumping or aeration, introducing additional energy penalties. At higher flow regimes, marginal productivity gains often plateau while power demand rises non-linearly, reducing overall system efficiency—particularly in small-scale or decentralized IAMS deployments [73,94].

Carbon availability constitutes another major bottleneck in IAMS, as fish respiration and microbial nitrification continuously deplete dissolved CO_2. Supplementing aeration streams with 0.2–0.3 vvm CO_2–air mixtures stabilizes pH, doubles biomass productivity, and enhances nitrogen and phosphorus assimilation by 20–30% [61,103,107]. Incorporating 1–5% CO_2 or flue gas further enhances carbon fixation while suppressing photorespiration [71,72,97]. Intermittent aeration strategies (e.g., 1 h ON/3 h OFF) prevent excessive pH elevation under high irradiance, balancing algal productivity with downstream plant nutrient uptake [94,104].

Temperature stability strongly influences metabolic performance and is best maintained using semi-closed reactor covers, greenhouse enclosures, or industrial waste-heat integration. These strategies reduce evaporative losses, improve thermal consistency, and extend annual cultivation windows from approximately 240 to over 300 days [70,97,102]. Warm-water aquaculture species such as tilapia naturally align with optimal microalgal growth temperatures (25–30 °C), reducing the need for independent climate control compared with conventional hydroponics.

Nutrient-specific optimization further enhances system performance. Controlled wastewater feed rates regulate N:P ratios and mitigate shock loading, improving nutrient-removal efficiency and culture stability [73]. Two-stage cultivation—initial growth under nutrient sufficiency followed by stress induction—promotes lipid or triacylglycerol accumulation without compromising primary nutrient uptake [71,92]. Mixotrophic and wastewater-based cultivation modes accelerate nutrient removal by enabling simultaneous phototrophic and heterotrophic carbon utilization, particularly in ammonium-rich effluents [73,93]. Co-culturing microalgae with beneficial bacteria enhances organic matter degradation, nitrogen turnover, and lipid biosynthesis [72,92]. Membrane-integrated PBRs employing air-scouring or electrocoagulation further reduce suspended solids, producing clarified effluent suitable for recirculation within IAMS [73,74].

Nevertheless, biomass harvesting remains a major operational bottleneck. Microalgal cultures typically contain less than 0.1% solids, necessitating energy-intensive separation techniques such as centrifugation or chemical flocculation. This “harvesting penalty” can account for 20–30% of total operating costs, representing a structural disadvantage relative to hydroponic systems where biomass removal is inherently passive [71,92,103].

System stability is further constrained by control sensitivity. Unlike passive biofilters, microalgal cultures can collapse within hours following abrupt shifts in pH, temperature, or nutrient availability. Maintaining operational resilience therefore requires continuous sensor-based monitoring and automated feedback control, increasing capital complexity and limiting accessibility for low-resource or decentralized installations [66,73,104].

Collectively, these cultivation strategies demonstrate that while coordinated control of illumination, hydrodynamics, carbon delivery, nutrient regimes, and operational modes can transform microalgae into a powerful stabilizing component of IAMS, their effectiveness is tightly coupled to energy efficiency, harvesting feasibility, and control robustness. Successful implementation thus depends not only on biological optimization but also on system-level trade-offs that balance productivity gains against operational cost, energy input, and technological complexity within circular food–water–energy frameworks.

4.5. Nutrient Recycling and Water Resource Recovery

A major innovation of IAMS is their ability to recapture and revalorize fish effluents, plant residues, and microbial metabolites through a closed-loop framework. Unlike conventional aquaponics—where nutrient cycling ends at the hydroponic bed and substantial nitrogen and phosphorus remain unutilized—microalgal photobioreactors (PBRs) provide a tertiary polishing step capable of removing >95% of dissolved nutrients while generating valuable biomass [69,89]. Table 5 synthesizes the optimization parameters that enhance these nutrient recovery pathways.

Microalgae assimilate ammonia, nitrate, and phosphate into cellular proteins, lipids, and pigments, converting waste nutrients into marketable bioproducts. Thin-layer cascades (3–6 cm) enhance mass transfer and photon absorption, strengthening N/P uptake efficiency [70]. HABR–PBR coupled systems have reduced phosphate concentrations from 29.3 ± 18.0 mg L^{-1} to 0.7 ± 0.2 mg L^{-1}, demonstrating strong polishing capacity even under variable wastewater loading [104]. Membrane-integrated PBRs further remove suspended solids and enable water recovery suitable for continued recirculation [73,74]. Continuous cultivation stabilizes nutrient profiles by capturing peaks in fish-driven nitrogen loads more effectively than plant-driven cycles [69].

However, nutrient removal in IAMS is inherently selective. While microalgae efficiently assimilate nitrogen and phosphorus, they do not remove conservative ions such as sodium or chloride. In fully closed or semi-closed loops, evaporative losses and mineral inputs from fish feed progressively concentrate these salts, leading to salinity accumulation that can impair freshwater fish health and suppress nutrient uptake in sensitive crops such as lettuce. Periodic water exchange or ion-specific removal processes therefore remain necessary, challenging claims of fully closed-loop operation [70,91].

Water conservation represents another central efficiency gain. Semi-closed PBRs reduce evaporative losses compared with open ponds while enabling the reuse of harvested water within the cultivation loop [70,91]. Fully IAMS reportedly consume <0.1 m^3 water kg^{-1} of fish produced—substantially lower than recirculating aquaculture systems (RAS) or standalone hydroponics [89]. Treated algal effluent is often suitable for reuse in aquaponic recirculation, irrigation, or non-potable municipal applications [104,108].

Nevertheless, "zero-discharge" operation introduces the risk of micropollutant accumulation. Trace contaminants originating from fish feed additives, veterinary pharmaceuticals, and metal impurities are not biologically degraded by microalgae and may concentrate within the recirculating loop over time. This raises bioaccumulation concerns for edible fish, crops, and algal biomass, particularly in long-term or high-density operations, necessitating periodic purge streams or advanced treatment barriers to maintain food safety [89,108].

Microalgal integration also enhances carbon recovery. Approximately 1.83 kg of CO_2 is biologically fixed per kg of algal biomass produced [91]. The use of flue gas as a carbon source further closes industrial carbon loops while boosting growth rates and nutrient assimilation efficiency [72,97]. Harvested algal biomass can be anaerobically digested to produce biogas, with the resulting digestate recycled as a nutrient-rich substrate within IAMS, reducing reliance on external fertilizers [92].

Organic matter removal is strengthened through algal–bacterial consortia that biodegrade dissolved organic carbon and promote synergistic nutrient turnover. Pretreatment systems such as hybrid anaerobic bioreactors (HABR) improve N:P ratios to approximately 3:1, generating feedstocks that enhance PBR stability and nutrient uptake [104]. Biofilm-based PBRs have demonstrated the effective removal of nitrogen, phosphorus, and organic carbon even in saline wastewater streams relevant to coastal agriculture [73].

Despite these circular pathways, IAMS are not truly zero-waste systems. Recalcitrant sludge composed of dead algal cells, uneaten feed, fish feces, and bacterial biomass contin-

https://doi.org/10.3390/phycology6010014

ues to accumulate and requires external handling through anaerobic digestion, composting, or off-site disposal. While this residual stream can be valorized for energy or fertilizer recovery, it represents an unavoidable mass balance loss that must be incorporated into realistic system design and life cycle assessments [92,104].

Importantly, captured nutrients are transformed into usable biomass rather than discharged waste. Algal biomass can replace 30–35% of commercial fishmeal without compromising aquaculture performance [61]. Additional valorization routes include slow-release fertilizers, bioplastics, pigments, and bioenergy carriers [108,109]. Co-digestion with sewage sludge further increases methane yields and improves overall system energy recovery [92].

Collectively, IAMS achieve high nutrient-retention rates (>85% nitrogen and >80% phosphorus over 30 days), substantially reduce discharge losses, and convert waste nutrients and atmospheric CO_2 into productive resources. However, long-term system sustainability depends on managing ion accumulation, trace contaminant build-up, and residual sludge generation—constraints that define the practical limits of circularity rather than undermining its core advantages.

5. Scaling-Up Challenges, Policy Considerations, and Future Research Directions

5.1. The Critical Gap Between Laboratory Potential and Field Reality

A critical interrogation of the literature reveals a sharp divergence between the reported removal efficiencies and operational reality. While removal rates exceeding 95% are frequently cited in microalgal studies [10,52], these values are predominantly derived from short-term, batch-mode laboratory trials conducted under sterile conditions with optimized illumination. In contrast, continuous-flow pilot systems operating under variable solar irradiance often exhibit significantly lower performance (40–60% removal) due to hydraulic short-circuiting, self-shading in dense cultures, and biological instability caused by invasive grazers [70,73]. Consequently, the high efficiencies reported in the technical sections of this review should be interpreted as theoretical maxima rather than reliable baselines for commercial-scale IAMS operation. The following sections evaluate the specific barriers—economic, technological, and regulatory—that currently prevent these laboratory achievements from translating into industrial success.

5.2. Economic Viability and Market Analysis

The long-term commercial viability of Integrated Microalgal–Aquaponic Systems (IAMS) depends heavily on the ability to balance relatively high upfront investment costs with long-term operational savings and multi-output revenue generation. While IAMS offer clear advantages in nutrient reuse, water conservation, and diversified product portfolios, their integration with photobioreactors (PBRs) introduces substantial capital expenditure (CAPEX), often 30–60% higher than conventional aquaponics due to the inclusion of CO_2 delivery systems, PBR modules, and advanced monitoring platforms [6,110]. This is consistent with economic assessments of standalone microalgal systems, where PBR infrastructure can represent up to 77% of total setup costs [111,112].

A major determinant of economic feasibility is the structural difference in CAPEX and OPEX across cultivation architectures. Evidence consistently shows that open systems (raceway ponds) have the lowest CAPEX and low OPEX but suffer from contamination risks, large land requirements, and low productivity [73]. Closed PBRs, in contrast, offer contamination control and higher product consistency but impose significantly higher investment burdens, especially in helical or flat-panel systems where installed capital costs may exceed USD 1.2 billion at commercial scales [113]. Plastic-bag PBRs remain the lowest-CAPEX PBR variant but require frequent replacement, increasing OPEX [73,113]. These comparative cost structures are summarized in Table 6, which contextualizes the economic positioning of IAMS relative to other microalgal production systems.

Operational expenditure (OPEX) is strongly influenced by energy demand for mixing, illumination, and temperature regulation. Artificial lighting and cooling represent major cost burdens in enclosed PBRs, with temperature control alone contributing energy ratios exceeding 70–260 in some modeling scenarios—rendering such systems economically "unrealistic" for low-value biofuel production [114]. Dewatering and harvesting constitute an additional bottleneck, sometimes accounting for 40–50% of total cultivation costs [115]. Integrating wastewater streams, as enabled in IAMS, reduces OPEX by replacing costly fine-chemical nutrient media with waste-derived nitrogen and phosphorus, thereby improving cost competitiveness [73,112].

Market performance depends on the multi-product revenue stream of IAMS. Unlike aquaponics—which yields only fish and vegetables—IAMS generate additional revenue from algal biomass, which can be valorized into biofertilizers, feed additives, pigments, polymers, nutraceuticals, or even biodiesel. Techno-economic analyses show that systems combining aquaculture, plant production, and algal biorefineries can generate annual profits exceeding USD 30 million when scaled to industrial capacities [111]. However, microalgal biofuel pathways alone remain economically challenging. Fuel-only HTL systems produce gasoline-equivalent fuels at USD 5.37–11.90 per gallon—far above market parity [116–118]. Economic resilience therefore depends on coupling bulk biomass utilization with high-value co-products such as astaxanthin or β-carotene, although market saturation and demand elasticity constrain large-scale expansion [119].

Cultivation strategy plays a decisive role in economic feasibility. Semi-continuous systems consistently outperform batch systems, achieving Minimum Biomass Selling Prices (MBSP) of USD 1035–1200 per ton, compared to USD 1380–2040 in batch configurations [120,121]. The key differentiator is seed-train cost: batch systems require extensive inoculum production, often in costly PBRs, making them economically unfavorable. Semi-continuous operation aligns well with IAMS, where continuous nutrient flows from fish and plants support stable algal growth cycles.

Financial barriers persist, particularly regarding investor uncertainty, limited techno-economic data from full-scale installations, and the absence of supportive financing mechanisms. Conventional agriculture benefits from well-established subsidy regimes, whereas IAMS lack comparable recognition within green finance frameworks. Studies highlight the necessity of government incentives such as carbon credits, wastewater reuse subsidies, preferential loans, and tax benefits to ensure competitive deployment [115,122]. Carbon pricing, in particular, can significantly reduce the net production costs by providing credits for CO_2 capture associated with algal growth [117].

Despite these constraints, IAMS hold a strong competitive advantage in regions with high fertilizer costs, water scarcity, or limited arable land. Their internal nutrient recycling buffers producers from volatile global fertilizer markets and reduces reliance on external inputs [6]. Moreover, integrating algal PBRs with wastewater treatment yields dual benefits: reduced treatment costs and additional biomass revenue [112,116]. As summarized in Table 6, the economic performance of IAMS is maximized when modular PBR designs are combined with wastewater valorization and biorefinery-oriented product portfolios rather than fuel-only pathways.

Table 6. Comparative Analysis of Nutrient Removal Efficiencies, Biomass Productivity, and Co-Product Generation across IAMS Studies.

System Type	CAPEX Level	OPEX Profile	Economic Suitability/MBSP	References
Open Raceway Ponds	Very Low	Low	Lowest MBSP (~$494/ton); suitable for low-value bulk biomass and wastewater integration	[73,113,120]
Plastic-Bag PBRs	Low	Moderate (bag replacement)	MBSP ~$639/ton; ideal for moderate-value products; contamination control improved	[73,113]
Tubular PBRs (Horizontal/Helical)	Moderate–High	High (mixing/cooling)	MBSP ~$708–1737/ton; viable for mid-tier products; high energy demand	[113,115]
Flat-Panel/Vertical PBRs	High	Moderate–High	MBSP ~$1793/ton; suited for high-value products (pigments, nutraceuticals)	[73,113]
Semi-Continuous Operation in IAMS	Moderate	Low–Moderate	MBSP ~$1035–1200/ton; best alignment with nutrient flux from aquaponics	[120,121]

5.3. Technological Challenges in Scaling and Stability

Despite the strong sustainability potential of IAMS, their large-scale deployment remains constrained by tightly coupled technological, operational, and biological barriers. Compared with conventional aquaponics—where system control is limited to balancing fish and plants—IAMS introduce a third biological domain, microalgae, substantially increasing system sensitivity, control complexity, and failure pathways [6,110]. Scaling therefore requires synchronization across three subsystems with partially incompatible environmental optima.

A primary constraint arises from conflicting physicochemical requirements. Warm-water fish such as tilapia perform optimally at near-neutral pH (7.0–7.5), hydroponic crops favor mildly acidic conditions (5.5–6.5) for micronutrient availability, while several industrially relevant microalgae—including Spirulina—exhibit maximum productivity under alkaline conditions (pH 8.5–9.0). Operating IAMS under a single compromise, pH, inevitably suppresses at least one trophic component, forcing engineering trade-offs such as buffering, partial loop decoupling, or compartmentalization, each of which increases capital complexity and operational overhead.

Hydrodynamic stability and reactor scalability present additional bottlenecks. Open pond systems scale readily but remain vulnerable to predation, fungal contamination, and invasion by fast-growing native algal strains [72,93], as well as rainfall dilution and large land footprints [70]. Closed photobioreactors (PBRs) provide superior environmental control, yet experience oxygen accumulation, thermal stress, and non-uniform flow regimes during scale-up [71,74,102]. Tubular PBRs are particularly affected, with scale-induced vortex clustering, dead zones, and sedimentation occurring at local velocities below 0.1 m s^{-1}, resulting in biomass loss and cell mortality [73,105].

Computational fluid dynamics (CFD) analyses confirm that laboratory-scale mixing conditions cannot be linearly transferred to industrial dimensions due to mismatches in turbulence intensity, shear distribution, and light attenuation profiles [73,105]. Hybrid PBRs employing partial covers, ventilation tubes, or internal baffles reduce contamination and improve mixing efficiency, yet introduce mechanical complexity and elevated maintenance requirements [70]. As system scale increases, hydrodynamic optimization shifts from a design challenge to a continuous operational burden.

Biofouling remains one of the most persistent operational barriers to IAMS stability. Transparent PBR surfaces rapidly accumulate biofilms that reduce light transmittance by up to 40%, directly impairing photosynthetic performance [110]. Empirical studies indicate that typical operational shear stresses (0.3–1.0 Pa) are insufficient to remove mature biofilms, while detachment requires stresses exceeding 6 Pa—levels that risk damaging shear-sensitive microalgal cells [73]. Flat-panel and tubular reactors are particularly susceptible, necessitating mechanical cleaning strategies such as foam balls, scouring pads, or automated pigging systems [71,97]. Membrane-integrated PBRs face additional fouling resistance, elevating energy demand and cleaning frequency [74].

Process stability is further constrained by dissolved oxygen (DO) accumulation. In closed systems, DO concentrations frequently exceed 400% saturation, triggering photorespiration, oxidative stress, and growth inhibition [71,74]. Advanced reactor geometries such as tangent double-tube PBRs improve gas stripping and maintain near-ambient DO levels [94], but their cost and limited commercial availability restrict widespread adoption. Thermal control presents parallel challenges: greenhouse-based IAMS often exceed 35 °C during summer months, reducing productivity and increasing cooling-related energy consumption by up to 12% [102]. These effects are especially pronounced in tropical and arid climates.

Harvesting represents a dominant bottleneck in scaling IAMS. Microalgal cells are typically <10 μm in diameter, requiring energy-intensive separation methods including centrifugation, filtration, flocculation, or sedimentation [72,108]. While conical PBRs allow partial gravity settling [104] and emerging techniques such as magnetic nanoparticle harvesting show promise [92], industrial-scale harvesting remains capital- and energy-intensive. Rigid cell walls in species such as Scenedesmus further necessitate mechanical, thermal, or enzymatic pretreatment prior to downstream processing, increasing operational cost and system complexity [72].

Contamination risk persists throughout scaled operations, particularly when wastewater-derived effluents are employed. Pretreatment using hybrid anaerobic bioreactors (HABRs) can remove approximately 75% of total solids and 59% of fecal coliforms [104], yet open ponds and semi-open PBRs remain vulnerable to grazers, bacteria, fungi, and invasive algal taxa [74,93]. Mitigation strategies—including ultrasonication, extreme pH or salinity shifts, and foam flotation—reduce contamination pressure but introduce additional energy and chemical demands [74].

Energy demand constitutes a central scaling constraint. Sustained microalgal productivity requires continuous illumination, aeration, and hydraulic circulation. Producing 1 kg of algal biomass under artificial lighting consumes approximately 3–5 kWh—substantially higher than the energy intensity of hydroponic crop production or fish culture [6]. Structural enhancements such as static mixers or ribbed reactors improve light–dark cycling but simultaneously increase hydraulic resistance and pumping losses [95]. At scale, cumulative thermal, hydraulic, and electrical loads threaten net-energy positivity unless carefully optimized.

Finally, operational complexity and monitoring requirements limit adoption beyond research or high-tech commercial settings. Because fish, plants, and microalgae are dynamically interdependent, disturbances in light intensity, mixing rates, nutrient loading, or carbon supply can propagate rapidly across subsystems, leading to hypoxia, fish stress, or nutrient imbalance. Maintaining stability increasingly requires high-resolution sensors, IoT-enabled monitoring, predictive control algorithms, and digital twins, yet these tools remain costly and underutilized in low-resource contexts [6]. The reliance on skilled operators further restricts scalability relative to simpler aquaponic or hydroponic systems.

Collectively, these barriers indicate that while IAMS deliver exceptional nutrient recovery and circularity potential, their scalability depends on advances in reactor engineering, fouling mitigation, energy optimization, subsystem decoupling, and automated control. Addressing these challenges is essential to transition IAMS from experimental or pilot-scale demonstrations to robust, commercially viable production systems.

5.4. Regulatory and Policy Frameworks

Despite strong alignment with sustainability and circular-economy objectives, Integrated Microalgal–Aquaponic Systems (IAMS) face substantial regulatory and market-entry barriers arising from their multi-functional and cross-sectoral nature. Because IAMS simultaneously operate as aquaculture facilities, hydroponic farms, wastewater polishing units, and algal bioprocessing platforms, they do not conform to existing regulatory classifications, which are typically designed for linear, single-output agricultural systems. In contrast, conventional aquaponics and hydroponics benefit from clear legal recognition, standardized certification pathways, and streamlined permitting processes [6]. This structural mismatch places IAMS at a regulatory disadvantage, slowing commercialization despite superior environmental performance.

A major and frequently underappreciated regulatory bottleneck concerns microbial safety within recirculating loops. Fish-rearing units inherently contain fecal coliforms and opportunistic pathogens such as Escherichia coli, Salmonella, and Aeromonas species derived from fish excreta, uneaten feed, and biofilms in recirculating systems [123,124]. When microalgae are cultivated on aquaculture effluent—particularly in systems lacking complete sterilization or physical separation—there exists a risk of pathogen attachment or surface colonization of algal biomass. This raises food- and feed-safety concerns, rendering the biomass unsuitable for human consumption or direct aquafeed use without extensive downstream processing and microbial verification. This regulatory burden is largely absent in hydroponic systems, which rely on sterile or synthetic nutrient solutions and therefore avoid pathogen-transfer scrutiny.

Equally restrictive are concerns related to contaminant bioaccumulation. Microalgae are efficient bioaccumulators of trace metals (e.g., cadmium, lead, arsenic, mercury) and can assimilate residual antibiotics, antiparasitic agents, and disinfectants used in aquaculture operations [125–127]. When such biomass is recycled as fish feed, a closed contamination loop may emerge in which pollutants are repeatedly transferred between fish, effluent, and algae, intensifying concentrations over time. This recursive bioaccumulation risk fundamentally differentiates IAMS from hydroponics and vertical farming, where nutrient inputs are tightly controlled and contaminant exposure is minimal.

These safety concerns directly influence legal biomass classification. Regulatory bodies such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) commonly classify algae cultivated on substrates defined as “wastewater” or “waste-derived effluent” as non-food-grade, irrespective of subsequent treatment or purification [128]. Consequently, algal biomass produced within IAMS is frequently excluded from human food, nutraceutical, and even aquafeed markets, despite originating from food-grade aquaculture systems. This regulatory “dead end” sharply contrasts with the permissive frameworks governing hydroponic crops and PBR-grown algae cultivated on synthetic media.

Permitting fragmentation presents an additional institutional barrier. IAMS facilities often require multiple overlapping permits covering aquaculture discharge, water reuse, biomass processing, waste valorization, and food production—each overseen by different agencies with distinct compliance metrics [129]. This administrative complexity increases transaction costs and regulatory uncertainty. In comparison, hydroponic and vertical farms are often governed by a single agricultural or urban-farming permit, highlighting an asymmetry in regulatory burden rather than environmental risk.

Policy support mechanisms also remain poorly aligned with IAMS requirements. While subsidies and incentives exist for renewable energy, biosecure aquaculture, and climate-smart agriculture, few frameworks explicitly support circular nutrient recovery systems incorporating microalgal bioprocessing. Given the capital intensity of PBR-based systems, the absence of tailored funding instruments—such as carbon credits, wastewater reuse incentives, or circular-economy certifications—exposes early adopters to elevated financial risk [110]. This stands in contrast to hydroponics and vertical farming, which have benefited from rapid policy endorsement through innovation grants, tax incentives, and urban-agriculture financing schemes.

Finally, regulatory acceptance is shaped by institutional familiarity and public perception. Hydroponics and aquaponics are widely promoted through extension services and educational programs, fostering regulatory trust. Microalgal systems, however, are often perceived as industrial biotechnology or wastewater-treatment technologies rather than food-production platforms, prompting conservative risk assessments. Targeted communication strategies—supported by demonstration facilities, transparent microbial monitoring, and standardized safety protocols—are therefore essential to reframe microalgae as legitimate components of integrated food systems.

Encouragingly, circular-economy initiatives such as the European Commission's Circular Cities and Regions Initiative (CCRI) acknowledge nutrient recycling and biomass valorization as priority actions. However, current frameworks emphasize post-consumer waste and industrial byproduct streams rather than integrated food-production platforms [130]. Embedding IAMS explicitly within national water–energy–food nexus strategies, carbon-credit mechanisms, and multi-output certification schemes would substantially reduce regulatory friction. Ultimately, enabling policies that address pathogen safety, contaminant accumulation, and biomass classification—while recognizing the integrated nature of IAMS—will be decisive for mainstream adoption.

5.5. Environmental Impact and Alignment with Sustainable Development Goals

IAMS represent an ecologically regenerative production paradigm that strongly aligns with circular resource management and sustainable intensification. By integrating microalgae, fish, plants, and microbial processes into a single recirculating loop, IAMS generate synergistic environmental benefits that exceed those of aquaculture, hydroponics, or monoculture systems operating independently [6,110]. Their sustainability relevance is most clearly articulated through contributions to the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action).

In the context of SDG 2, IAMS enhance food-system sustainability by delivering multiple nutrient-dense outputs within a compact land footprint. Microalgae offer exceptionally high protein yields—often 60–70% of dry biomass—without competing for arable land or freshwater resources, unlike terrestrial oilseed or legume crops [70,105]. Protein productivity per unit area can exceed that of conventional legumes by up to twentyfold [110]. Closed and semi-closed cultivation architectures further reduce evaporative losses and water-intensive inputs relative to open-pond systems [71,74]. By simultaneously producing fish, vegetables, and algal biomass, IAMS diversify local food supply chains and reduce dependency on single-crop systems, enhancing resilience in food-insecure and climate-vulnerable regions.

Regarding SDG 6, IAMS substantially reduce freshwater demand while enhancing wastewater remediation. Integrated microalgal photobioreactors routinely remove over 90% of chemical oxygen demand (COD), total suspended solids (TSS), and dissolved nutrients from wastewater streams [73,104]. High-rate algal systems further support the removal of pathogens, heavy metals, and trace pollutants, improving effluent quality prior to recirculation [108,131,132]. By utilizing wastewater as a nutrient medium, IAMS avoid the extreme freshwater demands associated with conventional algal biofuel production, which can exceed 3700 L per liter of fuel [104]. Compared with soil-based agriculture and semi-open hydroponic systems, IAMS recycle more than 90% of water internally, minimize discharge, and significantly reduce eutrophication risk—positioning them as viable water-conservation technologies in arid and water-stressed regions.

Contributions to SDG 13 arise from both direct carbon sequestration and indirect emissions reduction. Microalgae biologically fix approximately 1.8–1.83 kg of CO_2 per kilogram of biomass [72,108], with advanced reactor configurations achieving fixation rates up to 0.8 g L^{-1} d^{-1} [94]. These rates surpass those of most terrestrial crops and contribute meaningfully to climate mitigation. Closed PBRs reduce CO_2 loss to the atmosphere, enhance light-use efficiency, and limit evaporative water losses [74]. Additionally, replacing synthetic fertilizers—whose production is carbon-intensive—with recycled nutrients lowers the embodied carbon footprint of food production [73,95]. Valorization of algal biomass into biofuels, bioplastics, and biofertilizers further displaces fossil-derived products and strengthens circular material flows.

Beyond direct SDG metrics, IAMS embody circular-economy principles by converting wastewater, CO_2, and nutrient-rich effluents into productive biomass streams. Integration with renewable-energy-powered or energy-efficient photobioreactors has demonstrated reductions in greenhouse gas emissions and operational waste [131]. Modular flat-panel systems, semi-closed hybrid PBRs, and multi-tubular arrays improve energy efficiency while reducing land and water footprints [71,102]. However, environmental trade-offs persist: large-scale algal cultivation can exhibit high energy and water demands [92], and disposal of polymer-based PBR components introduces material sustainability concerns [74]. When embedded within aquaponic loops, these impacts are partially mitigated through shared infrastructure, higher productivity per unit input, and reduced effluent discharge [42].

Overall, IAMS offer a transformative pathway toward integrated food production, wastewater reclamation, and climate mitigation. Their modularity and adaptability enable deployment across diverse socio-economic and environmental contexts, particularly in regions facing land scarcity, water stress, and climate volatility. When strategically implemented and supported by enabling policies, IAMS can accelerate progress toward multiple SDGs simultaneously while strengthening systemic resilience across food–water–energy nexuses.

5.6. Research Gaps, Uncertainties, Design Priorities and Future Directions

Despite the strong performance of IAMS in laboratory studies and pilot-scale demonstrations, their transition toward widespread adoption remains constrained by unresolved technical, economic, and contextual uncertainties. Advancing IAMS from experimental platforms to scalable sustainability solutions requires coordinated research efforts that extend beyond proof-of-concept performance toward long-term validation, system-level optimization, and contextual adaptability. Such efforts are essential not only for improving technical robustness but also for informing policy design, investment decisions, and supporting infrastructure development [6,110].

A central research gap lies in the limited availability of long-duration, field-scale demonstrations across diverse climatic and socio-economic settings. While conventional aquaponics have been extensively tested in urban, peri-urban, and rural contexts, IAMS remain largely confined to controlled laboratory or short-term pilot environments. This restricts the understanding of system behavior under variable solar irradiance, seasonal temperature fluctuations, and changing influent water quality. Field deployments in low-resource and climate-vulnerable regions are particularly important, where IAMS may function simultaneously as decentralized food-production units, wastewater treatment platforms, and educational tools. Comparative benchmarking of IAMS against hydroponics or recirculating aquaculture systems (RAS) under identical environmental conditions is notably absent and represents a priority for evaluating resilience, labor demands, and cost–performance trade-offs.

Equally critical is the development of techno-economic assessment (TEA) frameworks that reflect the multifunctional nature of IAMS. Existing agricultural and aquaculture TEA models are predominantly linear, focusing on single outputs such as crop yield or fish biomass. In contrast, IAMS generate multiple co-products—including algal biomass, vegetables, fish, and treated water—while internally recycling nutrients and CO_2. This complexity challenges conventional modeling approaches. Future TEA tools must integrate circular resource flows, co-product valorization, and avoided externalities such as fertilizer displacement and emission reductions to accurately represent system value. Without such system-specific TEA models, economic comparisons with hydroponics, vertical farming, or standalone algal biofuel systems risk underestimating the true performance and societal benefits of IAMS [6].

Biological optimization remains another underdeveloped research frontier. Effective pairing of microalgal species with specific aquaponic configurations is essential for maximizing nutrient recovery, maintaining system balance, and enhancing biomass productivity. While well-studied strains such as *Chlorella vulgaris* and *Spirulina platensis* dominate current research, alternative species—including *Tetradesmus obliquus* and *Nannochloropsis* spp.—offer potential advantages in lipid content, salinity tolerance, and environmental resilience. Comparative physiological studies examining nutrient uptake kinetics, pH tolerance, and photosynthetic efficiency across species are needed to guide rational system design. This contrasts with traditional aquaponics research, which has historically emphasized plant–fish interactions while neglecting the role of tertiary biological layers such as microalgae.

Genetic and metabolic engineering present additional opportunities to enhance IAMS performance under suboptimal conditions. Targeted modifications aimed at improving CO_2 fixation, nutrient affinity, or stress tolerance have been widely explored in algal biofuel and pharmaceutical research but remain underrepresented in integrated, food-oriented systems. Analogous advances in vertical farming—such as genetically optimized lettuce cultivars achieving yield gains of up to 40% per unit area—demonstrate the transformative potential of biological optimization. Translating similar strategies to IAMS will require careful consideration of regulatory acceptance, biosafety, and the development of compliant algal strains suitable for food or feed applications [110].

Operational control and system intelligence constitute another major research priority. The tri-trophic complexity of IAMS demands the simultaneous regulation of light intensity, pH, nutrient availability, dissolved oxygen, and hydraulic residence time across fish, plant, and algal compartments. While Internet-of-Things (IoT) platforms and automated control systems are increasingly applied in hydroponics and aquaculture, IAMS-specific monitoring architectures capable of capturing dynamic biological interactions remain scarce. The integration of low-cost sensors, edge computing, and machine-learning algorithms tailored to tri-trophic systems could reduce labor intensity, stabilize productivity, and improve system resilience under fluctuating operating conditions.

Finally, the social and institutional dimensions of IAMS adoption require greater scholarly attention. Long-term system viability depends not only on technical efficiency but also on stakeholder acceptance, regulatory compatibility, and contextual relevance. Participatory research involving farmers, policymakers, and community organizations can help identify adoption barriers, cultural preferences, and local resource constraints. Unlike hydroponics, which primarily targets commercial urban producers, IAMS may deliver greater impact at community or regional scales—particularly in areas facing fertilizer scarcity, water stress, or climate instability. Designing context-specific system configurations that align with local governance structures and livelihood strategies will be essential for ensuring equitable and sustainable integration of IAMS into future food systems.

6. Conclusions

The IAMS represent a meaningful evolution in sustainable food production and water resource recovery, offering a biologically integrated framework to address interconnected challenges related to food insecurity, nutrient pollution, and climate vulnerability. By incorporating a tertiary microalgal trophic level into conventional aquaponic configurations, IAMS enhance nutrient retention and extend system functionality beyond what is achievable through standalone aquaculture or hydroponics. This review demonstrates that under optimized laboratory and pilot-scale conditions, appropriately configured IAMS have been reported to achieve nitrogen and phosphorus removal efficiencies exceeding 95%, while simultaneously producing protein-rich biomass suitable for aquafeeds, biofertilizers, or other value-added applications. Relative to linear agricultural models, these systems exhibit improved environmental performance through closed-loop nutrient cycling, internal carbon fixation, and multi-product biomass valorization.

However, translating pilot-scale success into commercial deployment remains a significant challenge. The broader implementation of IAMS is constrained by the inherent complexity of maintaining stable multi-trophic interactions under variable field conditions, high initial capital costs associated with photobioreactors and control infrastructure, and regulatory uncertainty surrounding the use of algal coproducts derived from nutrient-rich effluents. Reported performance metrics vary substantially across reactor designs, species selection strategies, and climatic contexts, highlighting the need for cautious interpretation of laboratory-scale efficiencies. In particular, unresolved policy issues related to product certification, biosafety standards, and subsidy eligibility continue to limit market adoption, especially for food- and feed-grade algal biomass.

Future research should therefore prioritize long-term, field-scale validation of IAMS across diverse operational environments to bridge the gap between experimental performance and real-world reliability. Integrated techno-economic and life cycle assessments that explicitly account for circular resource flows, energy demand, and downstream biomass utilization pathways will be critical to establishing realistic sustainability benchmarks. In parallel, the development of IAMS-specific automation, sensing, and predictive control frameworks is essential to reduce operational complexity and improve system robustness.

As food, energy, and water systems become increasingly interdependent, IAMS should be viewed not as a universal solution, but as a context-sensitive convergence technology with the potential to transform fragmented resource management into a more integrated and regenerative paradigm when appropriately designed, governed, and scaled.

Author Contributions: Conceptualization, C.A.D.; methodology, C.A.D.; validation, C.A.D.; formal analysis, C.A.D.; investigation, C.A.D.; data curation, C.A.D.; writing—original draft preparation, C.A.D.; writing—review and editing, J.C.K., T.A.P., D.R. and R.H.; visualization, C.A.D., and I.A.W.;

supervision, J.C.K., T.A.P., D.R. and R.H.; project administration, R.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available in the article.

Acknowledgments: The authors wish to acknowledge the Kalama Mithuro organization for their support during this research. We extend our sincere gratitude to Dhammika Dharmaratne for his valuable support. We also thank the technical officers W. B. U. Rukma, L. M. Dushantha, and D. M. B. Wickramasinghe for their technical assistance, and W. J. Shantha for his support in the laboratory.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tian, X.; Engel, B.A.; Qian, H.; Hua, E.; Sun, S.; Wang, Y. Will reaching the maximum achievable yield potential meet future global food demand? *J. Clean. Prod.* **2021**, *294*, 126285. [CrossRef]
2. Dodangodage, C.A.; Kasturiarachchi, J.; Perera, T.; Rajapakshe, D.; Halwatura, R. Valorization of Canteen Wastewater Through Optimized *Spirulina platensis* Cultivation for Enhanced Carotenoid Production and Nutrient Removal. 2025. Available online: https://www.preprints.org/manuscript/202511.0752 (accessed on 11 November 2025).
3. Molotoks, A.; Smith, P.; Dawson, T.P. Impacts of land use, population, and climate change on global food security. *Food Energy Secur.* **2021**, *10*, e261. [CrossRef]
4. Wudil, A.H.; Usman, M.; Rosak-Szyrocka, J.; Pilař, L.; Boye, M. Reversing Years for Global Food Security: A Review of the Food Security Situation in Sub-Saharan Africa (SSA). *Int. J. Environ. Res. Public Health* **2022**, *19*, 14836. [CrossRef]
5. Xia, Y.; Zhang, M.; Tsang, D.C.W.; Geng, N.; Lu, D.; Zhu, L.; Igalavithana, A.D.; Dissanayake, P.D.; Rinklebe, J.; Yang, X.; et al. Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: Current practices and future prospects. *Appl. Biol. Chem.* **2020**, *63*, 8. [CrossRef]
6. Renganathan, P.; Puente, E.O.R.; Sukhanova, N.V.; Gaysina, L.A. Hydroponics with *Microalgae* and *Cyanobacteria*: Emerging Trends and Opportunities in Modern Agriculture. *BioTech* **2024**, *13*, 27. [CrossRef]
7. Suhl, J.; Dannehl, D.; Kloas, W.; Baganz, D.; Jobs, S.; Scheibe, G.; Schmidt, U. Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. *Agric. Water Manag.* **2016**, *178*, 335–344. [CrossRef]
8. Aslanidou, M.; Elvanidi, A.; Mourantian, A.; Levizou, E.; Mente, E.; Katsoulas, N. Nutrients Use Efficiency in Coupled and Decoupled Aquaponic Systems. *Horticulturae* **2023**, *9*, 1077. [CrossRef]
9. Goddek, S.; Delaide, B.; Mankasingh, U.; Ragnarsdottir, K.V.; Jijakli, H.; Thorarinsdottir, R. Challenges of sustainable and commercial aquaponics. *Sustainability* **2015**, *7*, 4199–4224. [CrossRef]
10. Mujtaba, G.; Rizwan, M.; Kim, G.; Lee, K. Removal of nutrients and COD through co-culturing activated sludge and immobilized *Chlorella vulgaris*. *Chem. Eng. J.* **2018**, *343*, 155–162. [CrossRef]
11. Kube, M.; Jefferson, B.; Fan, L.; Roddick, F. The impact of wastewater characteristics, algal species selection and immobilisation on simultaneous nitrogen and phosphorus removal. *Algal Res.* **2018**, *31*, 478–488. [CrossRef]
12. Ibrahim, L.A.; Shaghaleh, H.; El-Kassar, G.M.; Abu-Hashim, M.; Elsadek, E.A.; Alhaj Hamoud, Y. Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency. *Water* **2023**, *15*, 4310. [CrossRef]
13. Wong, C.F.; Saif, U.M.; Chow, K.L.; Wong, J.T.F.; Chen, X.W.; Liang, Y.; Cheng, Z.; Tsang, Y.F.; Wong, M.H.; Man, Y.B. Applications of charcoal, activated charcoal, and biochar in aquaculture—A review. *Sci. Total Environ.* **2024**, *929*, 172574. [CrossRef] [PubMed]
14. Ma, S.L.; Sun, S.; Li, T.Z.; Yan, Y.J.; Wang, Z.K. Application research and progress of microalgae as a novel protein resource in the future. *Crit. Rev. Food Sci. Nutr.* **2025**, *65*, 5790–5813.
15. Barta, D.G.; Coman, V.; Vodnar, D.C. Microalgae as sources of omega-3 polyunsaturated fatty acids: Biotechnological aspects. *Algal Res.* **2021**, *58*, 102410. [CrossRef]
16. Del Mondo, A.; Smerilli, A.; Sané, E.; Sansone, C.; Brunet, C. Challenging microalgal vitamins for human health. *Microb. Cell Factories* **2020**, *19*, 201. [CrossRef]
17. Muys, M.; Sui, Y.; Schwaiger, B.; Lesueur, C.; Vandenheuvel, D.; Vermeir, P.; Vlaeminck, S.E. High variability in nutritional value and safety of commercially available *Chlorella* and *Spirulina* biomass indicates the need for smart production strategies. *Bioresour. Technol.* **2019**, *275*, 247–257. [CrossRef]
18. Dodangodage, C.A.; Premarathne, H.; Kasturiarachchi, J.C.; Perera, T.A.; Rajapakshe, D.; Halwatura, R.U. Algae-Based Protective Coatings for Sustainable Infrastructure: A Novel Framework Linking Material Chemistry, Techno-Economics, and Environmental Functionality. *Phycology* **2025**, *5*, 84. [CrossRef]
19. Fimbres-Acedo, Y.E.; Servín-Villegas, R.; Garza-Torres, R.; Endo, M.; Fitzsimmons, K.M.; Emerenciano, M.G.C.; Magallón-Servín, P.; López-Vela, M.; Magallón-Barajas, F.J. Hydroponic horticulture using residual waters from *Oreochromis*

niloticus aquaculture with biofloc technology in photoautotrophic conditions with *Chlorella* microalgae. *Aquac. Res.* **2020**, *51*, 4340–4360.

20. Onyeaka, H.; Miri, T.; Obileke, K.C.; Hart, A.; Anumudu, C.; Al-Sharify, Z.T. Minimizing carbon footprint via microalgae as a biological capture. *Carbon Capture Sci. Technol.* **2021**, *1*, 100007. [CrossRef]
21. Roy, A.; Moradkhani, H.; Mekonnen, M.; Moftakhari, H.; Magliocca, N. Towards strategic interventions for global food security in 2050. *Sci. Total Environ.* **2024**, *954*, 176811. [CrossRef]
22. Beyer, R.M.; Hua, F.; Martin, P.A.; Manica, A.; Rademacher, T. Relocating croplands could drastically reduce the environmental impacts of global food production. *Commun. Earth Environ.* **2022**, *3*, 49. [CrossRef]
23. Verma, A.K.; Chandrakant, M.H.; John, V.C.; Peter, R.M.; John, I.E. Aquaponics as an integrated agri-aquaculture system (IAAS): Emerging trends and future prospects. *Technol. Forecast. Soc. Change* **2023**, *194*, 122709. [CrossRef]
24. Ende, S.; Henjes, J.; Spiller, M.; Elshobary, M.; Hanelt, D.; Abomohra, A. Recent advances in recirculating aquaculture systems and role of microalgae to close system loop. *Bioresour. Technol.* **2024**, *407*, 131107. [CrossRef] [PubMed]
25. Fischer, R.A.; Connor, D.J. Issues for cropping and agricultural science in the next 20 years. *Field Crops Res.* **2018**, *222*, 121–142. [CrossRef]
26. Rose, D.; Heller, M.C.; Roberto, C.A. Position of the Society for Nutrition Education and Behavior: The Importance of Including Environmental Sustainability in Dietary Guidance. *J. Nutr. Educ. Behav.* **2019**, *51*, 3–15. [CrossRef]
27. Bununu, Y.A.; Bello, A.; Ahmed, A. Land cover, land use, climate change and food security. *Sustain. Earth Rev.* **2023**, *6*, 16. [CrossRef]
28. Mok, W.K.; Tan, Y.X.; Chen, W.N. Technology innovations for food security in Singapore: A case study of future food systems for an increasingly natural resource-scarce world. *Trends Food Sci. Technol.* **2020**, *102*, 155–168. [CrossRef]
29. Saleem, A.; Anwar, S.; Nawaz, T.; Fahad, S.; Saud, S.; Ur Rahman, T.; Khan, M.N.R.; Nawaz, T. Securing a sustainable future: The climate change threat to agriculture, food security, and sustainable development goals. *J. Umm Al-Qura Univ. Appl. Sci.* **2025**, *11*, 595–611. [CrossRef]
30. Barrett, C.B. Overcoming global food security challenges through science and solidarity. *Am. J. Agric. Econ.* **2021**, *103*, 422–447.
31. Rosa, L.; Chiarelli, D.D.; Tu, C.; Rulli, M.C.; D'odorico, P. Global unsustainable virtual water flows in agricultural trade. *Environ. Res. Lett.* **2019**, *14*, 114001. [CrossRef]
32. Liu, X.Y.; Hong, Y. Microalgae-Based Wastewater Treatment and Recovery with Biomass and Value-Added Products: A Brief Review. In *Current Pollution Reports*; Springer Science and Business Media Deutschland GmbH: Berlin, Germany, 2021; Volume 7, pp. 227–245. [CrossRef]
33. Tom, A.P.; Jayakumar, J.S.; Biju, M.; Somarajan, J.; Ibrahim, M.A. Aquaculture wastewater treatment technologies and their sustainability: A review. *Energy Nexus* **2021**, *4*, 100022. [CrossRef]
34. Smith, M.D.; Sikka, A.; Taguta, C.; Dirwai, T.L.; Mabhaudhi, T. Embracing complexities in agricultural water management through nexus planning. *Irrig. Drain.* **2024**, *73*, 1695–1716. [CrossRef] [PubMed]
35. Jat, M.L.; Chakraborty, D.; Ladha, J.K.; Parihar, C.M.; Datta, A.; Mandal, B.; Nayak, H.S.; Maity, P.; Rana, D.S.; Chaudhari, S.K.; et al. Carbon sequestration potential, challenges, and strategies towards climate action in smallholder agricultural systems of South Asia. *Crop Environ.* **2022**, *1*, 86–101. [CrossRef]
36. Kumar, V.S.; Sarkar, D.J.; Das, B.K.; Samanta, S.; Tripathi, G.; Das Sarkar, S.; Nag, S.K. Utilizing microalgae biofilm for reducing arsenic toxicity on fish grown in contaminated waters: An innovative solution for safer and cleaner aquaculture in arsenic endemic areas. *Aquaculture* **2025**, *599*, 742121. [CrossRef]
37. Bailey, A.; Meyer, L.; Pettingell, N.; Macie, M.; Korstad, J. Agricultural practices contributing to aquatic dead zones. In *Ecological and Practical Applications for Sustainable Agriculture*; Springer: Singapore, 2020; pp. 373–393. [CrossRef]
38. Adegoke, A.A.; Amoah, I.D.; Stenström, T.A.; Verbyla, M.E.; Mihelcic, J.R. Epidemiological evidence and health risks associated with agricultural reuse of partially treated and untreated wastewater: A review. *Front. Public Health* **2018**, *6*, 337. [CrossRef]
39. Gao, J.; Li, F.; Gao, H.; Zhou, C.; Zhang, X. The impact of land-use change on water-related ecosystem services: A study of the Guishui River Basin, Beijing, China. *J. Clean. Prod.* **2017**, *163*, S148–S155. [CrossRef]
40. Castillo Sánchez, V.M.; Álvarez-Salgado, X.A.; Camarero, J.J.; Campo Á, A.D.; García-Palacios, P.; Gómez Peris, A.; Yúfera, M. Challenge 5: Impact of Global Change on Managed Ecosystems. White Paper 7: Global Change Impacts. 2021. Available online: https://hdl.handle.net/10261/272613 (accessed on 1 December 2021).
41. Sukla, L.B.; Pradhan, D.; Subbaiah, T. Future Prospects of Microalgae. In *The Role of Microalgae in Wastewater Treatment*; Springer: Singapore, 2018; p. 129.
42. Dodangodage, C.A.; Gamage, G.N.; Fernando, K.V.; Kasturiarachchi, J.C.; Perera, T.A.; Rajapakshe, S.D.; Halwatura, R.U. Production of Carbohydrate-Rich *Chlorella* sp. Biomass Using Clarified Aquaponics Effluent for Bioethanol Feedstock Applications. 2025. Available online: https://www.preprints.org/manuscript/202512.1475 (accessed on 12 December 2025).
43. Farré, G.; Gómez-Galera, S.; Naqvi, S.; Bai, C.; Sanahuja, G.; Yuan, D.; Zorrilla-López, U.; Codony, L.; Rojas, E.; Fibla, M. *Encyclopedia of Sustainability Science and Technology*; Springer: New York, NY, USA, 2012.

44. Baganz, G.F.M.; Junge, R.; Portella, M.C.; Goddek, S.; Keesman, K.J.; Baganz, D.; Staaks, G.; Shaw, C.; Lohrberg, F.; Kloas, W. The aquaponic principle—It is all about coupling. *Rev. Aquac.* **2022**, *14*, 252–264. [CrossRef]
45. Okomoda, V.T.; Oladimeji, S.A.; Solomon, S.G.; Olufeagba, S.O.; Ogah, S.I.; Ikhwanuddin, M. Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. *Food Sci. Nutr.* **2023**, *11*, 1157–1165. [CrossRef]
46. Zhu, Z.; Yogev, U.; Gross, A.; Keesman, K.J. Environmental assessment of industrial aquaponics in arid zones using an integrated dynamic model. *Inf. Process. Agric.* **2025**, *12*, 260–277. [CrossRef]
47. Behr, L.M.; Hu, A.H.; Heck, P. Assessing the environmental impact and advantages of a commercial aquaponic system in Taiwan through life cycle assessment. *Aquaculture* **2024**, *595*, 741589. [CrossRef]
48. Al Tawaha, A.R.; Megat Wahab, P.E.; Jaafar, H.Z.E. Optimizing nutrient availability in decoupled recirculating aquaponic systems for enhanced plant productivity: A mini review. *Nitrogen* **2025**, *6*, 3. [CrossRef]
49. Kushwaha, J.; Priyadarsini, M.; Rani, J.; Pandey, K.P.; Dhoble, A.S. Aquaponic trends, configurations, operational parameters, and microbial dynamics: A concise review. *Environ. Dev. Sustain.* **2025**, *27*, 213–246.
50. Goddek, S.; Espinal, C.A.; Delaide, B.; Jijakli, M.H.; Schmautz, Z.; Wuertz, S.; Keesman, K.J. Navigating towards decoupled aquaponic systems: A system dynamics design approach. *Water* **2016**, *8*, 303. [CrossRef]
51. Zhanga, H.; Gaoa, Y.; Liua, J.; Lina, Z.; Leeb, C.T.; Hashimb, H.; Wuc, W.-M.; Lia, C. Recovery of nutrients from fish sludge as liquid fertilizer to enhance sustainability of aquaponics: A review. *Chem. Eng.* **2021**, *83*, 55–60.
52. Wongkiew, S.; Hu, Z.; Chandran, K.; Lee, J.W.; Khanal, S.K. Nitrogen transformations in aquaponic systems: A review. *Aquac. Eng.* **2017**, *76*, 9–19. [CrossRef]
53. Akinnawo, S.O. Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. In *Environmental Challenges*; Elsevier: Amsterdam, The Netherlands, 2023; Volume 12. [CrossRef]
54. Benner, P.; Meier, L.; Pfeffer, A.; Krüger, K.; Oropeza Vargas, J.E.; Weuster-Botz, D. Lab-scale photobioreactor systems: Principles, applications, and scalability. *Bioprocess Biosyst. Eng.* **2022**, *45*, 791–813. [CrossRef]
55. Hariz, H.B.; Takriff, M.S.; Ba-Abbad, M.M.; Mohd Yasin, N.H.; Mohd Hakim, N.I.N. CO_2 fixation capability of *Chlorella* sp. and its use in treating agricultural wastewater. *J. Appl. Phycol.* **2018**, *30*, 3017–3027. [CrossRef]
56. Anila, M.; Daramola, O. Applications, technologies, and evaluation methods in smart aquaponics: A systematic literature review. *Artif. Intell. Rev.* **2025**, *58*, 25. [CrossRef]
57. Lesk, C.; Anderson, W.; Rigden, A.; Coast, O.; Jägermeyr, J.; McDermid, S.; Davis, K.F.; Konar, M. Compound heat and moisture extreme impacts on global crop yields under climate change. *Nat. Rev. Earth Environ.* **2022**, *3*, 872–889. [CrossRef]
58. Yildiz, H.Y.; Robaina, L.; Pirhonen, J.; Mente, E.; Domínguez, D.; Parisi, G. Fish welfare in aquaponic systems: Its relation to water quality with an emphasis on feed and faeces—A review. *Water* **2017**, *9*, 13. [CrossRef]
59. Goh, P.S.; Lau, W.J.; Ismail, A.F.; Samawati, Z.; Liang, Y.Y.; Kanakaraju, D. Microalgae-enabled wastewater treatment: A sustainable strategy for bioremediation of pesticides. *Water* **2022**, *15*, 70. [CrossRef]
60. Habib-ur-Rahman, M.; Ahmad, A.; Raza, A.; Hasnain, M.U.; Alharby, H.F.; Alzahrani, Y.M.; Bamagoos, A.A.; Hakeem, K.R.; Ahmad, S.; Nasim, W. Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. *Front. Plant Sci.* **2022**, *13*, 925548. [CrossRef] [PubMed]
61. Siringi, J.O.; Turoop, L.; Njonge, F. Growth and biochemical response of *Nile tilapia* (*Oreochromis niloticus*) to *spirulina* (*Arthrospira platensis*) enhanced aquaponic system. *Aquaculture* **2021**, *544*, 737134. [CrossRef]
62. da Silva Ferreira, V.; Sant'Anna, C. The effect of physicochemical conditions and nutrient sources on maximizing the growth and lipid productivity of green microalgae. *Phycol. Res.* **2017**, *65*, 3–13. [CrossRef]
63. Kim, K.; Kim, Z.-H.; Park, H.; Lee, Y.; Kim, K.; Kang, S.; Lim, S.-M.; Lee, C.-G. Enhancing microalgal biomass productivity in floating photobioreactors with semi-permeable membranes grafted with 4-hydroxyphenethyl bromide. *Macromol. Res.* **2020**, *28*, 145–151. [CrossRef]
64. Kim, Z.-H.; Park, H.; Ryu, Y.-J.; Shin, D.-W.; Hong, S.-J.; Tran, H.-L.; Lim, S.-M.; Lee, C.-G. Algal biomass and biodiesel production by utilizing the nutrients dissolved in seawater using semi-permeable membrane photobioreactors. *J. Appl. Phycol.* **2015**, *27*, 1763–1773. [CrossRef]
65. Vo, H.N.P.; Ngo, H.H.; Guo, W.; Nguyen, T.M.H.; Liu, Y.; Liu, Y.; Nguyen, D.D.; Chang, S.W. A critical review on designs and applications of microalgae-based photobioreactors for pollutants treatment. *Sci. Total Environ.* **2019**, *651*, 1549–1568. [CrossRef]
66. Benà, E.; Giacò, P.; Demaria, S.; Marchesini, R.; Melis, M.; Zanotti, G.; Baldisserotto, C.; Pancaldi, S. Winter Season Outdoor Cultivation of an Autochthonous *Chlorella*-Strain in a Pilot-Scale Prototype for Urban Wastewater Treatment. *Water* **2024**, *16*, 2635. [CrossRef]
67. Yadav, D.K.; Singh, A.; Agrawal, V.; Yadav, N. Algal Biomass: A Natural Resource of High-Value Biomolecules. In *Bioprospecting of Plant Biodiversity for Industrial Molecules*; John Wiley & Sons: Hoboken, NJ, USA, 2021; pp. 303–334.
68. Haldar, N.; Supraja, K.V.; Anamika Achhoda, M.; Mayank, M.; Sharma, M.; Thakur, N.; Mohanty, A.; Meena, S.S.; Rout, P.R. Production of value-added products using microalgae: A zero-waste biorefinery approach. In *Biotechnological Advances in Biorefinery*; Springer: New York, NY, USA, 2024; pp. 97–126.

69. Tejido-Nuñez, Y.; Aymerich, E.; Sancho, L.; Refardt, D. Treatment of aquaculture effluent with *Chlorella vulgaris* and *Tetradesmus obliquus*: The effect of pretreatment on microalgae growth and nutrient removal efficiency. *Ecol. Eng.* **2019**, *136*, 1–9. [CrossRef]
70. Tan, C.H.; Tan, X.; Ho, S.H.; Lam, S.S.; Show, P.L.; Nguyen, T.H.P. Conceptual design of a hybrid thin layer cascade photobioreactor for microalgal biodiesel synthesis. *Int. J. Energy Res.* **2020**, *44*, 9757–9771. [CrossRef]
71. Koller, M. Design of closed photobioreactors for algal cultivation. In *Algal Biorefineries: Volume 2: Products and Refinery Design*; Springer International Publishing: New York, NY, USA, 2015; pp. 133–186. [CrossRef]
72. Rahman, A.; Agrawal, S.; Nawaz, T.; Pan, S.; Selvaratnam, T. A review of algae-based produced water treatment for biomass and biofuel production. *Water* **2020**, *12*, 2351. [CrossRef]
73. Penloglou, G.; Pavlou, A.; Kiparissides, C. Recent Advancements in Photo-Bioreactors for Microalgae Cultivation: A Brief Overview. *Processes* **2024**, *12*, 1104. [CrossRef]
74. Qin, L.; Alam, M.A.; Wang, Z. Open pond culture systems and photobioreactors for microalgal biofuel production. In *Microalgae Biotechnology for Development of Biofuel and Wastewater Treatment*; Springer: Singapore, 2019; pp. 45–74. [CrossRef]
75. Nguyen, L.N.; Aditya, L.; Vu, H.P.; Johir, A.H.; Bennar, L.; Ralph, P.; Hoang, N.B.; Zdarta, J.; Nghiem, L.D. Nutrient Removal by Algae-Based Wastewater Treatment. *Curr. Pollut. Rep.* **2022**, *8*, 369–383. [CrossRef]
76. Amini, M.; Amini Khoei, Z.; Erfanifar, E. Nitrate (NO3−) and phosphate (PO43−) removal from aqueous solutions by microalgae *Dunaliella salina*. *Biocatal. Agric. Biotechnol.* **2019**, *19*, 101097. [CrossRef]
77. Gu, B.; Zhang, X.; Lam, S.K.; Yu, Y.; Van Grinsven, H.J.M.; Zhang, S.; Wang, X.; Bodirsky, B.L.; Wang, S.; Duan, J. Cost-effective mitigation of nitrogen pollution from global croplands. *Nature* **2023**, *613*, 77–84. [CrossRef]
78. Guedes, A.C.; Amaro, H.M.; Pereira, R.D.; Malcata, F.X. Effects of temperature and pH on growth and antioxidant content of the microalga *Scenedesmus obliquus*. *Biotechnol. Prog.* **2011**, *27*, 1218–1224. [CrossRef]
79. Lupatini, A.L.; Colla, L.M.; Canan, C.; Colla, E. Potential application of microalga *Spirulina platensis* as a protein source. *J. Sci. Food Agric.* **2017**, *97*, 724–732.
80. Seyfabadi, J.; Ramezanpour, Z.; Amini Khoeyi, Z. Protein, fatty acid, and pigment content of *Chlorella vulgaris* under different light regimes. *J. Appl. Phycol.* **2011**, *23*, 721–726.
81. Thakur, M.; Hurburgh, C.R. Quality of US soybean meal compared to the quality of soybean meal from other origins. *J. Am. Oil Chem. Soc.* **2007**, *84*, 835–843. [CrossRef]
82. Gerde, J.A.; Wang, T.; Yao, L.; Jung, S.; Johnson, L.A.; Lamsal, B. Optimizing protein isolation from defatted and non-defatted *Nannochloropsis* microalgae biomass. *Algal Res.* **2013**, *2*, 145–153. [CrossRef]
83. McKuin, B.; Kapuscinski, A.R.; Sarker, P.K.; Cheek, N.; Lim, J.; Sabarsky, M. Comparative life cycle assessment of marine microalgae, *Nannochloropsis* sp. and fishmeal for sustainable protein ingredients in aquaculture feeds. *Elementa* **2023**, *11*, 387–398. [CrossRef]
84. Chu, H.; Ren, L.; Yang, L.; Chen, J.; Zhou, X.; Zhang, Y. Metabolomics reveals a lipid accumulation mechanism involving carbon allocation in *Scenedesmus obliquus* under norfloxacin stress. *Renew. Energy* **2020**, *157*, 585–592. [CrossRef]
85. Martínez-Roldán, A.J.; Perales-Vela, H.V.; Cañizares-Villanueva, R.O.; Torzillo, G. Physiological response of *Nannochloropsis* sp. to saline stress in laboratory batch cultures. *J. Appl. Phycol.* **2014**, *26*, 115–121. [CrossRef]
86. Ishika, T. Sustainable Cultivation of Marine, Halotolerant and Halophilic Miccroalgae. Ph.D. Thesis, Murdoch University, Perth, WA, Australia, 2017.
87. Sui, Y.; de Souza Celente, G.; Navarro, L.B.; Garcia-Trinanes, P.; Harvey, P.J. Phosphorus and sulphur affecting the growth, nutrient uptake and amino acids composition in *Dunaliella salina*. *Process Biochem.* **2025**, *153*, 276–283. [CrossRef]
88. Xu, Y.; Ibrahim, I.M.; Wosu, C.I.; Ben-Amotz, A.; Harvey, P.J. Potential of new isolates of *dunaliella salina* for natural β-carotene production. *Biology* **2018**, *7*, 14. [CrossRef]
89. Álvarez-Gil, M.; Blanco-Vieites, M.; Suárez-Montes, D.; Casado-Bañares, V.; Delgado-Ramallo, J.F.; Rodríguez, E. Revolutionizing Agriculture: Leveraging Hydroponic Greenhouse Wastewater for Sustainable Microalgae-Based Biostimulant Production. *Sustainability* **2023**, *15*, 14398. [CrossRef]
90. Yin, Z.; Zhu, L.; Li, S.; Hu, T.; Chu, R.; Mo, F.; Hu, D.; Liu, C.; Li, B. A comprehensive review on cultivation and harvesting of microalgae for biodiesel production: Environmental pollution control and future directions. *Bioresour. Technol.* **2020**, *301*, 122804. [CrossRef]
91. Chen, M.; Chen, Y.; Zhang, Q. A review of energy consumption in the acquisition of bio-feedstock for microalgae biofuel production. *Sustainability* **2021**, *13*, 8873. [CrossRef]
92. Jabłońska-Trypuć, A.; Wołejko, E.; Ernazarovna, M.D.; Głowacka, A.; Sokołowska, G.; Wydro, U. Using Algae for Biofuel Production: A Review. *Energies* **2023**, *16*, 1758. [CrossRef]
93. Yun, J.H.; Cho, D.H.; Lee, S.; Heo, J.; Tran, Q.G.; Chang, Y.K.; Kim, H.S. Hybrid operation of photobioreactor and wastewater-fed open raceway ponds enhances the dominance of target algal species and algal biomass production. *Algal Res.* **2018**, *29*, 319–329. [CrossRef]

94. Cui, X.; Yang, J.; Cui, M.; Zhang, W.; Zhao, J. Comparative experiments of two novel tubular photobioreactors with an inner aerated tube for microalgal cultivation: Enhanced mass transfer and improved biomass yield. *Algal Res.* **2021**, *58*, 102364. [CrossRef]
95. Lei, Y.; Wang, J.; Wu, J. Optimization of tubular microalgal photobioreactors with spiral ribs under single-sided and double-sided illuminations. *Processes* **2019**, *7*, 619. [CrossRef]
96. Mink, A.; Schediwy, K.; Posten, C.; Nirschl, H.; Simonis, S.; Krause, M.J. Comprehensive Computational Model for Coupled Fluid Flow, Mass Transfer, and Light Supply in Tubular Photobioreactors Equipped with Glass Sponges. *Energies* **2022**, *15*, 7671. [CrossRef]
97. Mohler, D.T.; Wilson, M.H.; Fan, Z.; Groppo, J.G.; Crocker, M. Beneficial reuse of industrial CO2 emissions using a microalgae photobioreactor: Waste heat utilization assessment. *Energies* **2019**, *12*, 2634. [CrossRef]
98. Talaei, M.; Mahdavinejad, M.; Azari, R. Thermal and energy performance of algae bioreactive façades: A review. *J. Build. Eng.* **2020**, *28*, 101011. [CrossRef]
99. Johnson, T.J.; Katuwal, S.; Anderson, G.A.; Gu, L.; Zhou, R.; Gibbons, W.R. Photobioreactor cultivation strategies for microalgae and *cyanobacteria*. *Biotechnol. Prog.* **2018**, *34*, 811–827. [CrossRef]
100. Nwoba, E.G.; Parlevliet, D.A.; Laird, D.W.; Alameh, K.; Moheimani, N.R. Light management technologies for increasing algal photobioreactor efficiency. *Algal Res.* **2019**, *39*, 101433. [CrossRef]
101. Borella, L.; Sforza, E.; Bertucco, A. An internally LED illuminated photobioreactor to increase energy conversion efficiency: Design and operation. *Energy Convers. Manag.* **2022**, *270*, 116224. [CrossRef]
102. Sukačová, K.; Lošák, P.; Brummer, V.; Máša, V.; Vícha, D.; Zavřel, T. Perspective design of algae photobioreactor for greenhouses—A comparative study. *Energies* **2021**, *14*, 1338. [CrossRef]
103. Gabrielyan, D.A.; Gabel, B.V.; Sinetova, M.A.; Gabrielian, A.K.; Markelova, A.G.; Shcherbakova, N.V.; Los, D.A. Optimization of CO_2 Supply for the Intensive Cultivation of *Chlorella sorokiniana* IPPAS C-1 in the Laboratory and Pilot-Scale Flat-Panel Photobioreactors. *Life* **2022**, *12*, 1469. [CrossRef]
104. Khalekuzzaman, M.; Alamgir, M.; Islam, M.B.; Hasan, M. A simplistic approach of algal biofuels production from wastewater using a Hybrid Anaerobic Baffled Reactor and Photobioreactor (HABR-PBR) System. *PLoS ONE* **2019**, *14*, e0225458. [CrossRef]
105. Li, M.J.; Tong, Z.X.; Zhou, Z.J.; Huang, D.; Wang, R.L. A numerical model coupling bubble flow, light transfer, cell motion and growth kinetics for real timescale microalgae cultivation and its applications in flat plate photobioreactors. *Algal Res.* **2019**, *44*, 101727. [CrossRef]
106. Zampieri, R.M.; Touloupakis, E.; Faraloni, C.; Moia, I.C. Comparison of Photofermentative Hydrogen Production in Cylindrical Photobioreactors Using Different Mixing Systems. *Microorganisms* **2025**, *13*, 1386. [CrossRef] [PubMed]
107. Villalba, M.R.; Cervera, R.; Sánchez, J. Green Solutions for Urban Sustainability: Photobioreactors for Algae Cultivation on Façades and Artificial Trees. *Buildings* **2023**, *13*, 1541. [CrossRef]
108. Zabochnicka, M.; Krzywonos, M.; Romanowska-Duda, Z.; Szufa, S.; Darkalt, A.; Mubashar, M. Algal Biomass Utilization toward Circular Economy. *Life* **2022**, *12*, 1480. [CrossRef]
109. Dębowski, M.; Zieliński, M.; Świca, I.; Kazimierowicz, J. Algae Biomass as a Potential Source of Liquid Fuels. *Phycology* **2021**, *1*, 105–118. [CrossRef]
110. Ajeng, A.A.; Rosli, N.S.M.; Abdullah, R.; Yaacob, J.S.; Qi, N.C.; Loke, S.P. Resource recovery from hydroponic wastewaters using microalgae-based biorefineries: A circular bioeconomy perspective. *J. Biotechnol.* **2022**, *360*, 11–22. [CrossRef]
111. Yousif, Y.I.D.; Mohamed, E.S.; El-Gendy, A.S. Using chlorella vulgaris for nutrient removal from hydroponic wastewater: Experimental investigation and economic assessment. *Water Sci. Technol.* **2022**, *85*, 3240–3258. [CrossRef]
112. Leflay, H.; Okurowska, K.; Pandhal, J.; Brown, S. Pathways to economic viability: A pilot scale and techno-economic assessment for algal bioremediation of challenging waste streams. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 3400–3414. [CrossRef]
113. Clippinger, J.; Davis, R. *Techno-Economic Analysis for the Production of Algal Biomass via Closed Photobioreactors: Future Cost Potential Evaluated Across a Range of Cultivation System Designs*; NREL: Golden, CO, USA, 2019. Available online: www.nrel.gov/publications (accessed on 20 September 2019).
114. Béchet, Q.; Shilton, A.; Guieysse, B. Full-scale validation of a model of algal productivity. *Environ. Sci. Technol.* **2014**, *48*, 13826–13833. [CrossRef]
115. Dębowski, M.; Świca, I.; Kazimierowicz, J.; Zieliński, M. Large Scale Microalgae Biofuel Technology—Development Perspectives in Light of the Barriers and Limitations. *Energies* **2023**, *16*, 81. [CrossRef]
116. Kohlheb, N.; van Afferden, M.; Lara, E.; Arbib, Z.; Conthe, M.; Poitzsch, C.; Marquardt, T.; Becker, M.-Y. Assessing the life-cycle sustainability of algae and bacteria-based wastewater treatment systems: High-rate algae pond and sequencing batch reactor. *J. Environ. Manag.* **2020**, *264*, 110459.
117. Cruce, J.R.; Quinn, J.C. Economic Viability of Multiple Algal Biorefining Pathways and the Impact of Public Policies. 2018. Available online: https://www.elsevier.com/open-access/userlicense/1.0/ (accessed on 28 October 2018).

118. Mousavi, S.; Damizia, M.; Hamidi, R.; De Filippis, P.; de Caprariis, B. Techno-economic assessment of gasoline production from Fe-assisted lignocellulosic biomass hydrothermal liquefaction process with minimized waste stream. *Energy Convers. Manag.* **2024**, *320*, 118982. [CrossRef]
119. Thomassen, G.; Egiguren Vila, U.; Van Dael, M.; Lemmens, B.; Van Passel, S. A techno-economic assessment of an algal-based biorefinery. *Clean Technol. Environ. Policy* **2016**, *18*, 1849–1862. [CrossRef]
120. Pizzera, A.; Bellucci, M.; Marazzi, F.; Mezzanotte, V.; Parati, K.; Ficara, E. Piggery Wastewater Treatment with Algae-Bacteria *Consortia*: Pilot-Scale 2 Validation and Techno-Economic Evaluation at Farm Level 3 4 S. 2022. Available online: https://ssrn.com/abstract=4028802 (accessed on 26 March 2022).
121. Busnel, A.; Samhat, K.; Gérard, E.; Kazbar, A.; Marec, H.; Dechandol, E.; Le Gouic, B.; Hauser, J.-L.; Pruvost, J. Development and validation of a screening system for characterizing and modeling biomass production from cyanobacteria and microalgae: Application to *Arthrospira platensis* and *Haematococcus pluvialis*. *Algal Res.* **2021**, *58*, 102386. [CrossRef]
122. Diatin, I.; Shafruddin, D.; Hude, N.; Sholihah, M.; Mutsmir, I. Production performance and financial feasibility analysis of farming catfish (*Clarias gariepinus*) utilizing water exchange system, aquaponic, and biofloc technology. *J. Saudi Soc. Agric. Sci.* **2021**, *20*, 344–351. [CrossRef]
123. Thaotumpitak, V. Prevalence and Molecular Characteristics of Antimicrobial Resistance of *Aeromonas hydrophila*, *Salmonella* spp., *Vibrio cholerae*, Fecal Coliform, and *Escherichia coli* in Hybrid *Red Tilapia* and Cultured Water. 2021. Available online: https://digital.car.chula.ac.th/chulaetd/4952 (accessed on 1 December 2021).
124. Karimi, R.D. The Bacterial Flora of *Tilapia* (*Oleochromis niloticus*) and *Catfish* (*Clarias gariepinus*) from Earthen Ponds in Sagana Fish Farm and Masinga Dam. Ph.D. Thesis, Kenyatta University, Nairobi, Kenya, 2015.
125. Filote, C.; Roșca, M.; Hlihor, R.M.; Cozma, P.; Simion, I.M.; Apostol, M.; Gavrilescu, M. Sustainable application of biosorption and bioaccumulation of persistent pollutants in wastewater treatment: Current practice. *Processes* **2021**, *9*, 1696. [CrossRef]
126. Emenike, E.C.; Iwuozor, K.O.; Anidiobi, S.U. Heavy Metal Pollution in Aquaculture: Sources, Impacts and Mitigation Techniques. *Biol. Trace Elem. Res.* **2022**, *200*, 4476–4492. [CrossRef]
127. Bao, R.; Yang, Y.; Chen, H.; Li, Y. Occurrence, distribution and health risk assessment of quinolone residues in cultured fish in southeast China. *J. Environ. Sci. Health Part B* **2024**, *59*, 714–724. [CrossRef]
128. Ahmad, T.; Mehmood, Z.; Ali, M.; Mawa, J.U.; Irshad, M.A. Navigating the nexus: Unraveling the impact of sustainability and the circular economy on food safety. *Ital. J. Food Saf.* **2025**, *14*, 12580. [CrossRef]
129. Theses, D.; Pilone, F.R. DUNE: DigitalUNE The Waste Management of Large-Scale Recirculating Aquaculture Systems and Potential Value-Added Products from the Waste Stream. 2021. Available online: https://dune.une.edu/theses (accessed on 21 August 2021).
130. Schipfer, F.; Pfeiffer, A.; Hoefnagels, R. Strategies for the Mobilization and Deployment of Local Low-Value, Heterogeneous Biomass Resources for a Circular Bioeconomy. *Energies* **2022**, *15*, 433. [CrossRef]
131. Susanty, E. Analisis Dampak Pemanfaatan Solar Photovoltaic Menggunakan Skema Performance Based Rental (PBR). *JIIP-Jurnal Ilmiah Ilmu Pendidikan* **2024**, *7*, 2729–2737. Available online: http://Jiip.stkipyapisdompu.ac.id (accessed on 3 March 2024).
132. Fuentes, J.L.; Garbayo, I.; Cuaresma, M.; Montero, Z.; González-Del-Valle, M.; Vílchez, C. Impact of microalgae-bacteria interactions on the production of algal biomass and associated compounds. *Marine Drugs* **2016**, *14*, 100. [CrossRef]

https://doi.org/10.3390/phycology6010014