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Chapter 6

Microbial and Single-Cell Ingredients: The Future of Fish Feed

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Abstract

The use of microbial and single-cell protein (SCP) ingredients in aquaculture feeds signifies a paradigm shift towards fostering sustainable and economically viable aquaculture systems. The aquaculture sector serves as a vital part of the food industry, addressing the rising food demand driven by the growing global human population and as a result, the demand for aqua feed is also increasing. The incorporation of microorganisms, including algae, fungi and bacteria, demonstrates the ability to transform low-cost organic substrates into nutrient-dense biomass, addressing the urgent need for alternatives to traditional feed sources such as fishmeal and fish oil. The nutritional profiles of microbial and SCP ingredients are particularly noteworthy, as they are rich in essential amino acids (EAA) and fatty acids (FA) that support optimal fish growth and health. Moreover, their cultivation often utilizes agricultural by-products, enhancing the overall sustainability of aquafeed production by mitigating waste and reducing reliance on finite marine resources. Despite their promising potential, the broader application of microbial and SCPs in aquaculture is impeded by regulatory hurdles and varying consumer acceptance, necessitating a concerted effort from industry stakeholders to navigate these challenges. Future research endeavours must focus on optimizing production processes, scaling up cultivation methods and elucidating the health benefits associated with these ingredients. By leveraging advancements in biotechnology and fostering collaborative networks within the aquaculture sector, the integration of microbial and SCPs could play a pivotal role in enhancing nutritional security and promoting environmental sustainability in aquaculture, ultimately contributing to the resilience of global food systems.

Keywords Fish Nutrition, Biochemistry and Physiology Division

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1. Introduction

Aquaculture plays a pivotal role in addressing the escalating global food demand driven by the rapidly growing human population. As traditional agricultural practices face limitations in productivity, land use and environmental sustainability, aquaculture has emerged as a sustainable alternative for ensuring food security (FAO, 2024). By harnessing the cultivation of aquatic organisms such as fish, mollusks and seaweed in controlled environments, aquaculture offers a means to increase protein production while minimizing the strain on terrestrial ecosystems. Its significance is further underscored by its potential to reduce overfishing pressures on wild fish stocks, support rural economies and contribute to balanced nutrition worldwide (Agboola *et al.*, 2021). As such, the sector is increasingly recognized as a crucial component of future food systems, capable of fulfilling the dietary needs of a growing population while addressing environmental and economic challenges associated with traditional food production methods. Microbial and single-cell products have emerged as promising alternative ingredients in fish feed, offering a sustainable and efficient solution to the challenges posed by traditional feed sources. Over the past decade, global fishmeal (FM) production has stagnated and the overexploitation of forage fish stocks poses a significant threat to the long-term sustainability of fishmeal supplies (Tacon and Metian, 2008). Beyond the environmental concerns associated with this overexploitation, the price of fishmeal has become increasingly volatile, with a sharp rise of approximately 70% over the past decade (Murthy *et al.*, 2023). This volatility underscores the urgent need for alternative, sustainable feed ingredients in aquaculture. In contrast, microbial biomass, including algae, bacteria, fungi and yeast, can be cultivated under controlled conditions with minimal environmental impact. These organisms are rich in essential nutrients such as proteins, lipids and omega-3 fatty acids, making them highly suitable for inclusion in aquafeed formulations (Couture *et al.*, 2019). The incorporation of these alternative feed ingredients not only reduces pressure on wild fish stocks but also contributes to improving the nutritional quality and environmental sustainability of aquaculture operations. Their utilization is a key innovation in advancing more resilient and resource-efficient aquaculture systems, aligning with global goals for sustainable food production.

2. Time to Search for Sustainable Alternatives

The extraction of fishmeal and fish oil from wild fish stocks has significant environmental implications. Globally, the fishmeal industry harvests approximately 20 million metric tons of small pelagic fish each year to meet the demands of aquafeed, exerting considerable pressure on marine ecosystems (FAO, 2024). This practice contributes to overfishing and disrupts marine food webs, where forage fish species, such as anchovies and sardines, play a pivotal role in the diets of various marine predators, including larger fish, seabirds and marine mammals. Overexploitation of these species can destabilize ecosystems, reduce biodiversity and weaken the resilience of marine environments. Moreover, the production of fishmeal and fish oil carries a substantial carbon footprint, contributing to greenhouse gas emissions and exacerbating climate change. According to a recent study, aquaculture's reliance on fishmeal and fish oil is responsible for nearly 5 million tons of CO_2 emissions annually (Shea, 2024). Transitioning to more sustainable feed ingredients is essential, as reducing fishmeal usage in aquaculture could lead to a marked decrease in the industry's carbon emissions (Sarker, 2023).

3. Price Volatility in the Fishmeal Market

Price volatility in the fishmeal market has emerged as a critical challenge, driven by fluctuations in wild fish populations, regulatory changes and increasing global demand for aquaculture products. Between 2010 and 2023, fishmeal prices surged by nearly 70%, significantly impacting the economic viability of small- and medium-scale aquaculture operations (FAO, 2023). This volatility is further compounded by environmental factors such as climate change, which alters oceanic conditions and fish stock availability, leading to unpredictable supply chain disruptions and escalating costs. Additionally, the overreliance on fishmeal in aquafeed creates market vulnerabilities, as reduced fish catches directly affect supply, creating price spikes and shortages (Jannathulla *et al.*, 2021). This dependency on a finite resource not only threatens the financial sustainability of aquaculture but also undermines long-term food security. Introducing cost-stable alternative ingredients, such as microbial proteins, insect-based meals and single-cell proteins, offers a potential solution to these economic and ecological pressures. These alternatives can alleviate market volatility by reducing reliance on wild-caught fish stocks, thereby stabilizing input costs and promoting the resilience of the aquaculture sector. Moreover, the integration of alternative protein sources aligns with broader sustainability goals by decreasing the industry's ecological footprint. Shifting towards these ingredients could enhance the scalability of aquaculture while reducing its environmental impact, particularly in terms of overfishing and carbon emissions (Pelletier *et al.*, 2018). Thus, the adoption of innovative feed solutions not only mitigates price volatility but also supports the sustainable growth of aquaculture.

4. Microbial and Single-Cell Ingredients are Promising Choice

Microbial and single-cell ingredients (SCIs) have emerged as cutting-edge solutions in the quest for sustainable aquafeed. These ingredients are produced from various unicellular organisms such as microalgae, bacteria, yeasts and fungi, each of which can be cultivated in highly controlled environments (Jannathulla *et al.*, 2021). Unlike traditional fishmeal and fish oil derived from marine capture, SCIs offer a more ecologically and economically sustainable alternative due to their lower environmental footprint, scalable production methods and rich nutrient profiles.

The large-scale cultivation of SCIs involves advanced biotechnological processes, including fermentation and photobioreactor technologies. These methods allow for precision in controlling growth conditions, nutrient supply and production rates, enabling the efficient generation of high-quality proteins, essential fatty acids, vitamins and bioactive compounds. As a result, SCIs not only meet the nutritional demands of fish but also contribute to improved growth performance, feed efficiency and immune system enhancement.

5. Microalgae: A Nutritional Goldmine

Microalgae, among the most extensively researched microbial sources for aquafeed, are distinguished by their remarkable capacity to synthesize long-chain omega-3 polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Nagappan *et al.*, 2021). These fatty acids are essential for the health of farmed fish and benefit human consumers further along the food chain. Additionally, microalgae produce bioactive compounds, including antioxidants and pigments, such as carotenoids, which enhance fish health and coloration. Microalgae can be cultivated in either open ponds or closed photobioreactor systems, with the latter offering improved control over contamination and environmental conditions, leading to greater yield consistency. Notable species such as Chlorella, Spirulina and Schizochytrium are particularly valued for their advantageous nutrient profiles. For instance, Schizochytrium is an excellent source of DHA, critical for neural and visual development in both fish and humans. Furthermore, the ability of microalgae to utilize industrial CO_2 emissions for growth significantly enhances their environmental sustainability. The potential of microalgae primarily resides in their optimal ratios of protein, lipid and carbohydrate, which are crucial for promoting fish health (Rizwan *et al.*, 2018). In comparison to other alternative ingredients such as yeast and bacteria, microalgae exhibit a notably higher concentration of both protein and lipid content. Additionally, they possess a well-balanced amino acid profile, effectively negating the need for costly amino acid supplements within aquaculture diets. For instance, microalgae species such as Chlorella, Chlamydomonas, Porphyridium, Isochrysis and Nannochloropsis are particularly rich in methionine, an amino acid frequently deficient in plant-based sources (Jannathulla *et al.*, 2021; Abdelghany *et al.*, 2020).

The specific carbohydrate composition in aquafeed is another significant characteristic. The starch content, a readily digestible carbohydrate, varies among different microalgal species, ranging from 7% to 45%. Notably, species such as *Tetraselmis subcordiformis*, *Chlamydomonas rheinhardtii* and *Chlorella vulgaris* demonstrate comparatively elevated starch levels (30-49%) relative to other microalgae. The fiber content, which constitutes a complex carbohydrate, spans from 5% to 18% in microalgal species. Unlike terrestrial plants, the fiber found in microalgae is devoid of lignin and contains minimal hemicellulose, thereby suggesting enhanced digestibility (Niccolai *et al.*, 2019). Specifically, microalgae species such as Spirulina and Chlorella vulgaris exhibit low fiber contents of 8.5% and 5.6%, respectively, while species belonging to the genera Nannochloropsis, Tetraselmis, Tisochrysis and Phaeodactylum demonstrate higher fibre concentrations (Nagappan *et al.*, 2021; Rizwan *et al.*, 2018).

Studies indicate that nutrient limitations can further augment the carbohydrate and lipid profiles in microalgae. Furthermore, microalgae are characterized by a rich diversity of pigments with antioxidant properties and certain species synthesize substantial amounts of vitamins and immunostimulants, which can positively affect the health of aquatic organisms. Microalgal pigments, such as astaxanthin, have the additional benefit of enhancing the coloration of fish, thereby increasing their marketability. Moreover, microalgae are abundant in organic minerals, a characteristic attributed to their structural features that facilitate the high-affinity binding of metals, coupled with a significant surface-to-volume ratio. This unique property effectively mitigates the challenges associated with mineral leaching before ingestion by fish. Certain microalgae are particularly high in omega-3 fatty acids, including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which confer health benefits not only to fish but also to humans. These omega-3 fatty acids are naturally present in high concentrations in selected marine fish species that consume algae. Research has demonstrated that omega-3 fatty acid-rich microalgae are viable substitutes for lipids in both feed formulations and fish oil, thus supporting sustainable aquaculture practices (Cottrell *et al.*, 2020).

6. Bacterial Proteins: A Sustainable Solution

Bacterial single-cell proteins (SCPs) offer a highly viable alternative to traditional fishmeal, characterized by their rapid growth rates, high protein content and ability to thrive on diverse carbon substrates, including organic waste materials. Bacteria such as *Methylococcus capsulatus* and *Cupriavidus necator* exemplify this potential, as they can be cultivated using methane and hydrogen gas, respectively (Sharif *et al.*, 2021). This process allows for the transformation of these low-cost substrates into valuable biomass that is rich in protein, reaching levels of up to 70%. This protein concentration positions bacterial SCPs as a competitive substitute for high-quality fishmeal. Several bacterial species have emerged as promising protein sources for aquafeed, expanding the options beyond the well-known *Methylococcus capsulatus* and *Cupriavidus necator*. One such species, *Ralstonia eutropha*, is notable for its versatility in utilizing a range of substrates, including organic acids and sugars, to achieve high biomass yields. This bacterium is rich in essential amino acids, making it an attractive protein source for aquaculture applications. Another significant player is *Bacillus subtilis*, recognized for its probiotic properties. Not only does this bacterium contribute valuable protein, but it also enhances gut health in fish. By producing enzymes that improve nutrient digestibility and promote the growth of beneficial gut microbiota, *Bacillus subtilis* can lead to better feed utilization and overall fish health. *Pseudomonas putida* has also gained attention for its ability to convert waste materials into high-protein biomass. Capable of growing on various carbon sources, including aromatic compounds, this species presents a sustainable option for protein production in aquafeed. *Corynebacterium glutamicum*, commonly utilized in the fermentation industry for amino acid production, can be employed to generate single-cell protein. It is particularly rich in lysine, addressing a common deficiency in many plant-based fish diets. Lastly, *Kocuria rhizophila* is recognized for its high protein content and digestibility (Pekala *et al.*, 2018). This bacterium can be cultivated using agricultural by-products, providing an economically viable and sustainable source of protein for aquaculture. The incorporation of these bacterial species into aquafeeds not only enhances the nutritional profiles of fish diets but also supports sustainability in aquaculture by reducing dependence on traditional fishmeal sources and utilizing waste materials for protein production.

7. Yeast: Functional and Nutritive Benefits

Yeasts have emerged as promising sustainable ingredients in aquaculture, particularly due to their ability to transform low-value, non-food biomass from the forestry and agricultural sectors into high-value feed. This conversion process effectively reduces reliance on arable land, minimizes water usage and mitigates the impacts of climate change. Yeast cells typically exhibit a substantial crude protein content, ranging from 40% to 55%, along with various bioactive components beneficial for fish growth and development (Agboola *et al.*, 2021).

Recent research highlights the incorporation of yeast products in fish diets, emphasizing their roles as both nutritional and functional supplements. These supplements have been shown to enhance immune responses and promote gut health across various fish species. The cell walls of yeasts, constitute approximately 26% to 32% of their dry weight, are particularly rich in mannan-oligosaccharides (MOS), β-glucan and chitin, which have documented health benefits (Schiavone *et al.*, 2014). However, there is still a relative lack of information regarding the role of yeast as a macro-ingredient in aquafeeds. Key yeast species, including *Saccharomyces cerevisiae* and various non-Saccharomyces species such as *Cyberlindnera jadinii*, *Kluyveromyces marxianus*, *Blastobotrys adeninivorans* and *Wickerhamomyces anomalus*, are receiving increasing attention for their nutritional advantages and functional properties in aquaculture diets. *Saccharomyces cerevisiae* is particularly esteemed for its high protein content, which ranges from 40% to 55%, as well as its diverse array of vitamins and bioactive compounds. This yeast is commonly utilized as a probiotic and nutritional supplement, recognized for its ability to enhance gut health and bolster immune responses in various fish species (Schiavone *et al.*, 2014). *Cyberlindnera jadinii*, previously classified as *Candida utilis*, has attracted interest due to its capability to utilize agricultural by-products, thereby providing a sustainable protein source. Its favorable amino acid profile makes it a beneficial addition to aquafeeds. Likewise, *Kluyveromyces marxianus* is noted for its rapid growth and ability to ferment lactose, which enables it to produce protein from dairy by-products. The inclusion of this yeast in fish diets can significantly enhance growth performance and overall health.

Furthermore, *Blastobotrys adeninivorans* is recognized for its versatility in substrate utilization, contributing positively to sustainable aquaculture practices. Meanwhile, *Wickerhamomyces anomalus* demonstrates potential for improving the gut microbiome of fish, thereby further supporting their growth and health. The exploration of these yeast species highlights their significant potential as valuable feed ingredients, capable of providing high-quality nutrition while simultaneously reducing dependence on traditional feed sources in aquaculture (Agboola *et al.*, 2021).

8. Innovative Fungi: Fuelling the Next Wave of Aquafeed

Fungal single-cell proteins (SCPs), particularly those derived from species such as *Aspergillus oryzae* and *Rhizopus oligosporus*, have gained significant attention as sustainable alternatives for aquafeed (Glencross *et al.*, 2020). These fungi are cultivated *via* solid-state or submerged fermentation processes, using agricultural by-products, organic waste and industrial side streams. This conversion of low-cost substrates into protein-rich biomass presents an environmentally sustainable alternative to traditional fishmeal, aligning with circular economy principles in aquaculture. With protein concentrations ranging between 30% and 50%, fungal SCPs are highly digestible and offer an excellent source of essential amino acids, such as lysine and methionine, which are typically lacking in plant-based feeds. Research has demonstrated that fish diets supplemented with fungal SCPs can achieve growth rates comparable to, or even surpass, those seen with conventional fishmeal-based diets. In addition to their nutritional value, fungi provide functional benefits. They produce enzymes such as proteases and cellulases, which aid in the digestion of complex feed components, thereby improving nutrient absorption and feed efficiency. Fungal SCPs also contain bioactive compounds like β-glucans and antimicrobial peptides, which enhance immune responses, reduce infection rates and decrease reliance on antibiotics in aquaculture. Their low allergenic potential further ensures that fungal SCPs are well-tolerated by a wide range of aquaculture species (Glencross *et al.*, 2020; Jannathulla *et al.*, 2018).

9. Protists: A New Frontier in Aquafeed

Protists, as a diverse group of unicellular organisms, are emerging as highly valuable components in sustainable aquafeed due to their ability to synthesize critical nutrients. Several protist species are being investigated for their exceptional nutritional profiles, particularly in terms of lipids and proteins, which make them viable alternatives to traditional fishmeal and fish oil sources. Among these species, Schizochytrium stands out for its high concentrations of docosahexaenoic acid (DHA), a key omega-3 fatty acid that is crucial for fish growth and development. Given its DHA content, Schizochytrium serves as an effective substitute for fish oil in aquaculture, providing a renewable source of essential fatty acids without depleting marine ecosystems. Similarly, Thraustochytrium is noted for its substantial DHA and eicosapentaenoic acid (EPA) content, both of which are fundamental to fish immune function and overall health (Raghukumar, 2008). In addition to their lipid richness, protists like *Crypthecodinium cohnii* are cultivated for their omega-3 fatty acid content and offer scalable, cost-effective production using low-cost substrates such as agricultural waste. This makes them an economically attractive option for large-scale aquaculture operations. Their rapid growth rates further enhance their utility in industrial feed formulations.

Other species, like *Phaeodactylum tricornutum*, a microalgae-protist hybrid, contribute not only high protein levels but also carotenoids, which play an essential role in fish pigmentation and health. These nutrient-dense species not only improve the nutritional quality of aquafeeds but also provide functional benefits, including enhanced immune response and stress resistance. Overall, protists offer a multifaceted solution for aquafeed formulations by delivering essential nutrients such as omega-3 fatty acids and proteins, while their sustainable cultivation aligns with the growing demand for eco-friendly feed alternatives. By integrating a broader spectrum of species, including Schizochytrium, Thraustochytrium, *Crypthecodiniumcohnii* and *Phaeodactylu mtricornutum*, the aquaculture industry can significantly reduce its reliance on conventional feed resources, promoting a more sustainable and ecologically sound future for aquaculture.

10. Bioengineered Microbial Ingredients

10.1. Enhancing Nutritional Profiles of Aquafeeds through Genetic Modification of Algae

Genetically engineered algae have garnered substantial attention within aquaculture nutrition due to their capacity to enhance the biochemical composition of aquafeeds. Advanced bioengineering techniques allow for the precise modification of algal strains such as Nannochloropsis and Schizochytrium, which are manipulated to significantly boost the synthesis of long-chain polyunsaturated fatty acids, including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) (Abdelghany *et al.*, 2020). These omega-3 fatty acids are indispensable for optimal fish development, cellular membrane integrity and immune function, making them a crucial component in aquafeed formulations. The genetic enhancement of these algal species has been further expanded to elevate their protein and vitamin contents, particularly carotenoids and antioxidants, which are vital for maintaining the health and pigmentation of cultured fish species.

This biotechnological intervention not only augments the nutritional profiles of algae but also optimizes their growth kinetics and productivity, utilizing minimal external resources such as carbon dioxide and sunlight, thus positioning these organisms as highly sustainable alternatives to traditional fish-derived oils. The scalable cultivation of genetically modified algae has further been demonstrated to yield higher concentrations of essential nutrients while utilizing lower-cost substrates, making them a commercially viable option for addressing the increasing global demand for aquafeed ingredients. Furthermore, genetic modifications in algae allow for precise tailoring of nutrient profiles to meet the specific dietary requirements of diverse aquaculture species, thus enhancing feed conversion efficiency and overall growth performance (Glencross *et al.*, 2020).

Recent research corroborates the potential of genetically modified algae in replacing conventional feed ingredients, particularly fish oil, without compromising the nutritional quality of aquafeeds. The integration of these engineered algae into feed formulations represents a sustainable solution that could significantly alleviate pressures on overexploited marine resources and contribute to a circular economy in the aquaculture sector (Jannathulla *et al.*, 2021).

11. Advances in Synthetic Biology for Optimizing Single-Cell Protein Production

Synthetic biology has revolutionized the field of single-cell protein (SCP) production by enabling precise genomic manipulation of microbial species, including bacteria, yeast and fungi, to enhance protein yield, optimize amino acid profiles and introduce functional bioactive compounds. By employing metabolic engineering and gene editing technologies, microbial platforms such as *Escherichia coli*, *Pichia pastoris* and *Corynebacterium glutamicum* can be engineered to produce SCPs with high concentrations of essential amino acids like lysine and methionine, which are critical for meeting the dietary requirements of aquaculture species but are often limited in plant-based feed formulations (Jones *et al.*, 2020; Jannathulla *et al.*, 2021).

Additionally, synthetic biology has enabled the development of microbial SCP systems capable of utilizing non-conventional substrates, including lignocellulosic biomass, agricultural residues and industrial by-products. This substrate flexibility dramatically enhances the sustainability and cost-effectiveness of SCP production, reducing the reliance on traditional feedstock resources and significantly lowering the environmental footprint associated with protein production. Engineered SCPs can also be optimized for rapid growth and high biomass yields, making them scalable for large-scale commercial applications.

Moreover, synthetic biology techniques have enabled the biosynthesis of bioactive molecules such as antimicrobial peptides, immunostimulatory β-glucans and enzymes like proteases and cellulases, which confer additional functional benefits to aquaculture feeds. These bioactive compounds not only improve feed digestibility and nutrient absorption but also enhance the immune resilience of farmed fish, mitigating the risk of pathogen outbreaks and reducing the dependence on antibiotics. For instance, engineered yeast strains can be designed to express cellulolytic enzymes that degrade complex plant polysaccharides, thus improving the bioavailability of nutrients in plant-based aquafeeds. As advancements in synthetic biology continue to evolve, there is significant potential for further refinement of SCP production platforms, particularly in the context of tailoring the lipid composition and nutrient profiles of SCPs to specific aquaculture species. These innovations are expected to play a pivotal role in the transition towards more resilient, nutritionally optimized and environmentally sustainable aquafeed systems.

12. Environmental and Economic Impacts of Microbial and Single-Cell Protein in Aquaculture Nutrition

12.1. Ecological Sustainability and Resource Efficiency

The incorporation of microbial and single-cell protein (SCP) ingredients into aquafeeds presents considerable environmental advantages, particularly in resource utilization and ecological conservation. The traditional aquaculture industry heavily relies on fishmeal and fish oil, leading to significant overexploitation of marine resources and ecological degradation. In contrast, microbial and SCPs can be cultivated on non-arable land, utilizing waste substrates such as agricultural by-products and industrial effluents. This not only reduces competition with food crops but also mitigates waste accumulation in ecosystems.

Microbial fermentation processes typically exhibit a lower carbon footprint than conventional feed production methods. The cultivation of algae and fungi sequesters carbon dioxide and enhances nutrient cycling within ecosystems. The application of waste streams for microbial cultivation addresses nutrient pollution, as certain microalgal species can absorb excess nitrogen and phosphorus from wastewater, thereby improving aquatic ecosystem health. Moreover, the production of SCPs contributes to biodiversity conservation by lessening reliance on wild-caught fish and promoting the use of sustainably sourced ingredients. The controlled cultivation of these microorganisms offers a reliable alternative that can help alleviate pressure on marine ecosystems, supporting broader environmental sustainability goals (Sarker, 2023).

12.2. Economic Viability and Market Stability

The economic viability of incorporating microbial and SCP ingredients into aquafeeds is increasingly supported by advancements in production technologies and bioprocess optimization. The ability to produce SCPs at lower costs, particularly through the utilization of low-value substrates, enhances their attractiveness as practical alternatives to traditional feed sources. For instance, using waste materials reduces input costs and contributes to operational sustainability for aquaculture producers (Sarker, 2023). Additionally, SCPs can lead to enhanced growth rates and improved feed conversion efficiencies in farmed fish, resulting in greater profitability for aquaculture operations. Evidence indicates that fish diets enriched with SCPs yield better health outcomes, increased marketability and reduced mortality rates, collectively contributing to more stable and predictable economic returns. As market dynamics for conventional fishmeal fluctuate, often influenced by supply chain constraints and overfishing concerns, microbial ingredients provide a measure of price stability. The scalable nature of microbial production systems, along with their independence from wild fisheries, positions them as a robust solution for satisfying the global demand for aquafeed (Ellahi and Firdous, 2023).

13. Overcoming Challenges and Future Prospects

13.1. Regulatory Frameworks and Consumer Perception

Despite the substantial potential benefits of microbial and SCP ingredients, significant challenges remain, particularly in regulatory frameworks and consumer acceptance. The regulatory landscape governing genetically modified organisms (GMOs) and novel feed ingredients varies considerably across different jurisdictions, complicating the commercialization of these products. Establishing clear safety protocols and nutritional guidelines is essential for fostering industry confidence and ensuring compliance with international standards (Pereira *et al.*, 2022; Ellahi and Firdous, 2023).

Consumer perceptions play a critical role in the acceptance of microbial and SCP ingredients. Although awareness of environmental benefits is growing, misconceptions regarding the safety and nutritional equivalence of these ingredients persist. Educational campaigns aimed at demystifying microbial feeds and highlighting their advantages are crucial for enhancing consumer trust and acceptance. Collaborative efforts involving stakeholders from academia, industry and regulatory bodies will be necessary to develop transparent communication strategies that address consumer concerns.

13.2. Production Scalability and Cost-Effectiveness

The scalability of microbial and SCP production poses additional challenges that necessitate ongoing research and innovation. While advancements in metabolic engineering and fermentation technology have improved yields, establishing economically viable production systems remains a priority. Research suggests that optimizing fermentation conditions and exploring alternative substrates can further enhance biomass productivity and reduce overall production costs (Matassa *et al.*, 2016; Jannathulla *et al.*, 2021).

Investment in bioprocessing technologies and infrastructure is vital for scaling up production to meet global aquaculture demands. Collaborative initiatives between public and private sectors, as well as increased funding for research and development, are essential for driving innovation in microbial feed production. In conclusion, the integration of microbial and single-cell ingredients into aquafeeds holds great promise for enhancing environmental sustainability and economic viability. However, addressing regulatory, consumer and production challenges will be critical to realizing their full potential within sustainable aquaculture practices.

14. Conclusion

In summary, the incorporation of microbial and single-cell protein (SCP) ingredients into aquaculture feeds represents a significant paradigm shift toward achieving both ecological sustainability and economic robustness in the aquaculture industry. These microorganisms demonstrate remarkable proficiency in utilizing low-cost substrates, thereby facilitating the formulation of nutrient-dense feeds that address the pressing demands for environmentally responsible aquaculture practices. The inherent advantages of these ingredients extend beyond nutritional enhancement; they also play a crucial role in mitigating the reliance on conventional feed sources that often impose considerable stress on marine ecosystems.

However, to fully capitalize on the potential of microbial and SCPs, it is essential for stakeholders, including producers, regulatory agencies and consumers, to collaboratively navigate the regulatory landscape and address consumer acceptance challenges that currently impede widespread integration. Establishing comprehensive guidelines and safety standards for the application of these innovative ingredients will be vital in fostering public trust and enabling market penetration. Moreover, sustained research and development efforts are crucial for enhancing production scalability and cost-effectiveness, ensuring that microbial and SCPs can effectively replace traditional feed sources without compromising the quality of aquaculture outputs or the health of aquatic species. As the aquaculture sector continues to adapt to global challenges regarding food security and sustainability, the strategic integration of these advanced microbial ingredients offers a promising trajectory toward a more resilient and nutritionally optimized aquaculture framework. Such innovations not only enhance the industry's capability to meet increasing consumer demands but also contribute significantly to global initiatives aimed at environmental stewardship and sustainability. Ultimately, by embracing these innovative approaches, the aquaculture industry is positioned to play a pivotal role in addressing contemporary challenges while fostering a sustainable future for global food production.

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