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Review Article

Advancing Sustainable U.S. Aquaculture: Microalgae as a Fishmeal Alternative for Rainbow Trout

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About Article

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ABSTRACT

As the need for environmentally friendly aquaculture operations grows, more people are looking for other sources of protein. Microalgae are becoming a possible alternative to traditional fishmeal in rainbow trout diets. This review looks at how microalgae might be used instead of fishmeal, focussing on their nutritional benefits, growth performance, and environmental benefits. Microalgae including *Chlorella*, *Spirulina*, and *Nannochloropsis* are good sources of protein (30–60% dry weight), essential amino acids, and long-chain omega-3 fatty acids. These nutrients help improve feed conversion ratios and keep omega-3 levels high in trout meat. Life-cycle evaluations show that feeds made from microalgae can cut down on greenhouse gas emissions and phosphorus loading compared to regular fishmeal. These benefits notwithstanding, issues include elevated manufacturing costs (estimated at $50–400/kg dry weight), possible nutritional imbalances, and regulatory impediments continue to pose substantial barriers to widespread use. Ongoing research into optimising production techniques, wastewater integration, and genetic engineering of microalgae offers promise for addressing these restrictions. Adding microalgae to U.S. aquaculture might make the sector more sustainable and profitable, as well as lessen its impact on the environment and reliance on wild-caught fish. To fully realise the promise of microalgae as a key part of sustainable aquaculture, we need to keep investing in research, create supportive legislative frameworks, and encourage collaboration between industry and academia.

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1. INTRODUCTION

1.1. Background

Aquaculture is one of the fastest-growing parts of the world's food supply. There is a rising need for sustainable methods that will guarantee long-term food security. As fish farming grows, fishmeal, which comes from wild-caught fish, is still an important part of fish nutrition. Fishmeal is a key part of fish feeds because it gives farmed species like rainbow trout the proteins and minerals they need. But the high demand for fishmeal has led to overfishing of wild fish supplies, which is bad for marine biodiversity and makes many worry about the long-term health of aquaculture. To solve these problems, we need to quickly look into other sources of protein that can fulfil the nutritional needs of farmed fish without making environmental problems worse (Sarker, 2023).

1.2. Nutritional composition variability

While microalgae are considered a promising alternative to fishmeal due to their high protein and essential fatty acid content, studies show significant variability in their nutritional composition. This variability is influenced by factors such as species, cultivation conditions, and environmental factors. For example, while *Chlorella* and *Spirulina* may contain up to 60% protein by dry weight, other species like *Nannochloropsis* may show a lower protein content. This variability needs to be further explored to better understand the nutritional consistency of microalgae in aquaculture feeds.

Fishmeal is made from more than 4–5 million metric tonnes of wild fish caught each year across the world. The U.S. relies significantly on imports to satisfy the needs of aquaculture. Farmers of rainbow trout alone use hundreds of tonnes of formulated meals every year. This puts economic strain on them since the price of fishmeal changes. Researchers have looked at other sources of protein, such soybean meal and insect meal, but these have problems that make them less useful: soy has anti-nutritional characteristics, and insects are hard to scale up. Microalgae are unique because they provide high-quality proteins and long-chain omega-3 fatty acids. This makes them a more complete nutritional choice than plant-based equivalents, and they don't have the land-use and ethical problems that other options have (Macusi *et al.*, 2023).

1.3. Problem statement

U.S. aquaculture uses fishmeal, which harms the ecology and economy. Fishmeal extraction depletes marine ecosystems and increases fishing sector carbon emissions. Aquaculture enterprises can struggle due to rising fishmeal prices due to global fish population shifts and geopolitical worries. U.S. aquaculture is struggling to meet the growing demand for sustainably produced seafood while minimising environmental impact. The future of sustainable U.S. aquaculture depends on developing new protein sources that reduce fishmeal use (Majluf *et al.*, n.d.).

1.4. Objective of the review

This analysis examines how microalgae may replace fishmeal in rainbow trout diets over time. Microalgae are abundant in protein, nutrients, and may be farmed on a large scale in an environmentally friendly method. Modern studies on microalgae in fish diets will highlight their nutritional benefits, effects on fish health and growth, and potential to reduce U.S. aquaculture's environmental and economic dependence on conventional fishmeal sources. This study integrates the literature to examine microalgae's contribution to sustainable aquaculture.

2. LITERATURE REVIEW

2.1. Microalgae as a sustainable fishmeal alternative

2.1.1. Microalgae characteristics

Light-dependent microalgae thrive in freshwater and saltwater and create food. They grow fast and produce many bioactive compounds, making them a promising aquaculture protein source. The nutritional value of microalgae makes it a popular fishmeal alternative (Ahmad & Ashraf, 2025). Microalgae include protein (30% to 60% of their dry weight), amino acids, vitamins, minerals, and lipids, notably omega-3 fatty acids, which are vital to rainbow trout farming (Ahmad *et al.*, n.d.). More sustainable and healthier than fishmeal, microalgae may provide protein. Fishmeal from wild fish may cause overfishing and habitat degradation. However, regulated microalgae growth requires fewer resources and has a lower environmental effect.

2.2. Types of microalgae used

Researchers have examined many microalgae for fish feeds. Each variety has benefits depending on nutrition and growth. Some common species are:

- *Chlorella spp.: Chlorella* is studied for its ability to develop fish and improve feed conversion. It's high in protein and essential amino acids. Many antioxidants help fish battle illnesses and stress (Xi *et al.*, 2022).
- *Spirulina spp.:* Aquaculture diets often include this blue-green algae, which is abundant in protein and pigments like phycocyanin, which may have antioxidant and anti-inflammatory properties. *Spirulina* provides nutrition and fatty acids for farmed fish (Ogbuewu & Mbajiorgu, 2025).
- *Nannochloropsis spp.:* This microalgae is recognised for producing omega-3 fatty acids, notably EPA, which is essential for fish growth. High in lipids, *Nannochloropsis* provides energy for farm-raised fish (Zahran *et al.*, 2023).

2.3. Nutritional composition inconsistencies

Despite the promising benefits of microalgae, there are inconsistencies in their nutritional profiles across various studies. Factors such as light intensity, temperature, and growth medium can significantly affect the nutrient content of microalgae, especially protein and omega-3 fatty acids. For instance, while *Spirulina* is known for its high protein content, its omega-3 levels are often reported as lower compared to *Nannochloropsis.* This variability in nutrient quality may affect the overall nutritional value when used as a fishmeal substitute, highlighting the need for standardized cultivation practices to ensure consistency in microalgal feed formulations.

Researchers have also examined Haematococcus pluvialis (rich in astaxanthin, an antioxidant) and Tetraselmis spp. (high in lipids and omega-3s) as fish diet additions. Microalgal species are chosen for large-scale aquaculture due to their nutritional value, ease of growth, and affordability (Oslan *et al.*, 2021). Table 1 compares microalgae and fishmeal macronutrient and micronutrient compositions. The primary rainbow trout nutrition issues are also included.

Table 1. Nutritional composition of fishmeal and selected microalgae species for use in aquaculture feeds

Feed Ingredient	Protein (%dry wt)	Lipids (%dry wt)	Key Fatty Acids	Notable Micronutrients	Limitations
Fishmeal	60–72	8–12	EPA, DHA	B12, Calcium, Phosphorus	Reliance on wild fish; high cost(Fishmeal and Fish Oil – European Fishmeal, n.d.)
Chlorella spp.	45–60	10–20	ALA, some EPA	Iron, Vitamin A, B-complex	High fiber content(Widyaningrum & Prianto, 2021)
Spirulina spp.	55–70	6–9	GLA	Phycocyanin, Antioxidants	Limited EPA/DHA(Podgórska-Kryszczuk, 2024)
Nannochloropsis spp.	30–40	20–30	Rich in EPA	Vitamin E, Minerals	Low digestibility without treatment(Chaves *et al.*, 2024)
Haematococcus spp.	25–35	20–30	Minor EPA/ DHA	Astaxanthin (antioxidant)	Expensive cultivation(Oslan *et al.*, 2021)

This table illustrates the nutritional advantages and disadvantages of prevalent microalgae species in comparison to conventional fishmeal. Fish entrée remains a protein-rich food source that contains an appropriate ratio of essential fatty acids. In contrast, microalgae such as *Chlorella*, *Spirulina*, and *Nannochloropsis* are rich in protein, omega-3 fatty acids, and critical micronutrients. Additionally, they can be cultivated in an environmentally friendly manner. Nevertheless, in order to ensure that rainbow trout diets incorporate them in the most effective manner, it is necessary to address issues such as digestibility, fibre content, and manufacturing costs.

Benefits of Microalgae

Aquaculture feeds made from microalgae have many advantages over fishmeal:

• *Sustainability:* Photobioreactors or open ponds may produce microalgae without much arable land, fresh water, or fertilisers. Microalgae farming is a more sustainable protein source than wild fish, which harms marine ecosystems. Microalgae may absorb CO_2 during development, fighting climate change.

Many microalgae have 30% to 60% protein by dry weight, making them a valuable protein source. They provide a lot of protein for farmed rainbow trout, who require it to grow and breed (Balasubramaniam *et al.*, 2025).

• *Omega-3 fatty acids:* Microalgae naturally include EPA and DHA, which are essential for fish growth, immune function, and health. Fishmeal, a major omega-3 source in fish diets, is replaced with microalgae. Rainbow trout require these fatty acids for health, therefore this is great (Ahmad *et al.*, n.d.).

• *Vitamins and minerals:* Microalgae include proteins, lipids, vitamins A, B12, D, and E, and minerals iron, magnesium, calcium, and potassium. These micronutrients boost growth and disease resistance in farmed fish. Growing microalgae is less harmful to the environment than fishmeal. It grows with factory CO_2 and requires less room and water. This suggests that microalgae might reduce aquaculture's environmental effect while maintaining feed quality (Sheikhzadeh *et al.*, 2024).

• *Bioactive chemicals:* Microalgae include antioxidants including carotenoids, which increase farmed fish immunity and reduce oxidative stress. Chemicals can also improve fish taste (Ahmad *et al.*, n.d.). When you consider nutrition, the environment, and health, microalgae in aquaculture feeds makes sense. Figure 1 (Adapted from Utilisation of Microalgae in Aquaculture Feeds, Aquahoy, n.d.) summarises these linked advantages (Utilization of Microalgae in Aquaculture Feeds, 2023).

aquaculture. Microalgae in rainbow trout diets has several benefits, as seen in this diagram. High protein, necessary amino acids, and long-chain omega-3s are nutritional benefits. Environmental benefits include reduced wild-caught fish use, lower carbon footprint, and possibility for CO_2 capture and wastewater integration. Bioactive substances, antioxidants, and vitamins boost fish immunity, stress tolerance, and development. These qualities make microalgae a multifunctional sustainable aquaculture option. Microalgae in Aquaculture Feeds. The use of microalgae in aquaculture feeds is available at Aquahoy (2025).

2.4. Life-cycle assessment (LCA) Gaps

While many studies suggest that microalgae can reduce the environmental impact of aquaculture by lowering greenhouse gas emissions and phosphorus loading, there is a lack of comprehensive life-cycle assessments (LCAs) that evaluate microalgae farming in various environmental settings. Some studies have shown significant environmental benefits, while others point to high resource consumption in certain cultivation methods, such as photobioreactors, which require large amounts of energy. Additionally, the impact of microalgae production on local ecosystems is still under-researched, indicating a gap in the current literature regarding the full environmental footprint of large-scale microalgae farming.

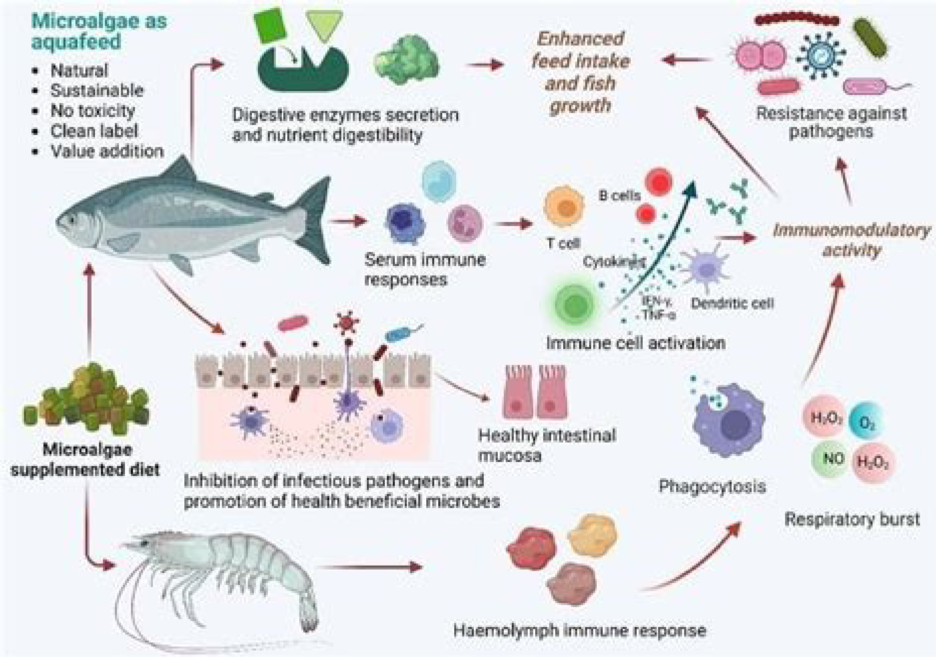

Figure 1. Key benefits of microalgae as a sustainable fishmeal alternative in rainbow trout

3. METHODOLOGY

This review follows a systematic and structured approach to synthesize the current literature on the potential of microalgae as a replacement for fishmeal in U.S. aquaculture, particularly focusing on rainbow trout (Oncorhynchus mykiss). The methodology was divided into the following stages: literature search, selection criteria, data extraction, data synthesis, and analysis.

3.1. Literature search and selection criteria

A comprehensive literature search was conducted using the following scientific databases: Google Scholar, PubMed, Scopus, and ScienceDirect. The search was limited to studies published from 2010 to 2025 to ensure relevance and currency. The keywords used in the search included *"microalgae," "fishmeal replacement," "rainbow trout aquaculture," "sustainable aquaculture,"* as well as species names such as *Chlorella*, *Spirulina*, and *Nannochloropsis*.

The inclusion criteria for selecting studies were:

• Studies that evaluated microalgae as a feed ingredient for rainbow trout or other aquaculture species.

• Research that discussed the nutritional composition of microalgae, including protein content, amino acids, omega-3 fatty acids, and essential micronutrients.

• Studies comparing microalgae-based feeds with traditional fishmeal in terms of growth performance, feed conversion ratios (FCR), and health outcomes.

• Articles that performed life-cycle assessments (LCAs) or other environmental impact evaluations of microalgae-based feeds.

Studies were excluded if they:

• Were not peer-reviewed.

• Did not provide sufficient data on the nutritional, environmental, or economic parameters related to microalgae.

• Focused on species or contexts irrelevant to U.S. aquaculture or rainbow trout.

3.2. Data extraction

From the selected studies, the following data were extracted:

• *Microalgae Species:* The types of microalgae examined (e.g., *Chlorella*, *Spirulina*, *Nannochloropsis*, etc.).

• Nutritional Composition: Information on protein content, lipids, omega-3 fatty acids, essential amino acids, vitamins, and minerals.

• *Growth Performance:* Data on weight gain, feed conversion ratios (FCR), and overall health improvements or impacts on rainbow trout fed with microalgae-based diets.

• *Environmental Impact:* Life-cycle assessments (LCAs) that measured reductions in greenhouse gas emissions, phosphorus loading, and potential for carbon sequestration from microalgae cultivation.

• *Economic Considerations:* Information on the costs of microalgae production, including biomass production costs, scalability, and cost comparisons with traditional fishmeal and other alternative proteins.

3.3. Data synthesis and analysis

The extracted data were analyzed using a thematic analysis approach, which involved several systematic steps to ensure rigorous synthesis of the evidence:

i. Initial coding: The key findings from each study were coded based on recurring themes related to the nutritional benefits (e.g., protein quality, omega-3 content), environmental impact (e.g., greenhouse gas reduction, phosphorus loading), and economic feasibility (e.g., production costs, scalability).

ii. Theme identification: Following initial coding, the data were grouped into broader themes.

These primary themes included:

• *Nutritional benefits:* Focused on the protein quality, essential amino acids, omega-3 fatty acids, and micronutrient content of various microalgae species.

• *Environmental impact:* Covered the life-cycle environmental benefits of microalgae cultivation, including reductions in greenhouse gas emissions, phosphorus loading, and potential integration into carbon capture systems.

• *Economic feasibility:* Addressed the economic challenges, including the high cost of microalgae production and scalability issues, and compared it to traditional fishmeal and other alternative protein sources like soy and insect meal.

iii. Cross-study comparison: Once the themes were identified, a comparison was made across studies to identify consistencies and discrepancies. Studies with similar findings were grouped together, and areas of disagreement, such as variations in cost estimates or the nutritional profiles of different microalgal species, were highlighted.

iv. Interpretation and synthesis: After categorizing the findings into the identified themes, the data were synthesized to draw conclusions regarding the feasibility of microalgae as a sustainable replacement for fishmeal. This synthesis involved interpreting the results from different studies to assess whether the evidence supports the widespread adoption of microalgae-based feeds in U.S. aquaculture and the associated benefits and challenges.

This thematic analysis allowed for a robust, evidence-based synthesis of the literature, providing a clear understanding of the potential and limitations of microalgae as an alternative to fishmeal.

3.4. Limitations and future research directions

While this review synthesizes a broad range of studies, several gaps in the existing literature were identified:

• *Long-Term Health Studies:* There is a lack of long-term studies examining the impact of microalgae-based feeds on fish health over extended periods. Future research should focus on evaluating potential long-term health risks or benefits associated with microalgae consumption in aquaculture.

• *Economic Feasibility:* Despite several studies on the high production costs of microalgae, there is limited research on the cost-effectiveness of large-scale microalgae production for aquaculture, particularly in comparison with other alternative feed sources. Research on cost-reduction strategies, such as hybrid feeds or integration with waste-streams, would be valuable.

• *Regulatory Issues:* Further research is needed to explore the regulatory landscape for microalgae-based feeds, particularly in the U.S., to understand the barriers to commercialization and market adoption.

• *Hybrid Feed Formulations:* Combining microalgae with other protein sources (e.g., plant-based proteins or insect meal) could address some of the nutritional imbalances identified in certain microalgal species. Research into hybrid formulations and their effects on fish health and feed efficiency should be prioritized.

4. RESULTS AND DISCUSSION

4.1. Research on microalgae in aquaculture diets

4.1.1. Growth performance

Microalgae can substitute fishmeal in rainbow trout diets without affecting development, according to recent studies. The marine microalga *Nannochloropsis* sp. QH25 entirely replaced fishmeal in a UC Santa Cruz feed composition. Trout fed this microalgae-based diet grew at rates equivalent to those fed traditional fishmeal diets, preserving nutritional value and feed efficiency (Sarker *et al.*, 2025a).

A research that replaced fishmeal with *Nannochloropsis* sp. QH25 at 33%, 66%, and 100% observed no significant growth differences between the experimental and reference diets. Microalgae inclusions of moderate to high levels may help young rainbow trout thrive (Sarker *et al.*, 2025b)

4.1.2. Feed conversion ratio (FCR)

In trout diets, microalgae improves the Feed Conversion Ratio (FCR), a key measure of feed efficiency. The UC Santa Cruz study found that trout fed microalgae had FCR values equivalent to fishmeal, indicating efficient feed utilisation (Sarker *et al.*, 2025c).

In rainbow trout, enzyme treatments on microalgal co-products improve nutrient digestibility and minimise phosphorus waste, enhancing FCR and feed efficiency (Sarker *et al.*, 2025c).

4.1.3. Nutritional quality

Microalgae contain nutrients that benefit fish and humans. *Nannochloropsis* sp. QH25 contains omega-3 fatty acids, particularly EPA, which are essential for cardiovascular health. Studies reveal that trout fed this microalga retain high omega-3 levels in their meat, meeting human nutritional criteria(Liu *et al.*, 2022) Fish nutrition is enhanced by microalgae's amino acids, vitamins, and minerals. This enrichment improves aquaculture products by boosting fish growth, immunity, and disease resistance.

4.1.4. Sustainability and environmental impact

The environmental advantages of microalgae in aquaculture diets are enormous. Reducing wild-caught fish use with microalgae lessens marine ecological impact. Microalgae farming may also employ industrial carbon dioxide emissions to reduce greenhouse gas emissions.

Microalgae-based meals with different quantities of *Nannochloropsis* sp. QH25 had a lower environmental effect than fishmeal-based diets, according to a life cycle evaluation. In particular, phosphorus input decreased, which is essential for reducing aquatic environment eutrophication (Ahmad *et al.*, n.d.)

In circular bioeconomy techniques, waste products from other sectors may be used to grow microalgae, improving aquaculture sustainability (Nagarajan *et al.*, 2024).

Quantitative life-cycle analysis demonstrate microalgae-based diets' environmental advantages. Microalgae can cut greenhouse gas emissions by 1.5-2.0 metric tonnes of CO_2-equivalent and phosphorus loading by up to 40% when replacing one metric tonne of fishmeal. Integration of microalgae growing systems with industrial flue gases or aquaculture effluent captures nutrients that would otherwise cause eutrophication. These co-benefits show that microalgae are nutritious and circular bioeconomy-friendly (Sarker *et al.*, 2024).

4.2. Challenges and limitations

4.2.1. Cost and availability

Economic issues arise when scaling up microalgae production for aquaculture feeds. Depending on the culture technique and size, microalgal biomass production costs \$50–\$400 per kilogramme of dry weight (Tan *et al.*, 2020). Open raceway ponds (ORPs) are cheaper but more subject to pollution and environmental factors. However, photobioreactors (PBRs) have regulated conditions but greater running costs (Yahaya *et al.*, 2025). The higher production costs of microalgae compared to fishmeal and soybean meal prevent its widespread use in aquaculture diets.

4.2.2. Economic feasibility and cost barriers

Despite the promising potential of microalgae as a fishmeal alternative, the high production costs remain a significant barrier. Microalgae biomass production can range from \$50 to \$400 per kilogram of dry weight, depending on the cultivation system and scale. This cost is still considerably higher compared to traditional fishmeal and other alternative protein sources, such as soybean meal or insect meal. While open pond systems are cheaper, they are more susceptible to contamination, while photobioreactors, though more controlled, have higher operational costs. Furthermore, there is a lack of comprehensive studies comparing the economic viability of microalgae to other sustainable feed options, such as insect-based proteins or plant-based meals, which may offer more cost-effective solutions for aquaculture.

4.2.3. Nutritional imbalances

Despite microalgae's high protein content, several species show nutritional imbalances that may limit their effectiveness as a complete replacement for fishmeal. For example, microalgae often have high fiber content, which can negatively affect digestibility and nutrient absorption in fish. Additionally, some microalgal species lack essential amino acids or omega-3 fatty acids needed for optimal fish growth and health, requiring supplementation with other feed ingredients. Addressing these nutritional gaps is crucial for improving the suitability of microalgae as a full replacement for fishmeal in aquaculture (Wu *et al.*, 2023).

4.2.4. Regulatory and commercial barriers

The U.S. market for microalgae-based feeds confronts regulatory and acceptance issues. Complex and time-consuming regulatory regimes for novel feed ingredients hinder product clearance and market introduction (Feed & Additive Magazine). Microalgae used in aquaculture feeds lacks quality control and safety standards. Investors and manufacturers may avoid the market due to regulatory uncertainty (Martínez-Ruiz *et al.*, 2025).

Limited consumer knowledge, perceived dangers of novel feed ingredients, and the entrenched usage of existing feed components hamper commercial adoption of microalgae-based feeds. Scaling microalgae production for large-scale aquaculture operations is also difficult (Saadaoui *et al.*, 2021).

Consumer approval is another issue. Market surveys show that U.S. customers are wary of new feed components, even though trout fed microalgae-based diets have equivalent fillet quality and omega-3 content. Clear communication of sustainability advantages and certification and labelling schemes may boost public trust and market adoption.

One of the major barriers to the commercial adoption of microalgae-based feeds in the U.S. is the complex and time-consuming regulatory framework for novel feed ingredients. These regulations create uncertainty for both manufacturers and investors, which delays market approval and product commercialization. The lack of standardized safety and quality control protocols for microalgae in aquaculture feeds further complicates market acceptance. Additionally, regulatory discrepancies between regions, such as the U.S. and the EU, may impede the global expansion of microalgae as a feed ingredient. More research is needed to explore these regulatory challenges and create clearer pathways for microalgae-based feed products to enter the market.

4.3. Future directions and research gaps

4.3.1. Optimization of production

For broad use in aquaculture feeds, microalgae production must be cheaper. Current estimates put microalgae biomass around \$50–\$400 per kilogramme of dry weight, depending on growth technique and scale (Ansari *et al.*, 2021). Several cost-effectiveness measures are being considered:

- *Improved cultivation systems:* Scalable manufacturing solutions like tubular photobioreactors and cost-cutting measures can minimise production costs. A research at 1500m² revealed a cost price of €23.47 per kilogramme of dry weight after employing cost reduction techniques (Penloglou *et al.*, 2024)
- *Optimising growth conditions:* Adjusting light intensity, temperature, and nutrient concentrations can boost biomass production and quality. A study found that biomass output was best at 22-24°C and 110-220 μmol m^{-2} s^{-1} light intensity (Jui *et al.*, 2024).
- *Wastewater treatment integration:* Growing microalgae in aquaculture wastewater reduces nutrient loading and generates feed biomass. Studies suggest that microalgae may extract nutrients from wastewater, improving feed production and sustainability (Ahmad *et al.*, n.d.).

4.3.2. Genetic engineering

Genetic engineering might improve microalgae feeding and growth:

- Genetic changes can boost lipid production in microalgae, promoting omega-3 fatty acid production for fish health. CRISPR/Cas9 is used to modify genomes precisely (SpringerLink).

In metabolic engineering, microalgae's metabolic networks are modified to optimise synthesis of desirable components like proteins and pigments (Ahmad Kamal *et al.*, 2024).

- High-throughput screening: Utilising high-throughput screening methods to identify microalgae strains with improved digestibility and bioactive content for aquaculture (Ayon, 2023).

Integration into U.S. Aquaculture

Key aspects must be addressed to integrate microalgae into mainstream U.S. aquaculture:

Why Clear regulatory frameworks for microalgae-based feeds are essential. Genetically engineered microalgae must be safe and effective, and their commercial acceptability must be facilitated.

- Assessing the cost-effectiveness of microalgae-based feeds compared to standard fishmeal is crucial for economic feasibility. This includes considering production costs, feed conversion ratios, and market pricing (Auzins *et al.*, 2024).
- Industry collaboration: Promoting collaboration among researchers, aquaculture producers, and feed makers can speed microalgae-based feed uptake. Collaboration can provide standardised processes and shared resources (Lu, 2025).
- Educating the public about the benefits of microalgae in aquaculture can increase consumer demand. Educational programs may teach stakeholders about microalgae-based feeds' environmental and nutritional benefits (Sarker & Kaparaju, 2024).

Hybrid feed techniques are promising too. Partial substitution of fishmeal with microalgae and plant-based or insect-derived proteins may balance nutritional profiles and reduce dependency on any one ingredient at a lower cost. Rapid advances in synthetic biology allow the production of microalgal strains that overproduce certain amino acids or omega-3 fatty acids. These methods might greatly enhance U.S. trout aquaculture feed efficiency and profitability.

Adopting microalgae-based aquaculture feeds presents economic, nutritional, and regulatory obstacles(Aragão *et al.*, 2022).

4.3.3. Long-term studies on fish health

While short-term studies have demonstrated the effectiveness of microalgae in improving the growth performance and feed conversion ratios of rainbow trout, there is a lack of long-term research on the health impacts of microalgae-based diets. Long-term studies are needed to evaluate whether microalgae-based feeds could lead to any adverse health effects, such as the accumulation of certain compounds in fish tissues or changes in immune response over time. More comprehensive research into the long-term impacts on fish health is essential to fully understand the viability of microalgae as a sustainable fishmeal replacement.

4.3.4. Addressing nutritional imbalances

Given the nutritional imbalances found in some microalgal species, further research is needed to optimize their nutrient profiles. One potential solution is the development of hybrid feeds that combine microalgae with other alternative protein sources, such as insect meal or plant-based proteins. Additionally, genetic engineering of microalgae could be explored to enhance their nutritional content, particularly to increase the levels of essential fatty acids like EPA and DHA, which are crucial for fish growth and human health. Addressing these nutritional gaps will be essential for making microalgae a fully viable alternative to fishmeal in aquaculture.

5. CONCLUSION

In conclusion, microalgae hold substantial potential as a sustainable alternative to fishmeal in U.S. aquaculture, as evidenced by numerous studies reviewed in this article. Microalgae species such as *Chlorella*, *Spirulina*, and *Nannochloropsis* offer high-quality protein, essential amino acids, and omega-3 fatty acids, all crucial for the growth and health of rainbow trout. The environmental advantages, including reduced greenhouse gas emissions, lower phosphorus loading, and the potential for carbon sequestration, make microalgae a promising solution to the ecological concerns associated with fishmeal production.

However, while the nutritional and environmental benefits are well-documented, significant barriers remain. The high production costs, which can range from $50 to $400 per kilogram of dry weight, present a major challenge to the widespread commercial adoption of microalgae-based feeds. Additionally, the nutritional imbalances in some microalgal species, such as the lack of certain essential amino acids or fatty acids, require supplementation to ensure optimal fish health. Regulatory hurdles and the lack of standardized safety protocols further hinder the scalability of microalgae in aquaculture.

Thus, the evidence suggests that while microalgae can replace fishmeal at a small to medium scale, scaling this replacement to a commercial level in U.S. aquaculture will require addressing the high production costs and nutritional limitations. Optimizing cultivation techniques, genetic engineering to enhance nutrient profiles, and the integration of microalgae cultivation with waste-streams from aquaculture could reduce production costs and improve efficiency. Furthermore, collaboration between researchers, industry stakeholders, and regulatory bodies is essential to streamline approval processes and promote market acceptance.

In summary, microalgae present a compelling case for replacing fishmeal in aquaculture feeds, but significant investment in research and innovation is needed to overcome current economic and nutritional barriers. With continued advancements, microalgae could play a pivotal role in the transition toward more sustainable and resilient U.S. aquaculture systems.

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