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

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

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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. This review critically examines the latest advances in IAMS design, nutrient recovery strategies, and system integration approaches, with a focus on their potential to address limitations inherent in traditional agriculture, aquaponics, and hydroponics. Key topics include microalgal species selection, photobioreactor configurations, and cultivation parameters optimized for nutrient recycling, water conservation, and biomass valorization. Comparative analyses reveal that IAMS can achieve over 95% nitrogen and phosphorus recovery while reducing water consumption by up to 90% relative to conventional systems. The integration of algal subsystems not only enhances nutrient retention and carbon capture but also enables diversified co-product streams, including biofertilizers, aquafeeds, and protein-rich biomass. Technical and regulatory challenges, ranging from biological synchronization and operational stability to permitting fragmentation and market entry barriers, are discussed alongside economic considerations and system scalability. The environmental performance of IAMS is evaluated through alignment with the United Nations Sustainable Development Goals, particularly SDGs 2, 6, and 13. Finally, the review identifies future research directions involving techno-economic modeling, strain engineering, digital automation, and socio-environmental integration. Collectively, the findings position IAMS as a transformative solution capable of delivering circular, climate-resilient, and nutrient-efficient food systems at both local and global scales.

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Introduction

Global food insecurity, environmental degradation, and climate variability are converging to exert unprecedented pressure on modern agricultural systems. With the global population expected to exceed 9.7 billion by 2050, the need for sustainable, resource-efficient food production frameworks is more critical than ever [1]. This challenge is exacerbated by diminishing arable land, stagnating yield growth, and the intensifying effects of climate change. Projections indicate that agricultural productivity may decline by 3.1–7.4% for every 1 °C rise in global temperature, with the adverse impacts disproportionately affecting vulnerable regions such as sub-Saharan Africa, where over 346 million people remain undernourished [2,3]. Concurrently, almost 40% of the global population is affected by water scarcity, posing significant constraints on agricultural sustainability and food system resilience [2].

Amid these interconnected pressures, nutrient runoff from agriculture has emerged as a leading contributor to water quality deterioration. Excessive application of nitrogen and phosphorus-based fertilizers results in nutrient leaching that drives eutrophication, biodiversity loss, and freshwater degradation. For instance, in China's Taihu Lake Basin, agricultural runoff is responsible for over half of both total nitrogen and phosphorus inputs. Similar patterns of nutrient-induced ecological disruption have been documented in multiple regions, including Europe and North Americ [3,4]. Although strategies such as buffer strips and precision agriculture have shown localized benefits, their scalability and long-term effectiveness remain limited.

Aquaponics has gained increasing attention as a closed-loop solution that integrates aquaculture with hydroponics to enable water and nutrient recirculation. These systems can reduce freshwater usage by up to 90% compared to conventional agriculture, offering substantial resource savings [5]. Advanced configurations such as double recirculating aquaponics systems (DRAPS) have demonstrated improvements in both water efficiency and fertilizer utilization, achieving crop yields comparable to traditional hydroponics with significantly reduced input demands [6]. Nonetheless, aquaponic systems often face persistent challenges related to the limited availability and recycling of key nutrients, particularly nitrogen and phosphorus, which constrain productivity and hinder alignment with global sustainability targets such as SDG 6 (Clean Water and Sanitation) [7,8].

To overcome these constraints, the integration of microalgae has been proposed as a complementary nutrient recovery strategy within aquaponic systems. Strains such as Chlorella vulgaris have demonstrated nitrogen and phosphorus removal efficiencies exceeding 90%, while concurrently producing biomass with applications in agriculture, biofertilizer production, and bioenergy generation [9,10]. Beyond nutrient removal, harvested or immobilized algal biomass can be reintegrated into the food chain or applied as soil amendments, thereby closing internal nutrient loops and minimizing environmental discharge [5]. The relatively low heavy metal content in aquaponic effluents further enhances the usability of algal biomass in food and agricultural applications [11,12].

In addition to nutrient recovery, microalgae offer notable biofunctional advantages that align with broader goals of food security and environmental resilience. Algal dry biomass typically contains 45–65% protein and provides essential micronutrients such as omega-3 fatty acids (DHA, EPA) and vitamins B12, D, and K **[13–15]**. Notably, Chlorella vulgaris contains up to 58% protein by dry weight, significantly exceeding conventional protein sources such as soy (37%) and fish (24%) **[16]**. These attributes highlight the potential of microalgae not only as nutrient recovery agents but also as nutritionally dense components of future food systems.

Furthermore, microalgae contribute to climate change mitigation through their high carbon fixation capacity. Certain strains, including Chlorella, can sequester between 0.77 and 2.22 g CO_2/L/day, even when exposed to industrial flue gases containing NO_x and SO_x **[17]**. Modeling studies have projected that large-scale cultivation covering approximately 53,000 km^2 could remove around 0.54 Gt of CO_2 annually while generating over 324 million tons of biomass. Under optimized conditions, protein yields from algae can reach 22–44 tons per hectare annually, far surpassing terrestrial crops in both land and water use efficiency **[16]**.

The integration of aquaponic systems with microalgae cultivation therefore represents a synergistic and multifunctional approach to address food, water, and climate challenges. While individual systems have been independently validated, studies exploring their combined application remain scarce. Integrated Microalgal–Aquaponic Systems (IAMS) offer considerable potential as platforms for nutrient recycling, protein generation, water conservation, and carbon capture. However, a comprehensive assessment of their performance, design considerations, and sustainability outcomes is yet to be undertaken. This review addresses this gap by critically evaluating IAMS in terms of nutrient loop optimization, algal strain selection, photobioreactor integration, and system scalability, which are key factors necessary for their effective deployment in alignment with the United Nations Sustainable Development Goals.

2. Contextual Background: Food Security and Agricultural Constraints

2.1. Global Food Security Challenges

The anticipated growth of the global population to over 9.8 billion by 2050 presents a formidable challenge to global food security, necessitating a 50–100% increase in food production to satisfy caloric and nutritional needs **[18]**. This rising demand is set against the backdrop of finite natural resources, with agriculture already accounting for 38% of the planet's ice-free land and consuming approximately 70% of global freshwater supplies, making it the most resource-intensive human endeavor **[19]**. Conventional agricultural systems suffer significant inefficiencies, with up to 30–50% of applied irrigation water lost through evaporation and runoff. In contrast, closed-loop configurations such as aquaponics and microalgae cultivation systems demonstrate superior resource-use efficiency, achieving water recycling rates of up to 99% **[11,20]**.

The vulnerability of existing food systems is particularly acute in under-resourced regions such as Sub-Saharan Africa and South Asia, where demographic growth outpaces improvements in agricultural infrastructure. In these regions, limited access to irrigation hampers productivity. Globally, irrigated land constitutes only 20% of cropland but accounts for 40% of total food production, underscoring the yield disparity between irrigated and rain-fed systems **[18]**. Integrated systems, particularly those combining aquaculture and microalgae, offer a practical solution by leveraging nutrient-rich aquaculture effluents to support both plant and algal biomass generation **[21]**. These internal nutrient cycling mechanisms are largely absent in traditional agriculture, yet offer critical advantages for improving productivity under constraints of limited water and fertilizer availability.

Climate change introduces further strain, manifesting through increased temperature extremes, erratic precipitation, and progressive soil degradation. Traditional agriculture remains highly susceptible to such fluctuations. For example, global wheat yields are increasing at just 1.1% annually, which is below the 1.3% threshold necessary to stabilize food prices **[22]**. Conversely, aquaponic systems operate under controlled environmental conditions, enabling stable crop yields regardless of climatic variability. Moreover, while approximately 33% of global soils are degraded due to erosion, compaction, and excessive agrochemical use **[23]**, microalgae cultivation bypasses soil entirely and offers potential to rehabilitate degraded lands through biomass-based soil amendments.

Land scarcity, particularly in rapidly urbanizing regions such as Southeast Asia and West Africa, further constrains agricultural expansion. Fertile lands are increasingly appropriated for industrial and infrastructural development **[24]**. The spatial flexibility of aquaponic systems and microalgal bioreactors, capable of vertical integration or deployment on non-arable terrain, presents a viable alternative. Notably, producing 1 kg of protein from beef requires up to 258 m^2 of land, while the same protein yield from microalgae can be achieved using less than 2.5 m^2 **[25]**. This efficiency positions integrated systems as attractive options for urban agriculture and for regions with constrained land availability.

Nutrient mismanagement in conventional farming also contributes to productivity losses and environmental degradation. In Sub-Saharan Africa, nutrient mining due to limited fertilizer access leads to declining yields, whereas in parts of Asia, excessive fertilizer application results in nutrient runoff and water contamination **[26]**. Aquaponic systems mitigate these issues by repurposing fish waste as a continuous nutrient source. Integration with microalgae enhances this efficiency further, as algae can capture and valorize residual nutrients to produce biomass suitable for biofertilizers, animal feed, or protein supplements. For instance, co-cultivation of plants and microalgae in aquaponic systems has shown an 8% increase in biomass yield compared to monocultures, indicating a synergistic benefit **[27]**.

The increasing global demand for protein intensifies the urgency for alternative production systems. Livestock farming remains the dominant source of dietary protein but imposes heavy environmental costs. The production of 1 kg of beef protein emits up to 60 kg of CO_2-equivalent greenhouse gases, whereas microalgal protein cultivation, particularly when fueled by industrial waste CO_2, results in near-zero emissions **[28,29]**. These figures emphasize the environmental unsustainability of expanding conventional livestock systems and highlight the climate resilience of algae-based alternatives.

Despite advancements in Recirculating Aquaculture Systems (RAS), nutrient losses remain substantial, with nitrogen and phosphorus losses reaching 79% and 83%, respectively **[21]**. However, integration of microalgae with RAS enables near-complete nutrient recovery, transforming aquaculture effluents into high-value biomass. This conversion not only minimizes eutrophication risks but also enhances system circularity, offering a significant improvement over linear, extractive models prevalent in mainstream agriculture.

In view of mounting demographic and environmental pressures, the limitations of conventional agricultural systems are increasingly evident. High-input, land-intensive practices are no longer sustainable. Integrated solutions that combine aquaponics with microalgal cultivation represent a transformative approach capable of enhancing food production, conserving resources, and supporting climate goals. Their adaptability across diverse spatial and climatic contexts makes them particularly relevant in the transition toward sustainable and resilient food systems **[11,20,30]**.

2.2. Limitations of Traditional Agriculture

Conventional agriculture, though historically pivotal to global food production, now faces growing limitations in terms of efficiency, environmental sustainability, and resilience. Among its most pressing drawbacks is the unsustainable consumption of freshwater. Agriculture accounts for nearly 70% of global freshwater withdrawals, yet inefficiencies in irrigation, particularly flood irrigation, result in the loss of up to 60% of applied water through evaporation and runoff **[31,32]**. These losses are especially critical in regions already experiencing water stress, such as sub-Saharan Africa and western India, where groundwater levels are declining by 0.5–1.5 meters annually **[32]**. By contrast, integrated aquaponic systems recycle 95–99% of their water, offering a closed-loop alternative that drastically reduces wastage and enhances water-use efficiency **[33]**.

Environmental degradation associated with traditional agriculture further undermines system viability. Intensive tillage, monocropping, and deforestation have contributed to widespread land degradation, with over 33% of global arable land affected by erosion, salinization, and nutrient loss **[23]**. Soil conservation practices such as no-till agriculture offer partial mitigation, yet more transformative approaches are needed. Aquaponic systems eliminate soil use altogether, bypassing degradation risks while enabling productive cultivation on non-arable or marginal lands. In densely populated nations such as Bangladesh and Nigeria, where per capita arable land is declining rapidly, these systems provide spatially efficient alternatives **[24]**.

Nutrient inefficiency also remains a critical challenge. Despite rising global nitrogen fertilizer application—averaging 68.61 kg/ha and peaking at 228.48 kg/ha in China—plant uptake efficiency remains low, often under 50% [4]. The surplus nutrients frequently leach into surrounding ecosystems, driving eutrophication and contaminating water bodies. In contrast, microalgae-based systems demonstrate superior nutrient recovery, with removal efficiencies exceeding 90% for both nitrogen and phosphorus **[34]**. This capability transforms aquaculture waste streams into productive inputs, highlighting the functional advantages of closed-loop nutrient cycling over open-field fertilization practices that are prone to runoff and loss.

Land-use pressure adds another layer of complexity. Traditional agriculture relies on expansive tracts of fertile land, making it particularly vulnerable to urban encroachment. In countries like Vietnam and Egypt, rapid urbanization has consumed significant portions of fertile deltas, reducing overall food production capacity **[24]**. Conversely, integrated systems such as aquaponics and vertical microalgal cultivation can be deployed on rooftops, basements, or degraded sites, converting previously unusable spaces into productive growing environments. This adaptability is crucial in urbanizing regions where land scarcity and food demand are rising simultaneously.

In addition to land and nutrient limitations, conventional farming is a significant contributor to global greenhouse gas (GHG) emissions. Agricultural activities account for nearly 20% of total anthropogenic emissions, primarily due to livestock methane, fertilizer-induced nitrous oxide, and soil carbon depletion **[35,36]**. Integrated microalgal systems, on the other hand, not only avoid many of these emissions but also actively sequester CO_2 during biomass production. For instance, while conventional maize cultivation emits over 1.5 kg CO_2-equivalent per kilogram of grain, microalgae-based systems have demonstrated the potential for carbon-negative outcomes depending on growth conditions and energy sources **[21,28]**.

The fragility of traditional agriculture is further underscored by its sensitivity to climate variability. Open-field crops are increasingly exposed to extreme weather events such as droughts, floods, and heatwaves. For example, maize yields decline by approximately 1.7% for every 1 °C increase in temperature during drought periods **[37]**. In contrast, integrated aquaponic systems operate in controlled environments, enabling consistent yields and water efficiency even under erratic climatic conditions [11]. These resilience attributes position integrated systems as robust alternatives for regions experiencing heightened climate volatility, including the Sahel and parts of South Asia.

Taken collectively, the inefficiencies and environmental externalities inherent to traditional agriculture underscore the necessity for more sustainable and adaptive alternatives. Integrated systems that merge aquaponics with microalgal cultivation offer a multifaceted solution that addresses water scarcity, land pressure, nutrient loss, and climate vulnerability. As the next section explores, one of the most pressing consequences of these inefficiencies, nutrient-driven water pollution, further reinforces the need for holistic, closed-loop agricultural models.

2.3. Agricultural Runoff and Water Pollution

Nutrient runoff from conventional agriculture remains one of the most pervasive and ecologically damaging forms of water pollution, largely stemming from excessive fertilizer application and inefficient nutrient management. Unlike controlled-environment systems such as aquaponics, traditional open-field agriculture operates without mechanisms to retain surplus nutrients. As a result, significant quantities of nitrogen (N) and phosphorus (P) are lost through leaching and surface runoff, often entering adjacent water bodies where they accelerate eutrophication, trigger harmful algal blooms, and reduce dissolved oxygen levels [4]. In contrast, aquaponic systems operate within a closed-loop configuration, recirculating nutrients internally and effectively transforming waste into input while minimizing environmental discharge [20].

Regional case studies underscore the severity of nutrient-driven pollution. In China's Taihu Lake Basin, agriculture contributes over 50% of the total nitrogen and phosphorus loads, significantly degrading water quality. Similar patterns are evident in the U.S. Midwest, where fertilizer runoff from corn and soybean fields feeds directly into the Mississippi River Basin, contributing to the annual formation of a hypoxic "dead zone" in the Gulf of Mexico [4,38]. In 2017, this dead zone spanned over 22,500 km^2, an area vastly exceeding the footprint of integrated aquaponic systems, which can function with near-zero nutrient discharge [30]. These stark contrasts highlight the environmental costs of nutrient-leaky agricultural models and reinforce the value of closed-loop systems as practical alternatives.

Beyond ecological damage, the broader consequences of nutrient runoff extend to public health and economic stability. In many low- and middle-income countries, surface water contaminated by agricultural runoff is often reused for irrigation, increasing exposure to pathogens such as Escherichia coli and Cryptosporidium parvum, particularly in areas lacking centralized wastewater treatment infrastructure [39]. Conversely, water within aquaponic systems undergoes continuous biological filtration, reducing microbial contamination and enhancing water reuse safety [11]. Additionally, while conventional farms invest substantially in synthetic fertilizers, much of which is lost via runoff, microalgae-integrated systems reclaim these nutrients from aquaculture effluents, achieving nitrogen and phosphorus removal efficiencies exceeding 90% and simultaneously generating valuable algal biomass [34].

Land-use dynamics further exacerbate water pollution in conventional agricultural systems. Expanding urbanization and deforestation for agricultural development disrupt natural hydrological processes, increasing runoff volumes and nutrient export. For example, in China's Guishui River Basin, urban expansion during a rapid development phase led to an 11.6% increase in nitrogen export [40]. Phosphorus loss rates in heavily fertilized croplands can also reach 3.3%, reflecting both the inefficiency and environmental cost of unmanaged nutrient application [4]. In contrast, integrated aquaponic–microalgal systems operate independently of natural soil structures and allow precise nutrient dosing with minimal losses, benefits particularly valuable in space-limited or degraded urban environments.

The impacts of climate change compound these challenges by intensifying nutrient runoff through erratic rainfall events. Heavy downpours, especially following fertilizer application, result in episodic nutrient surges into nearby water bodies, accelerating eutrophication, oxygen depletion, and associated fish mortality events [41]. Open-field farms, lacking adequate retention and drainage systems, remain especially vulnerable to these episodic losses. In contrast, aquaponic systems retain full control over internal water circulation, maintaining operational resilience even under extreme weather conditions and enabling near-total nutrient recapture [11].

Economically, the costs associated with nutrient runoff are substantial. Across Europe and North America, governments allocate billions of dollars annually to mitigate nutrient pollution, restore aquatic ecosystems, and ensure safe drinking water supplies. By comparison, Recirculating Aquaculture Systems (RAS) coupled with microalgae cultivation can eliminate up to 100% of nutrient discharge through efficient internal cycling and algal uptake [21]. This level of resource circularity stands in stark contrast to the linear, waste-intensive design of conventional farming systems.

Collectively, these patterns reveal the growing ecological and economic liabilities of traditional agriculture. The persistent discharge of excess nutrients into freshwater systems is not only unsustainable but increasingly preventable through the adoption of integrated technologies. Systems combining aquaponics with microalgae cultivation represent a scalable and environmentally sound alternative, capable of minimizing pollution, maximizing nutrient reuse, and supporting resilient food production. As global pressures on water quality intensify, these closed-loop systems offer a pragmatic path forward, one that aligns environmental stewardship with agricultural productivity.

3. Aquaponic Systems: Promise and Limitations

3.1. Overview of Aquaponics

Aquaponics represents a biologically integrated system that combines aquaculture with hydroponics in a closed-loop configuration aimed at sustainable food production. In this system, nutrient-rich aquaculture effluent is recirculated to hydroponic grow beds, where plants absorb essential nutrients and, in turn, purify the water before it returns to the fish tanks. This dual-purpose mechanism not only reduces synthetic input requirements but also enhances waste reuse and resource circularity, offering clear environmental and operational advantages over conventional agriculture and aquaculture models that operate with linear, extractive inputs and generate substantial effluent volumes **[42,43]**. Unlike soil-based systems, where nutrient losses through leaching and surface runoff are common, aquaponics retains and reuses nutrients internally, improving nutrient-use efficiency while minimizing ecosystem degradation.

One of the most well-documented benefits of aquaponics is its exceptional water-use efficiency. Conventional irrigation practices consume 250–500 liters of water per kilogram of produce, while aquaponic systems can reduce this to as low as 25–50 liters through continuous recirculation **[42,44]**. Similarly, traditional intensive aquaculture operations may require up to 300 liters of water per kilogram of fish, whereas aquaponic systems typically operate with less than 100 l[42,43iters **[42]**. These reductions are particularly significant in arid and water-scarce regions such as sub-Saharan

Africa and the Middle East, where resource efficiency is critical. Comparative field studies have shown that lettuce cultivated in aquaponic systems requires 85% less water than soil-based farming and 60% less than standard hydroponics, underscoring aquaponics' water-saving potential even among modern controlled-environment systems **[43,45]**.

Beyond water conservation, aquaponics enables dual production of plant and aquatic species using a single nutrient stream, thereby enhancing land productivity and income diversification. For instance, basil grown in coupled aquaponic systems with Nile tilapia yielded 20% more biomass per square meter compared to hydroponic monocultures, attributed to optimized nutrient cycling and microbial interactions **[44]**. Fish performance remained stable across treatments, with feed conversion ratios comparable to conventional recirculating aquaculture systems. Such outcomes reinforce aquaponics' potential to intensify food production within a fixed spatial footprint, an important consideration given the increasing competition for fertile land in both rural and urban environments.

A further advantage lies in aquaponics' reduced reliance on synthetic nutrient inputs. While hydroponic systems require commercially prepared nutrient formulations, aquaponic systems derive most essential nutrients, including nitrogen, phosphorus, and micronutrients, from fish waste. In many configurations, chemical fertilizer substitution can reach up to 100%, dramatically lowering operational dependency on external inputs **[42]**. This shift has broad sustainability implications because fertilizer manufacturing is energy-intensive and a notable contributor to global greenhouse gas emissions. In contrast, aquaponics recycles internal nutrients in a near-zero discharge loop, while the controlled system design also eliminates the need for pesticides, further enhancing the environmental profile of the technology **[46]**.

Environmental performance can be further improved through renewable energy integration. Aquaponic systems powered by solar photovoltaics have demonstrated substantial reductions in greenhouse gas emissions, up to 70% lower than systems reliant on grid electricity, and 35% less freshwater eutrophication potential in comparative life cycle assessments **[46]**. When benchmarked against energy-intensive vertical farms or greenhouse hydroponics dependent on synthetic nutrient supplies, aquaponics presents a more sustainable and decentralized option, particularly suitable for food production in off-grid or resource-constrained settings.

In terms of spatial adaptability, aquaponic systems offer unique deployment advantages. Unlike conventional farming, which depends on fertile soil and extensive land, aquaponic units can be installed in unconventional locations such as rooftops, shipping containers, or degraded land unsuitable for agriculture **[42]**. Their modularity and climate resilience allow for continuous, year-round production regardless of external conditions. These traits have facilitated successful implementation across diverse geographies, from arid Middle Eastern environments to densely populated urban centers in East Asia, where conventional agricultural expansion is limited by land and water constraints.

Despite its numerous advantages, aquaponics is not without limitations. Challenges related to nutrient imbalances, energy consumption, and scalability continue to hinder widespread adoption. These limitations underscore the need for system enhancements. The following sections explore how integrating microalgae into aquaponic systems can address existing performance gaps, elevate resource recovery efficiency, and transform aquaponics into a more circular and resilient platform for future food systems.

3.2. Nutrient Management Issues

Despite its advantages in reducing chemical inputs and conserving water, aquaponics continues to face persistent challenges in nutrient management. A core limitation arises from the biological mismatch between the nutrient composition of fish effluent and the specific nutritional demands of many plant species. While fish waste provides a steady supply of nitrogen, it often lacks sufficient quantities of phosphorus, potassium, and calcium, nutrients that are essential for flowering and fruit-bearing crops **[42]**. As a result, up to 20% of the required nutrient load must be supplemented externally to sustain optimal plant productivity **[42]**. This dependency reveals a fundamental constraint of aquaponics: the system's reliance on fish metabolism limits the ability to tailor nutrient profiles, particularly for high-demand or specialty crops. By contrast, hydroponic systems enable precise, crop-specific nutrient dosing, resulting in consistent yields across a wider spectrum of plant varieties.

The complexity of nutrient dynamics in aquaponic systems further complicates this issue. Nutrient availability is influenced by multiple variables, including fish species, feed quality, feeding rates, biofilter performance, and environmental conditions such as water temperature. While leafy greens like lettuce and kale thrive under these fluctuating nutrient levels due to their relatively modest requirements, fruiting crops such as tomatoes and bell peppers often require targeted phosphorus and potassium supplementation to avoid deficiencies **[42]**. This creates selective crop compatibility, which limits economic diversification and scalability. To address this constraint, decoupled aquaponic systems have been introduced, allowing independent control of fish and plant nutrient loops. Although these configurations enable greater nutrient optimization, they compromise the biological symbiosis that defines traditional aquaponics, creating a trade-off between operational flexibility and ecological integrity.

In addition to internal imbalances, nutrient losses via discharge remain a notable concern, even in systems marketed as near-zero waste. Recirculating Aquaculture Systems (RAS) integrated within aquaponics still require occasional water exchange and sludge removal to maintain water quality. These waste streams often carry residual nitrogen and phosphorus, which, if not appropriately treated, can contribute to eutrophication and environmental degradation **[44]**. Although nutrient retention in aquaponics is significantly better than in conventional aquaculture, where nitrogen and phosphorus losses can reach 79% and 83%, respectively **[21]**, it remains inferior to certain decentralized treatment systems. For instance, constructed wetlands have demonstrated nitrogen removal efficiencies exceeding 90%, highlighting the performance gap between aquaponics' sustainability goals and real-world nutrient containment outcomes.

Sludge management within aquaponic systems introduces additional operational complexity. While repurposing sludge as biofertilizer can reduce freshwater eutrophication by up to 23% **[44]**, the variable composition and irregular volume of aquaponic sludge necessitate continuous monitoring and post-treatment. Compared to composting in organic farming, which yields more stable nutrient compositions and shelf-stable amendments, aquaponic sludge represents a less predictable resource. Moreover, high-protein fish feeds commonly used in aquaculture result in effluents rich in nitrogen but deficient in phosphorus and potassium, creating imbalanced nutrient profiles that require corrective supplementation **[42]**. Although switching to more balanced or plant-based diets may reduce nutrient skew, such adjustments often compromise fish growth performance and feed conversion efficiency, introducing a new trade-off between aquaculture productivity and nutrient optimization for crops.

Collectively, these nutrient-related limitations illustrate the systemic challenges in new trade-off circularity within aquaponic systems. Compared to hydroponics, aquaponics offers lower input dependency but reduced nutrient precision; compared to decentralized wastewater treatment, it enables food production but with diminished nutrient capture performance. Bridging these gaps will require innovative system redesigns and the incorporation of advanced biological solutions. As discussed in the following section, the integration of microalgae into aquaponic frameworks offers a promising avenue to recover residual nutrients, reduce discharge, and move aquaponics toward a more resilient, circular, and resource-optimized production model.

3.3. Untapped Potential for Integration

The unresolved nutrient inefficiencies and operational limitations of conventional aquaponic systems highlight the growing need for enhanced integration strategies that extend beyond traditional plant-based recovery. Among emerging solutions, the incorporation of microalgae presents a highly promising avenue for closing nutrient and resource loops. Unlike terrestrial crops, which are constrained by root architecture and species-specific nutrient uptake thresholds, microalgae demonstrate rapid growth kinetics and exceptional assimilation efficiencies. These traits enable them to address nutrient imbalances more effectively, particularly in aquaponic systems where conventional biofilters are designed to oxidize ammonia but fall short in capturing excess phosphorus or regulating micronutrient availability [43,47].

Under optimized conditions, microalgal systems have achieved over 90% removal efficiency for nitrogen and phosphorus in aquaculture effluents, substantially outperforming advanced plant-based nutrient recovery approaches, which often plateau at 60–70% due to crop saturation limits and harvesting cycles [47,48]. Compared to land-intensive constructed wetlands that require extended retention times, microalgae offer a compact, high-throughput solution well-suited to urban and space-constrained environments. Moreover, unlike chemical-based treatment technologies such as precipitation or ion exchange, microalgal nutrient recovery is entirely biological, simultaneously producing a secondary biomass stream with commercial value. This dual functionality, combining pollutant removal and biomass generation, makes microalgae particularly attractive for integrated food-water-energy systems.

In addition to nutrient remediation, microalgae play a pivotal role in carbon capture, a parameter of increasing relevance in climate-resilient agriculture. Species such as Chlorella sp. can fix carbon dioxide at rates up to 2.22 g/L/day, offering a natural alternative to energy-intensive carbon capture technologies [49]. In contrast, standard aquaponic and hydroponic systems lack any intrinsic carbon sequestration mechanism and may contribute to CO_2 emissions through energy use and microbial respiration. Even when powered by renewable energy, their carbon neutrality is limited by the absence of internal sinks. By incorporating microalgae, aquaponic systems can simultaneously reduce their net emissions and improve oxygenation, enhancing microbial performance in biofilters and further optimizing nutrient cycling.

The economic and functional versatility of aquaponic systems is also significantly enhanced through algal integration. Traditional sludge management, often reliant on offsite disposal or regulated land application, introduces logistical complexity and recurring operational costs. Microalgae, by contrast, can directly assimilate dissolved nutrients from decanted waste streams, producing biomass suitable for multiple downstream applications. Depending on the processing pathway, this biomass can serve as fish feed, organic fertilizer, bioplastic precursor, or even a substrate for high-value compounds [50,51]. In comparison, other waste valorization pathways such as composting or anaerobic digestion offer slower processing rates and generate end-products with more limited applications. For instance, digestate requires stabilization prior to use, whereas algal biomass can be harvested, processed, and reintegrated within the same production cycle, enhancing internal efficiency and reducing reliance on external systems.

From a discharge mitigation standpoint, algae-integrated systems also outperform conventional aquaponics. Even under best management practices, traditional systems experience nutrient leakage due to filtration inefficiencies, water exchange, and sludge removal. The addition of algal reactors, whether as side-loop photobioreactors or open raceways, enables continuous nutrient scavenging from effluent streams that would otherwise contribute to eutrophication. This approach offers a more ecologically integrated alternative to decoupled systems, which require chemically formulated nutrient solutions and increased energy inputs to compensate for biological separation. In contrast, algae-based configurations maintain ecological synergy while achieving enhanced nutrient precision, making them more cost-effective and sustainable over the long term.

Viewed through the lens of circular bioeconomy, microalgae serve as the keystone that transforms aquaponics from a semi-closed system into a regenerative platform. Even high-efficiency hydroponic or RAS models remain dependent on synthetic inputs and external waste management. By integrating microalgae, aquaponic systems can not only eliminate nutrient losses but also diversify outputs, producing fish, vegetables, protein-rich biomass, and bioactive compounds within a single infrastructure. Such multi-output potential remains unmatched by standalone food production systems [43,52]. As pressures on land, water, and nutrient resources continue to intensify, this integrated approach represents a critical step forward in aligning agricultural productivity with environmental stewardship.

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

4.1. Concept and System Architecture

The Integrated Microalgal–Aquaponic System (IAMS) represents a next-generation platform for sustainable food and water production, achieved by integrating aquaculture, hydroponics, and microalgal cultivation within a single biologically interconnected framework. Developed to address the nutrient imbalances and discharge challenges that persist in conventional aquaponic systems, IAMS introduces a tertiary biological unit composed of microalgae that enhances nutrient retention, facilitates advanced water purification, and contributes to carbon mitigation. This tri-trophic integration forms a continuous feedback loop that enables circular resource flows and the production of high-value coproducts within a closed system **[43,47]**.

At the core of the IAMS design is a sequential nutrient and water flow architecture encompassing three interlinked subsystems: aquaculture tanks, hydroponic beds, and microalgal photobioreactors (PBRs). Effluent from fish tanks, typically rich in ammonia and organic solids, first passes through mechanical and biological filters that initiate solid separation and ammonia oxidation. The partially treated water is then directed to hydroponic units, where plants absorb nitrates and available micronutrients. Unlike conventional aquaponics, where the effluent returns directly to the fish tanks, residual nutrient-rich water is further conveyed to microalgal PBRs. Here, strains such as Chlorella vulgaris and Scenedesmus obliquus assimilate remaining nitrogen, phosphorus, and trace elements while concurrently releasing oxygen through photosynthesis, completing a tertiary treatment phase that strengthens system performance **[53,54]**.

This additional algal treatment step delivers a marked improvement over the dual-loop configurations of standard aquaponic systems, which often plateau in nutrient removal due to plant uptake limits and seasonal productivity variation. Microalgae-integrated units have demonstrated nitrogen and phosphorus removal efficiencies exceeding 90%, whereas plant-only systems typically range between 60% and 70% due to physiological saturation thresholds **[43,48]**. Although alternative treatment strategies such as constructed wetlands or chemical precipitation can achieve comparable results, they generally demand larger land areas and higher energy inputs. In contrast, PBRs enable compact, biologically driven nutrient polishing with a smaller spatial footprint and lower operational cost.

Beyond nutrient optimization, IAMS addresses another fundamental inefficiency in aquaponic operations: dissolved oxygen management. Conventional systems often depend heavily on mechanical aeration to maintain aerobic conditions necessary for fish metabolism and biofilter activity. However, the photosynthetic activity of microalgae within the PBRs naturally enriches the system with oxygen during daylight hours, reducing the need for external aeration infrastructure. This photosynthetic oxygenation becomes particularly advantageous in off-grid or low-energy contexts where operational energy savings are critical. Compared to recirculating aquaculture systems (RAS) that rely exclusively on oxygen injection, IAMS offers a passive, self-sustaining alternative for maintaining oxidative balance.

The modularity and scalability of IAMS also enhance its applicability across diverse operational settings. In compact or urban environments, flat-panel PBRs can be mounted vertically or stacked to maximize space and light exposure. For industrial-scale deployments, horizontal and tubular PBR designs offer superior surface-area-to-volume ratios, enabling high biomass yields and efficient light utilization **[55,56]**. This flexibility compares favorably with vertical farms or rooftop hydroponics, which, despite their spatial efficiency, lack integrated nutrient recovery and multi-product outputs. Moreover, by harnessing microalgal CO_2 fixation, IAMS contributes actively to climate mitigation, in contrast to carbon-positive operations that remain reliant on synthetic inputs and grid-based energy.

Species selection within the algal module can be tailored to match specific environmental and production objectives. For instance, Chlorella vulgaris is well regarded for its high nitrogen and phosphorus assimilation capacity, while Spirulina platensis yields protein content as high as 65–70% dry weight, making it suitable for aquafeed or dietary supplement applications **[54,57]**. This functional diversity enables IAMS configurations to align with a broad spectrum of sustainability and economic performance goals.

4.2. Microalgal Species Selection

Species selection is a cornerstone of Integrated Microalgal–Aquaponic System (IAMS) design because it dictates nutrient-removal performance, biomass productivity, and downstream market value. Unlike conventional aquaponics, where plants provide the main nutrient sink, IAMS assigns the tertiary polishing role to microalgae, which must simultaneously deliver oxygenation, carbon capture, and valorisable biomass. Candidate strains are therefore evaluated based on three intersecting criteria: (i) balanced nitrogen and phosphorus assimilation, (ii) tolerance to the variable physico-chemical conditions typical of recirculating water loops, and (iii) capacity to accumulate protein, lipids, or specialty metabolites with commercial relevance **[54,57]**.

Chlorella vulgaris is the most frequently deployed strain and remains the benchmark for nutrient remediation. Under standard aquaponic effluent loads, it routinely achieves 95–98% nitrogen removal and over 92% phosphorus removal—figures that exceed the 55–70% uptake observed in hydroponic lettuce and outperform commercial algal staples such as Dunaliella salina (75–82% N; 70–78% P). Its broad pH tolerance (6.5–8.5) provides 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 match.

Where nutritional enrichment is paramount, Spirulina platensis provides a compelling alternative. Although its phosphorus capture is modestly lower (85–90%), its protein content reaches 65–70% of dry mass, surpassing C. vulgaris (45–55%) and eclipsing conventional protein sources such as soybean meal (~44%) and fish meal (~60%) **[54]**. For resource-limited regions facing dietary protein deficits, Spirulina offers an economical, scalable supplement. Comparatively, Nannochloropsis sp. provides similar protein yields (52–60%) but lags in growth rate and volumetric productivity (0.15–0.25 g L^{-1} day^{-1}), reducing its suitability for high-throughput facilities.

Systems targeting biofuel co-products often prioritize lipid accumulation, a niche where Scenedesmus obliquus excels. Under nitrogen-limited regimes, it reallocates carbon into neutral lipids more efficiently than Spirulina, which channels available nutrients predominantly into protein **[57]**. With moderate protein content (50–58%) and robust growth on aquaponic effluents, Scenedesmus supports dual-output strategies that couple nutrient polishing with feedstock generation for biodiesel or oleochemical extraction.

Several other taxa deliver situational advantages. Nannochloropsis sp. tolerates saline or brackish recirculating loops and maintains productivity under sub-optimal irradiance, making it suitable for coastal or low-light installations. Conversely, Dunaliella salina is valued for its high β-carotene content, positioning it for nutraceutical applications. However, its lower protein yield and moderate nutrient-removal rates confine it to secondary cultivation modules where space and light are not limiting.

Operational resilience under fluctuating field conditions is essential for decentralized deployments. Both C. vulgaris and Tetradesmus obliquus (syn. Scenedesmus) maintain consistent performance across variable light, temperature, and nutrient loads, making them reliable workhorses in low-infrastructure settings **[57]**. By contrast, D. salina and Nannochloropsis sp. demand tighter salinity and irradiance control, restricting their viability in dynamic or resource-constrained environments. These comparative insights reinforce the importance of selecting species that balance nutrient-removal goals with local environmental conditions and economic endpoints.

4.3. Photobioreactor (PBR) Designs and Integration Approaches

Photobioreactors (PBRs) form the functional and structural backbone of tertiary nutrient recovery and biomass generation in Integrated Microalgal–Aquaponic Systems (IAMS). While traditional aquaponic configurations rely on plant beds for nutrient uptake, the incorporation of microalgal PBRs introduces a biologically driven polishing stage that significantly enhances system efficiency. Compared to passive removal techniques such as constructed wetlands or gravel biofilters, PBRs offer a more compact, controllable, and scalable platform capable of supporting dense algal cultivation with high nutrient assimilation efficiency **[58,59]**.

Among the various configurations, flat-panel, tubular, and hybrid PBRs are most commonly deployed in IAMS applications. Flat-panel systems are frequently preferred due to their high surface-to-volume ratios and uniform light distribution, achieving biomass productivities up to 2.0 g/L and nutrient removal efficiencies exceeding 95% under controlled conditions **[55]**. Horizontal tubular reactors, while slightly less productive in volumetric terms (1.4–1.7 g/L), offer superior scalability and spatial optimization. These systems can reduce the overall footprint by up to 50% compared to flat-panel reactors of equivalent capacity, making them especially attractive for rooftop installations and greenhouse retrofits **[56,60]**. In contrast, open raceway ponds commonly used in wastewater treatment require five to ten times more land to achieve comparable output and are more susceptible to contamination and evaporative losses.

Hybrid PBRs, which combine the operational benefits of both flat-panel and tubular systems, have demonstrated consistent performance across variable light and temperature conditions. These designs typically achieve nitrogen and phosphorus removal efficiencies of 93–96% while offering improved gas exchange and internal mixing **[61,62]**. Compared to vertical column reactors, which often suffer from light attenuation and suboptimal hydrodynamics, hybrid configurations allow for better integration of high-protein strains such as Spirulina platensis. Additionally, the modular nature of hybrid PBRs supports the co-location of multiple microalgal species in parallel reactors, enabling tailored nutrient recovery and the production of distinct biomass coproducts within a single IAMS facility.

Material selection plays a pivotal role in optimizing PBR performance and longevity. While borosilicate glass has historically been used for its chemical stability and optical clarity, advances in materials science have led to the adoption of transparent polymers such as acrylic and polycarbonate. These materials offer comparable light transmittance (83–95%) while reducing reactor weight by more than 60%, thereby facilitating installation and minimizing structural load **[63,64]**. In mobile or low-resource settings, polymer-based PBRs outperform their glass counterparts in terms of durability and transportability. Furthermore, the malleability of polymer materials allows for curved or angular designs that optimize photon capture by adjusting to incident light angles more effectively than rigid, flat surfaces.

Lighting strategy is central to maximizing phototrophic growth efficiency. Red-blue LED systems have demonstrated photosynthetic conversion efficiencies up to 22%, significantly outperforming traditional white fluorescent lamps **[65,66]**. For example, algal biomass productivity in flat-panel PBRs equipped with red-blue LEDs has reached 40 $g/m^2/day$, compared to 25–28 $g/m^2/day$ under standard fluorescent lighting. Moreover, LED systems consume 50–60% less energy, making them more viable for off-grid or energy-sensitive IAMS applications. Unlike hydroponic lighting, which typically operates at high intensity to support fruiting crops, PBRs can maintain high productivity under intermittent or lower-intensity light, enabling energy savings through load shifting and demand-responsive lighting schedules.

Recent innovations have further expanded the design frontier of PBRs. The tangent double-tube photobioreactor (TDTP), for instance, utilizes vortex-induced mixing to enhance mass transfer and gas–liquid exchange. This configuration has demonstrated 124% higher biomass productivity and carbon fixation rates up to 0.8 g/L/day, well above the performance of standard tubular systems **[67]**. When compared to shallow raceway ponds, which rarely exceed 0.2 g/L/day and require continuous mechanical mixing, TDTPs offer significantly higher efficiency with a reduced spatial footprint and lower contamination risk, making them ideal for high-value biomass applications in controlled settings.

The modularity of PBRs is central to their integration potential within aquaponic infrastructures of varying scales. For small-scale or educational systems, vertically stacked flat-panel units enable efficient light utilization in confined urban settings. Larger installations, such as commercial aquaponic farms, may benefit from hybrid or tubular arrays arranged in series to accommodate higher nutrient loads and biomass throughput. Crucially, the ability to isolate, clean, and replace individual modules without disrupting the entire system grants IAMS operational flexibility not typically available in conventional hydroponics or aquaculture setups, which often require full system downtime during maintenance cycles.

4.4. Cultivation Strategies for Optimized System Performance

The performance and stability of Integrated Microalgal Aquaponic Systems (IAMS) are strongly influenced by microalgal cultivation parameters. Unlike hydroponic crops or conventional aquaponic plants that tolerate broad environmental fluctuations, microalgae are highly sensitive to physicochemical variations. Achieving high nutrient recovery, consistent biomass productivity, and long-term system resilience therefore depends on precise control of light regimes, carbon availability, pH, temperature, and cultivation mode **[55,56]**.

Among these parameters, light intensity and spectral composition are primary determinants of microalgal growth rates. Red and blue LED lighting, targeting the 620–680 nm (red) and 450–470 nm (blue) wavelengths, can enhance photosynthetic efficiency by up to 22% compared to full-spectrum or white sources, particularly in Chlorella vulgaris and Scenedesmus obliquus **[66]**. Comparative trials have shown that flat-panel photobioreactors (PBRs) illuminated at 300–400 μmol m^{-2} s^{-1} yield 30–45% more biomass than systems using natural light or fluorescent lamps. Unlike terrestrial hydroponic plants that require deep light penetration and extended photoperiods due to canopy shading, microalgae thrive in shallow cultures with uniform exposure, enabling efficient photon utilization and reduced energy consumption per surface area.

Aeration plays dual roles in IAMS by facilitating gas exchange and supplying carbon dioxide essential for autotrophic metabolism. Ambient air (about 0.04% CO_2) is insufficient for robust algal growth. Enriching aeration streams with 2–5% CO_2 enhances biomass productivity by 1.5–2 times and increases nitrogen assimilation by 20–30% **[54]**. In conventional aquaponics, carbon availability is often constrained by respiratory oxygen demand from fish and nitrifying microbes, resulting in localized carbon depletion, acidification, and reduced algal metabolism. Unlike hydroponic systems, which do not rely on external CO_2 supplementation, IAMS requires deliberate aeration strategies to maintain carbon balance and optimize nutrient uptake efficiency.

pH regulation is equally critical for integrated operation. Whereas hydroponic crops perform well between pH 5.5 and 7.5, most microalgae, including Chlorella and Spirulina, exhibit optimal growth in the 7.0–8.5 range. Deviations from this window can induce phosphorus precipitation, inhibit enzyme activity, and lower nutrient assimilation efficiency. Stabilization using CO_2 bubbling or sodium bicarbonate buffering has been shown to improve nutrient uptake by up to 20% **[58]**. Without active pH control, photosynthetic alkalinity spikes in daylight can raise pH above 9.0, impairing both microbial and algal processes. Buffered IAMS configurations maintain pH stability and thus ensure consistent nutrient conversion.

Temperature compatibility further supports synchronized subsystem performance. Warm-water aquaculture species such as tilapia and catfish thrive at 25–30 °C, conditions that also favor Scenedesmus obliquus and Spirulina platensis. Scenedesmus exhibits approximately 25% greater lipid accumulation at 28 °C than at 20 °C, aligning well with aquaculture temperature ranges. This thermal convergence allows IAMS to maintain stable productivity without differential climate control, unlike hydroponic crops such as lettuce or kale that prefer 18–22 °C and may require cooling to avoid heat stress when co-located with fish tanks.

Cultivation mode is another determinant of productivity and nutrient stability. Continuous cultivation, in which fresh medium is regularly added and biomass is incrementally harvested, provides more consistent operation than batch or semi-batch modes. Under continuous operation, nutrient removal rates can rise by up to 30%, and volumetric biomass productivity by around 40% **[57]**. In contrast, hydroponic and conventional aquaponic systems follow fixed crop cycles that cause episodic nutrient surpluses or deficits. The dynamic uptake of continuously cultured microalgae smooths these fluctuations, stabilizing system chemistry over time.

Hydraulic retention time (HRT) and nutrient loading are also central to optimization. High-rate PBRs perform best with nitrogen loads of 10–30 mg L^{-1} day^{-1} and HRTs of 3–7 days, depending on light intensity and strain kinetics **[67]**. Exceeding these limits can lead to biomass washout or incomplete assimilation, whereas low loading underutilizes available growth potential. In contrast to hydroponics, where nutrient inputs are precisely dosed, aquaponic nutrient levels fluctuate with fish feeding and metabolism. The algal module acts as a biological buffer by absorbing nutrient spikes during feeding cycles and maintaining low residual levels during quiescent phases.

Collectively, these cultivation strategies illustrate how fine-tuned environmental control underpins the effectiveness of IAMS. When tailored to strain-specific tolerances and coordinated with aquaculture and hydroponic subsystems, microalgae function as adaptive stabilizers that transform IAMS into a high-efficiency, climate-resilient food, water, and energy platform.

4.5. Nutrient Recycling and Water Resource Recovery

A defining innovation of Integrated Microalgal Aquaponic Systems (IAMS) lies in their ability to convert nutrient-rich effluents into valuable resources through closed-loop recycling. Unlike conventional aquaculture or hydroponics that operate under semi-open, linear input–output regimes, IAMS achieves near-total reuse of nitrogen, phosphorus, and water. This systems-level integration directly addresses one of modern agriculture's principal inefficiencies, the loss and mismanagement of essential nutrients and freshwater resources [54,57].

In standard aquaponic designs, nutrient cycling effectively terminates at the hydroponic bed, where plant uptake is constrained by physiological limits and asynchronous nutrient demand. Residual nitrogen, phosphorus, and dissolved organic matter often escape recovery, leading to discharge or water replacement. IAMS overcomes this limitation through a tertiary nutrient polishing stage facilitated by microalgal PBRs containing species such as Chlorella vulgaris and Scenedesmus obliquus. These strains have achieved nutrient removal efficiencies of up to 98% for phosphorus and over 95% for nitrogen in post-plant effluent streams. In comparison, plant-only systems typically attain 65–80% uptake under optimal conditions. Relative to alternative methods such as constructed wetlands or sand filtration, algal PBRs offer superior control, higher throughput, and smaller spatial requirements.

Crucially, nutrient recovery in IAMS simultaneously generates usable biomass. Assimilated nitrogen and phosphorus are converted into algal biomass that can be reintegrated within the system. Feeding trials indicate that algal biomass derived from IAMS can replace 30–35% of commercial fishmeal in aquaculture diets without compromising feed conversion ratios or fish growth [54]. This distinguishes IAMS from recovery methods such as struvite precipitation or membrane filtration, which produce non-edible by-products and require external processing. In contrast, IAMS converts waste directly into value-added bioproducts, including proteins, lipids, pigments, and bioactive compounds, enhancing both ecological and economic efficiency.

Water-use efficiency represents another major advantage of IAMS. Recirculating aquaculture systems (RAS) typically consume 0.5–1.0 m^3 of water per kilogram of fish, while hydroponic systems often require periodic flushing to control salt buildup and disease. In contrast, IAMS equipped with algal polishing and microbial filtration can reduce consumption below 0.1 m^3 per kilogram of fish, achieving retention rates above 95% [55,58]. Such water savings are especially valuable in arid climates and urban food systems constrained by limited freshwater availability.

Beyond internal efficiency, IAMS minimizes external nutrient discharge. Conventional aquaponics, though more sustainable than standalone aquaculture, still loses 15–25% of nutrients through sludge removal and water exchanges. Integration of PBRs can lower these losses to under 5%, matching the performance of advanced biological treatment systems. Case studies report nitrogen discharge reductions of approximately 92% and phosphorus reductions of about 94% in algae-integrated aquaponic systems compared with conventional controls operating under similar feed and hydraulic loads [67]. Unlike decentralized wastewater treatment setups that require dedicated infrastructure, IAMS achieves such reductions while simultaneously producing high-value biomass.

Material-flow analyses further confirm the strong retention capacity of IAMS. Closed-loop configurations have retained more than 85% of nitrogen and 80% of phosphorus within the system over 30 days of operation [57]. By contrast, hydroponic nutrient solutions often lose 30–40% of their nutrients between replenishment cycles. Moreover, IAMS recycles not only dissolved nutrients but also suspended solids and organic carbon through microbial mineralization and algal assimilation, processes largely absent in conventional plant-based systems. This holistic recovery framework sustains high productivity while minimizing reliance on external fertilizer and water inputs, advancing IAMS as a regenerative model for circular bioproduction.

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

5.1. Economic Viability and Market Analysis

The long-term scalability and mainstream adoption of Integrated Microalgal Aquaponic Systems (IAMS) will ultimately depend on their economic feasibility. While the ecological and resource efficiency benefits of IAMS are well established, their financial performance remains a central consideration, particularly in comparison with conventional aquaponic, hydroponic, or aquaculture systems. System integration, especially the inclusion of photobioreactors (PBRs), introduces capital and technical complexity that surpass traditional configurations. However, IAMS simultaneously internalize resource flows, minimize reliance on external inputs, and generate diversified outputs, positioning them as high-yield platforms when scaled with appropriate design and operational efficiencies **[5,27]**.

Capital expenditure (CAPEX) in IAMS is estimated to be 30–60% higher than in plant-based aquaponics, driven largely by the inclusion of PBR units, CO_2 delivery mechanisms, and nutrient recycling infrastructure. In standalone algal systems, PBRs may account for up to 77% of initial setup costs **[68]**. Hydroponic farms, by contrast, operate with lower infrastructure costs but incur recurring expenses for synthetic fertilizers and energy. Recirculating aquaculture systems (RAS) also require sophisticated biofiltration and water treatment, increasing long-term operating costs. Although IAMS are more capital intensive initially, they exhibit lower operational expenditure (OPEX) over time through reduced water use, fertilizer inputs, and energy consumption, benefits that are rarely consolidated in single-loop systems [5].

The economic appeal of IAMS is further enhanced by their ability to generate multiple revenue streams from a unified input cycle. Beyond fish and vegetable outputs, algal biomass from PBRs can be transformed into high-value coproducts such as aquafeeds, biofertilizers, pigments, and nutraceuticals. A techno-economic analysis of an IAMS integrated with biodiesel production reported annual profits exceeding USD 30 million at a biomass output of 32,900 tons per year, outperforming monoculture algal or aquaponic systems **[68]**. Traditional aquaponics typically produce only two saleable outputs, limiting profitability and resilience against market volatility. Even vertical farming models that emphasize spatial efficiency do not match the input-to-output conversion capacity of IAMS, particularly where nutrient recycling and waste valorization are prioritized.

In import-reliant or resource-constrained regions, the decentralization potential of IAMS provides additional economic and food security advantages. In sub-Saharan Africa, for instance, fertilizer prices have surged due to supply chain disruptions. IAMS can serve as internally buffered systems that minimize dependency on volatile agro-input markets [5]. Conventional farming operations remain vulnerable to fluctuating fertilizer, feed, and irrigation costs, which can account for over 50% of total expenditures in smallholder systems. By capturing and reusing internal nutrients, IAMS reduce external dependence and stabilize production, enhancing both economic and operational resilience.

Technological advances are improving the economic profile of IAMS. Modular hybrid PBRs optimized for light distribution and gas exchange have demonstrated 20–40% reductions in energy consumption compared with earlier designs **[27]**. Integration of IoT-enabled sensors and automated control systems allows real-time adjustment of lighting, nutrient dosing, and hydraulic flow, reducing labor costs and enhancing reliability. Compared with conventional aquaponics, which often rely on manual monitoring of pH and feeding, automated IAMS enable higher scalability and precision. These innovations lower downtime, minimize error, and shorten payback periods.

Nevertheless, scaling IAMS remains constrained by limited financial support. Conventional agriculture benefits from established subsidies, credit lines, and insurance instruments, whereas IAMS are still largely absent from national green finance frameworks. This funding gap hinders wider deployment, especially among early adopters and small enterprises. Public–private partnerships and targeted incentives, including carbon credits, wastewater reuse subsidies, and sustainable agriculture grants, will be crucial to support commercialization and reduce investor risk **[5,69]**. Similar mechanisms have been applied successfully to solar irrigation, composting, and anaerobic digesters in various regions. Extending equivalent recognition to IAMS is essential to strengthen competitiveness and accelerate mainstream adoption.

5.2. Technological Challenges in Scaling and Stability

Despite their promising sustainability and resource recovery potential, the broader adoption of Integrated Microalgal-Aquaponic Systems (IAMS) is constrained by a series of technological and operational challenges. Unlike conventional aquaponic or hydroponic systems that manage two relatively discrete biological subsystems, IAMS introduce a third biotic element—microalgae—into an already sensitive ecological loop. This added layer of biological complexity significantly elevates the demands placed on system design, synchronization, and long-term stability **[5,70]**.

A central technical barrier lies in the divergent environmental optima of fish, plants, and microalgae. Tilapia, a commonly farmed aquaponic species, thrive in neutral pH conditions (7.0–7.5), whereas Spirulina platensis prefers alkaline environments (pH 8.5–9.0), and leafy vegetables such as lettuce perform best under mildly acidic conditions (pH 5.5–6.5). Reconciling these contrasting pH requirements within a single recirculating loop is inherently difficult. In traditional aquaponics, pH management involves compromise between two subsystems, generally maintained near 6.8–7.2. Hydroponic systems, by contrast, can be finely tuned for plant-specific uptake without regard for microbial or aquatic life. Within IAMS, maintaining a stable operational pH often necessitates buffering strategies, multi-zone compartmentalization, or partial system decoupling—each of which increases complexity and monitoring demands.

Nutrient competition introduces further complications. All three biological domains—microalgae, plants, and microbial communities—draw from the same pool of essential nutrients, particularly nitrogen and phosphorus. Without dynamic control, microalgae can rapidly outcompete crops for available nutrients, resulting in suppressed plant growth, oxygen imbalances, and unintended algal blooms. Conversely, excessive plant uptake can limit algal proliferation, reducing biomass yields and diminishing the nutrient polishing capacity of the system. Unlike hydroponics, where nutrient dosing is precise and unidirectional, or conventional aquaponics, where the feedback loop is simpler and more predictable, IAMS require real-time nutrient balancing informed by continuous monitoring and responsive adjustment [5].

The potential for systemic fragility increases with integration. In IAMS, failures in one subsystem can cascade into others, amplifying operational risks. For example, a disruption in algal growth due to insufficient lighting or CO_2 delivery can lead to a drop in dissolved oxygen, thereby stressing fish populations and undermining biofilter performance. Such domino effects are less common in simpler systems where the feedback dynamics are either limited (as in hydroponics) or spatially buffered (as in decoupled aquaponics). Moreover, the increased biological diversity in IAMS heightens the risk of pathogen transmission, necessitating more stringent hygiene protocols, water quality surveillance, and early diagnostic interventions.

Maintenance burdens also increase substantially. Algal biofilms frequently form on photobioreactor surfaces, reducing light penetration by as much as 40% and diminishing biomass productivity if left unmanaged **[70]**. Mitigating this requires regular cleaning, deployment of anti-fouling coatings, or incorporation of automated backflushing systems—all of which introduce additional costs and mechanical dependencies. By contrast, maintenance in traditional aquaponics is generally limited to pump cleaning and periodic sludge removal, which are simpler and less resource-intensive. While advanced solutions such as robotic cleaning units and self-sanitizing PBR surfaces are emerging, their integration further escalates both capital expenditure and system complexity.

Energy intensity presents another constraint. IAMS rely on continuous illumination, aeration, and hydraulic recirculation, making them more energy-demanding than standalone aquaponic or hydroponic setups. For instance, producing 1 kg of algal biomass under artificial light can consume 3–5 kWh, compared to 1–2 kWh for hydroponic lettuce and approximately 0.4–0.8 kWh for aquaponic tilapia [5]. Without optimization through solar integration or energy-efficient LED technologies, these energy demands can offset some of the sustainability gains achieved through nutrient recovery. This challenge underscores the need for integrated energy modeling and hybrid system design strategies that combine passive elements with renewables to reduce operational load.

Automation and intelligent controls are increasingly necessary for managing the real-time dynamics of IAMS. Unlike conventional systems that can operate with minimal sensing and manual adjustments, IAMS demand multi-parameter monitoring, data integration, and predictive control to maintain environmental equilibrium across three biological subsystems. Technologies such as IoT-based platforms, machine learning algorithms, and digital twins are being developed to meet this need, but they remain under-deployed and cost-intensive—particularly in low-resource settings where power reliability and digital literacy may be limited. In such contexts, the technological overhead of IAMS may delay adoption relative to more analog-friendly systems such as traditional aquaponics or hydroponics.

Despite these barriers, progressive design solutions are beginning to address current limitations. Modular configurations—featuring semi-isolated compartments for algae, plants, and fish—allow environmental parameters to be fine-tuned locally while maintaining overall system connectivity. These designs reduce risk of cross-contamination and allow targeted interventions without disrupting entire system flows. Functionally, they parallel semi-decoupled aquaponic architectures that trade off some simplicity for greater adaptability. Ongoing research into strain compatibility, microbial symbiosis, and predictive control algorithms is also helping to refine IAMS performance and resilience at larger scales.

5.3. Regulatory and Policy Frameworks

Despite the multifaceted sustainability benefits offered by Integrated Microalgal-Aquaponic Systems (IAMS), their development remains largely constrained by fragmented and underdeveloped regulatory landscapes. By operating at the intersection of aquaculture, hydroponics, wastewater treatment, and algal biomass production, IAMS challenge conventional classification models, which were designed for more linear and sector-specific agricultural technologies. In contrast, standalone hydroponics or aquaponics benefit from clearer legal recognition and institutional familiarity, affording them more straightforward access to permits, incentives, and investment mechanisms **[5]**.

At the global level, policy frameworks such as the European Green Deal and the United Nations Sustainable Development Goals (SDGs) strongly advocate for sustainable and circular agricultural practices. SDGs 2 (Zero Hunger), 6 (Clean Water and Sanitation), and 13 (Climate Action) are particularly aligned with the environmental and resource efficiency objectives of IAMS. However, these high-level commitments have yet to translate into specific regulatory instruments that support integrated bio-loop systems. In contrast, vertical farming and hydroponics have gained rapid inclusion under urban agriculture initiatives, attracting targeted funding through innovation grants, tax breaks, and municipal pilot schemes. The absence of equivalent mechanisms for IAMS represents a missed opportunity to promote technologies that simultaneously address food security, water reuse, and nutrient circularity **[70]**.

A central regulatory bottleneck concerns the approval and classification of algal-derived coproducts. Despite being cultivated in controlled, food-grade environments, biomass produced within IAMS is often subject to the same scrutiny as algae grown in wastewater or industrial effluents. This results in extended regulatory timelines and limited access to markets for algal biofertilizers, aquafeeds, or nutraceuticals. In contrast, crops produced via hydroponics using synthetic nutrient solutions typically face minimal certification hurdles. This regulatory asymmetry diminishes the perceived value of algal subsystems and can disincentivize their inclusion in IAMS designs **[5]**.

Permitting fragmentation presents another major challenge. Because IAMS span multiple operational domains—including aquaculture, agriculture, waste reuse, and water treatment—facilities often require a patchwork of licenses from different authorities. These may include fish farming permits, agricultural water use approvals, effluent discharge clearances, and biomass processing certifications—each with distinct documentation and inspection requirements. By contrast, hydroponic or vertical farming operations frequently operate under a unified land-use or agricultural permit, significantly reducing administrative complexity. Establishing streamlined, cross-sectoral permitting frameworks that recognize the integrated nature of IAMS would help lower institutional entry barriers and improve regulatory parity.

Financial policy tools have also lagged behind technological innovation. While public funding exists for organic agriculture, solar-powered irrigation, and biosecure aquaculture, few instruments directly support circular nutrient systems that incorporate microalgal integration. Even in countries with climate-smart agriculture or sustainable intensification programs, support tends to favor mature technologies with simpler deployment profiles. However, forward-looking nations such as the Netherlands and Singapore have begun offering innovation credits, structured grants, and urban farming incentives for algae-integrated systems—providing a model that could be adapted in other contexts **[5]**. Without comparable financial scaffolding, IAMS face a competitive disadvantage despite delivering broader ecological returns.

Institutional awareness and public perception further influence the regulatory climate. Hydroponics and aquaponics have benefited from demonstrative visibility in educational programs, extension networks, and policy discourse. This exposure has cultivated regulatory familiarity and improved trust in their safety and functionality. In contrast, microalgae-based systems are often framed within industrial biotechnology or waste management narratives, which invite more conservative oversight—even when deployed under food-grade conditions. Strategic outreach, public communication tools, and technical training will be essential to shift this narrative and foster more supportive regulatory environments for IAMS.

Encouraging signs are beginning to emerge, particularly within circular economy initiatives. The European Commission's Circular Cities and Regions Initiative (CCRI), for example, emphasizes nutrient recovery, water reuse, and biomass valorization—core components of IAMS. However, current implementations largely focus on post-consumer waste and industrial co-processing, with limited engagement at the production system level. Incorporating IAMS into national sustainability strategies—through instruments such as carbon trading schemes, tax incentives, or green labeling—could help mainstream their adoption and unlock new innovation pathways. Policy recognition that reflects the integrated nature of IAMS will be key to overcoming current barriers and maximizing their contribution to sustainable development.

5.4. Environmental Impact and Alignment with Sustainable Development Goals

Integrated Microalgal-Aquaponic Systems (IAMS) offer a robust model for environmentally regenerative agriculture, combining high-efficiency food production with enhanced nutrient recovery, reduced emissions, and closed-loop resource cycling. Unlike conventional aquaculture, hydroponics, or monoculture systems that often function in isolation, IAMS unify biological processes across multiple trophic levels, delivering system-wide environmental co-benefits. These contributions can be effectively evaluated through their alignment with key global sustainability targets—particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action) **[5,70]**.

In relation to SDG 2, IAMS advance sustainable food production by generating multiple nutrient-rich outputs from a single integrated system. Compared to conventional cereal crops, which yield approximately 0.6–1.2 tons of protein per hectare per year, microalgae such as Spirulina platensis and Chlorella vulgaris offer significantly higher protein content—60–70% of dry weight—and can produce up to 20 times more protein per square meter than legumes. This protein yield is further supplemented by vegetable crops and fish, creating a diversified nutritional profile within a compact footprint **[70]**. Traditional aquaponics, in contrast, typically operate on two outputs and rely on imported feed or synthetic supplements. IAMS replace these linear dependencies with internal nutrient cycling, enhancing local food sovereignty and improving protein access in resource-constrained settings.

With regard to SDG 6, IAMS deliver substantial gains in water-use efficiency and nutrient containment. Whereas conventional aquaculture often discharges untreated effluent and hydroponic systems periodically release salt-accumulated wastewater, IAMS retain and recirculate over 90% of system water. When microalgal photobioreactors are integrated, nutrient removal rates for dissolved nitrogen and phosphorus routinely exceed 95%, rivalling or surpassing decentralized wastewater treatment technologies [5]. In water-scarce or arid regions, this capacity to sustain high productivity with minimal water loss offers a distinct advantage over both open-field agriculture and soil-free systems operating under open-loop configurations.

In the context of SDG 13, IAMS contribute to climate mitigation through direct carbon sequestration and indirect emission reductions. Algal cultivation within photobioreactors captures atmospheric or waste-stream CO_2, with Chlorella vulgaris capable of fixing up to 1.8 kg CO_2 per kilogram of dry biomass **[70]**. This internal carbon sink contrasts with the net-positive emissions profiles of fertilizer-dependent agriculture and hydroponic systems reliant on external nutrient solutions. Additionally, IAMS avoid greenhouse gas emissions associated with synthetic fertilizer production, which contributes approximately 1.4% of global anthropogenic CO_2 emissions. By producing nutrients internally and displacing fossil-derived inputs, IAMS significantly lower both upstream and operational emissions across the system lifecycle.

Beyond individual SDG contributions, IAMS embody the principles of a circular economy by transforming biological waste into productive inputs. Fish effluents, rather than being discharged, are recirculated to support plant and algal growth. The resulting algal biomass can be valorized into biofertilizers, protein-rich aquafeeds, or bioplastics—each offering a sustainable alternative to more carbon-intensive products. Comparative life cycle assessments (LCA) indicate that IAMS reduce nutrient losses by 60–80% compared to aquaponic systems without algae and achieve 30–50% lower water footprints than RAS or hydroponics operating in semi-open loops [5]. These efficiencies not only mitigate environmental harm but also improve overall system productivity.

Importantly, the modular and adaptive nature of IAMS enhances their relevance under conditions of climate uncertainty. Unlike hydroponic systems that typically depend on high energy inputs and climate-controlled greenhouses, IAMS can be configured to operate in semi-controlled environments using passive solar energy, local organic waste streams, and minimal infrastructure. In regions vulnerable to drought, flooding, or energy scarcity—particularly across the Global South—this low-input, high-yield architecture supports food and water security while building climate resilience. Compared to high-capital vertical farming or monoculture-based agriculture, IAMS offer a flexible and scalable solution suited to both urban and peri-urban deployment contexts.

5.5. Future Research Directions

Despite the considerable promise demonstrated by Integrated Microalgal-Aquaponic Systems (IAMS) in laboratory trials and pilot-scale setups, their broader adoption remains constrained by unresolved technical, economic, and contextual knowledge gaps. Advancing IAMS from a niche innovation to a scalable sustainability solution requires targeted research efforts focused on long-term demonstration, dynamic techno-economic modeling, and biological optimization. Such efforts are essential not only to validate system performance under real-world conditions but also to inform the design of enabling policy frameworks and support technologies [5,70].

A critical research priority is the deployment of long-duration pilot projects across diverse environmental and socio-economic contexts. Unlike conventional aquaponics, which have been extensively tested in both urban and peri-urban settings, IAMS remain largely confined to controlled laboratory environments. This limits understanding of system responses to variable inputs such as fluctuating solar irradiance, seasonal temperature shifts, and variable water quality. Field-scale studies in low-resource environments are especially important, where IAMS may serve not only as decentralized food production units but also as platforms for education and resource recovery. Comparative benchmarking of IAMS against hydroponics or RAS under equivalent climatic conditions would yield valuable insight into resilience, labor intensity, and cost-performance trade-offs.

Equally essential is the refinement of techno-economic assessment (TEA) tools tailored to the multifunctional nature of IAMS. Existing TEA frameworks in agriculture are typically linear, assessing inputs and outputs through simplified cost-benefit lenses focused on crop yield or fish biomass. In contrast, IAMS produce multiple co-products—algal biomass, vegetables, fish, and treated water—while internalizing inputs such as nutrients and CO_2. This complexity challenges conventional modeling approaches. Future TEA models must incorporate circular resource flows, avoided externalities (e.g., fertilizer savings, emission reductions), and co-product valuation to better capture the integrated economic value of IAMS. When compared to vertical farming or algae-based biofuel systems, a system-specific TEA framework will offer more accurate guidance for investors and policymakers [5].

The biological foundation of IAMS also demands further investigation. Matching appropriate microalgal strains with specific aquaponic configurations is essential for optimizing nutrient recovery, system balance, and biomass yield. While Chlorella vulgaris and Spirulina platensis are well-characterized, other strains such as Tetradesmus obliquus and Nannochloropsis sp. offer potential advantages in lipid content, salinity tolerance, or environmental resilience. Comparative physiological studies examining nutrient uptake kinetics, pH sensitivity, and photosynthetic efficiency across species would support more effective system pairing. This contrasts with traditional aquaponic research, which has largely focused on plant–fish nutrient dynamics without accounting for tertiary biological layers such as microalgae.

Genetic and metabolic engineering present additional opportunities for performance enhancement. Targeted strain modifications—such as improved CO_2 fixation, stress tolerance, or nutrient affinity—could increase productivity under suboptimal conditions. These approaches, widely adopted in algal biofuel and pharmaceutical research, remain underexplored within integrated, food-grade systems like IAMS. For example, genetically optimized lettuce varieties in vertical farming have shown yield increases of up to 40% per unit area; analogous gains in IAMS could substantially enhance system viability. However, future applications will depend on regulatory clarity and the development of safe, compliant algal strains suited for food or feed applications [70].

Operational control is another critical research frontier. The complexity of IAMS—requiring simultaneous regulation of light, pH, nutrient concentrations, and dissolved oxygen across three biological domains—demands advanced, real-time monitoring systems. Integration of low-cost sensors, edge computing, and machine learning algorithms could improve decision-making, reduce labor input, and stabilize performance. While IoT platforms are already in use within hydroponics

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and aquaculture for environmental control, IAMS-specific algorithms capable of modeling tri-trophic biological interactions are still lacking. Developing such platforms would close a key operational gap and support broader system scalability.

Finally, the social and institutional dimensions of IAMS merit focused study. Long-term viability depends not only on technical efficiency but also on stakeholder engagement, regulatory alignment, and contextual adaptability. Participatory research involving farmers, policy actors, and community groups can help identify local constraints, cultural preferences, and adoption drivers. Unlike hydroponics, which tend to target commercial urban producers, IAMS may prove more impactful at community or regional scales—particularly in areas facing fertilizer shortages, water scarcity, or climate stress. Tailoring system models to these contexts will be essential for ensuring equitable and sustainable integration into future food systems.

6. Conclusions

Integrated Microalgal-Aquaponic Systems (IAMS) represent a significant evolution in sustainable food and water production, offering a biologically integrated, resource-circular approach to address the multifaceted challenges of food insecurity, nutrient pollution, and climate vulnerability. By incorporating a tertiary trophic level—microalgae—into conventional aquaponic systems, IAMS improve nutrient retention, enhance water recycling efficiency, and expand the functional output of existing agro-ecological frameworks. Compared to traditional monoculture farming, hydroponics, or standalone aquaponics, IAMS demonstrate superior environmental performance through closed-loop nutrient cycling, in situ carbon capture, and high-value biomass generation.

This review highlights recent advancements in the architecture and operation of IAMS, with specific attention to photobioreactor (PBR) design, algal species selection, and cultivation strategies. Evidence shows that appropriately configured IAMS can achieve nitrogen and phosphorus removal efficiencies exceeding 95%, while simultaneously producing protein-rich algal biomass suitable for use in aquafeed, biofertilizers, or nutraceutical applications. Moreover, when optimized for energy use and environmental control, IAMS offer reduced water demand and GHG emissions, positioning them as a viable solution for climate-adaptive agriculture. The alignment of IAMS with multiple UN Sustainable Development Goals—specifically SDGs 2, 6, and 13—underscores their potential impact at both local and global scales.

However, the widespread implementation of IAMS remains constrained by systemic barriers. Biological balancing across three trophic levels introduces complexity in system control, while high capital costs and regulatory ambiguity surrounding algal coproducts continue to limit commercial scalability. Technological challenges—such as maintaining environmental stability, minimizing energy inputs, and automating system management—require further innovation. Similarly, policy gaps in permitting, subsidy access, and product certification must be addressed to enable broader market entry.

Future research should prioritize long-term field validation, integrated techno-economic analysis, and strain-specific biological optimization. The development of IAMS-specific automation platforms and predictive control algorithms will be critical to reduce operational burden and enhance system resilience. Moreover, inclusive stakeholder engagement and regionally adapted deployment models will be essential to realize the full potential of IAMS, particularly in water-scarce and resource-constrained contexts. As food, energy, and water systems become increasingly interdependent, IAMS stand out as a promising convergence technology—capable of transforming agricultural sustainability from a fragmented challenge into an integrated, regenerative solution.

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