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Research Article

Sustainability of fishmeal and fish oil production: Balancing aquaculture demand with food security and marine biodiversity

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Abstract

This review provides a comprehensive analysis of the challenges and opportunities associated with optimizing fish meal and fish oil (FMFO) production for sustainable food security and biodiversity conservation. FMFO is an important source of omega-3 fatty acids, but its production has negative environmental and social impacts. The article reviews various technological, market, and consumer trends that could shape the future of FMFO production, such as alternative protein sources, precision feeding technologies, circular economy models, and integrated multi-trophic aquaculture (IMTA) systems. The article emphasizes the need to balance food security and biodiversity conservation, highlighting the detrimental effects of overfishing wild fish stocks for FMFO production. To address this issue, the article advocates for informed consumer choices and sustainable sourcing practices, stressing the importance of transparency and traceability in the FMFO supply chain. A multi-stakeholder approach is necessary to optimize FMFO production for sustainability and conservation, taking into account the perspectives and needs of all stakeholders involved. By embracing sustainable practices and innovative technologies, FMFO production can become more efficient and environmentally friendly while meeting the growing demand for this essential source of omega-3 fatty acids.

Introduction

Fishmeal and fish oil (FMFO) production is a crucial component of the global food system, providing essential nutrients for aquafeed used in fish and shrimp farming (Sharifinia *et al.,* 2025a; Sharifinia *et al.,* 2025b). FMFO is produced by processing small pelagic fish, which are rich in protein and omega-3 fatty acids. As the global population grows and seafood demand intensifies, FMFO becomes increasingly important for ensuring food security (FAO, 2020). Notwithstanding its significance, the sustainability of FMFO production has come under scrutiny, particularly regarding its potential adverse impacts on marine ecosystems.

A disproportionate share of the most environmentally intensive feed resources is allocated to a limited segment of aquaculture production, thereby amplifying the environmental footprint per unit of edible output (Emerenciano *et al.,* 2025). This structural reliance has given rise to a fundamental sustainability paradox. While FMFO are widely regarded as indispensable, high-performance inputs for intensive aquaculture systems, their continued production exerts escalating pressure on marine ecosystems and undermines the foundations of ocean food security and biodiversity. The large-scale extraction of small, nutrient-dense forage fish, which serve as key prey for wild predatory fish, marine mammals, and seabirds, and their diversion into animal feed streams result in a net loss of biomass and essential nutrients from marine food webs. This process ultimately destabilizes trophic dynamics and undermines ecosystem resilience. (Naylor *et al.,* 2021; Costello *et al.,* 2023).

The FMFO industries has been shown to pose a significant threat to marine biodiversity (Tacon and Metian, 2013; Froehlich *et al.,* 2018; Costello *et al.,* 2020). Overfishing of small pelagic fish, a primary source of raw material for FMFO production, can lead to the depletion of target fish stocks, as well as the incidental capture of non-target species, including endangered and protected species, thereby negatively affecting marine biodiversity (Worm *et al.,* 2006; FAO, 2020). FMFO production can generate substantial waste that contribute to water pollution and negatively impact marine ecosystems (Froehlich *et al.,* 2018). In addition, the use of non-pelagic fish species for FMFO production can increase pressure on these species and their ecosystems, resulting in additional negative impacts on biodiversity (Tacon and Metian, 2013; Naylor *et al.,* 2021). However, the FMFO industry is only one of many factors affecting marine biodiversity, and other industries and activities, such as climate change and pollution, also play critical roles in degrading marine ecosystems (Worm *et al.,* 2006; Halpern *et al.,* 2008). Therefore, it is crucial to manage FMFO industry and other human activities sustainably, reducing overfishing, minimizing waste and pollution, and promoting responsible and sustainable fishing practices to minimize impacts on marine biodiversity and ensure the long-term health of our oceans (Troell *et al.,* 2014).

FMFO are crucial components of animal feed, providing essential nutrients for farmed animals such as poultry, pigs, and farmed fish. However, the production of FMFO can have serious negative impacts on marine ecosystems, including overfishing and habitat destruction (Tacon and Metian, 2008). As the global population continues to grow, it is essential to strike a balance between producing enough food to feed everyone and conserving marine biodiversity. To address this challenge, researchers and policymakers are exploring ways to optimize the production of FMFO through sustainable practices that minimize environment impacts and promote biodiversity conservation. By adopting such practices, we can ensure that we can meet food production needs without compromising the health of our oceans and marine life.

Growing awareness of the need to reconcile FMFO production with global food security and biodiversity has spurred significant research. Current efforts focus on exploring alternative ingredients and innovative production techniques that minimize environmental harm while safeguarding marine ecosystems (Tacon and Metian, 2013).

Despite growing research and efforts to optimize FMFO production for sustainable food security and biodiversity conservation, significant challenges persist. These include the need for robust policy and regulatory frameworks, as well as the promotion of sustainable practices throughout the entire FMFO supply chain (Tacon and Metian, 2009). Achieving a balance between FMFO production and biodiversity conservation is imperative to ensure a more sustainable and resilient food system for future generations. By adopting sustainable practices, we can preserve the health of our oceans and marine life while meeting the increasing demand for food as the global population continues to grow.

Therefore, the aim of the review is to emphasize the importance of balancing FMFO production with biodiversity conservation for sustainable food security. It also discusses the adverse effects of FMFO production on marine ecosystems and advocates the adoption of sustainable practices to reduce these impacts. The review highlights the challenges involved in achieving sustainable FMFO production and underscores the need of striking a balance between FMFO production and biodiversity conservation to ensure a more sustainable and resilient food system for future generations.

Materials and methods

This manuscript was developed using a structured and systematic approach to ensure comprehensive coverage of the scientific literature related to fishmeal and fish oil (FMFO) production, alternative protein sources, and sustainable aquaculture practices. The methodological framework included clearly defined search strategies, eligibility criteria, and thematic synthesis.

Literature search strategy

A systematic search of the scientific literature was conducted across major academic databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar. These sources collectively cover the biological, nutritional, technological, and ecological aspects of FMFO alternatives and sustainable aquaculture.

The references incorporated in the manuscript reflect studies on:

- Insect meals (e.g., *Tenebrio molitor*, *Hermetia illucens*)
- Biofloc-based meals and microbial floc systems
- Plant protein ingredients
- Aquaculture by-products and circular economy approaches
- Sustainability frameworks and One Health perspectives
- Optimization of fishmeal/oil extraction and environmental impact assessments

These publications form the exclusive data foundation for this manuscript.

Keywords and thematic terms

The selection of studies aligns with specific thematic keywords reflected throughout the manuscript, including:
"fishmeal replacement", "insect meal", "black soldier fly", "mealworm", "biofloc meal", "plant proteins", "soybean meal", "rapeseed meal", "cottonseed meal", "fermented proteins", "aquaculture by-products", "circular economy", "sustainable aquaculture", and "One Health". These terms match the topics represented in the tables (insects, biofloc, plant-based proteins) and cited literature.

Timeframe of literature

The dataset used in the manuscript spans the years 2007–2025, as indicated by the publication dates of the references included. Recent studies from 2023–2025 were incorporated to ensure up-to-date scientific coverage on emerging FMFO alternatives and aquafeed innovations.

Inclusion criteria

The literature included in this review consists solely of:

- Peer-reviewed journal articles cited in the manuscript
- Studies evaluating fishmeal replacement levels (0–100%) using insect, plant, or biofloc-derived ingredients
- Research providing measurable data (growth performance, feed efficiency, blood biochemical indices, immune responses, fatty acid profiles)
- Studies involving economically relevant species
- Research integrated into the manuscript's tables (insect-based protein, biofloc meal, plant protein sources)

Exclusion criteria

The review excluded:

- Non-peer-reviewed documents
- Gray literature not presents in the manuscript
- Publications unrelated to fishmeal replacement, aquaculture nutrition, or sustainability
- Speculative or non-data-driven studies
- Only the sources explicitly cited in the manuscript were used.

Data extraction and evidence synthesis

Data were extracted directly from the studies summarized in Tables 1–3 of the manuscript, which include:

- Insect meal studies evaluating substitution levels (e.g., 6.25–100% replacements), suitable inclusion rates, and species-specific outcomes.
- Biofloc and microbial floc studies involving wet biofloc biomass, ex-situ/in-situ floc, and processed floc meals with replacement values from 0 to 100%.
- Plant protein sources such as SBM, CSM, RSM, CM, PCM, CPC, FRP, CGM, SFM, and HP-DDG, including optimal inclusion percentages as reported in the literature.

These datasets were synthesized to evaluate comparative nutritional performance, growth outcomes, environmental implications, and applicability of FMFO alternatives in aquaculture.

Organization of the review

The narrative structure of the review, as reflected in the manuscript, follows the classification of the extracted data into major themes:

1. Insect-derived proteins and their physiological impacts
2. Biofloc technology and microbial-derived protein sources
3. Plant-based protein ingredients and fermented meals
4. Aquaculture and fishery by-products as circular economy resources
5. Implications for food security, biodiversity, and sustainable production systems

This organizational approach allowed for the integration of diverse data sources into a coherent synthesis aligned with the scope of the manuscript.

Current challenges in FMFO production and their impact on sustainability and conservation efforts

Ensuring the sustainability of FMFO production is crucial for its continued role in the aquaculture industry and the global food system. However, several challenges remain to be addressed to minimize its impact on marine ecosystems. Overfishing of small pelagic fish, which are the primary source of FMFO, can lead to a decline in their populations, ultimately affecting the wider marine ecosystem and biodiversity (Pauly *et al.,* 2002). Unsustainable fishing practices, such as the use of unregulated fishing gear and high levels of bycatch, can contribute to the depletion of marine ecosystems (FAO, 2018). Moreover, environmental impacts associated with FMFO production, such as the release of pollutants, greenhouse gases, and nutrients into the surrounding waters, can pose significant challenges to the quality of water and soil (Ghamkhar and Hicks, 2020; Hilmarsdóttir *et al.,* 2022). The limited availability of alternative protein sources is another challenge facing FMFO production. While the use of alternative protein sources in aquafeed can reduce the demand for FMFO, their nutritional value may not be as high as that of FMFO, and their availability is limited (Naylor *et al.,* 2009). To address these challenges, a range of strategies must be employed. Improving fishing practices, reducing bycatch, and promoting sustainable aquaculture practices can reduce the demand for FMFO (Tacon and Metian, 2009, 2013; FAO, 2018). Additionally, using alternative protein sources, such as plant-based proteins, can help minimize the impact of FMFO production on marine ecosystems and reduce the demand for FMFO (Naylor *et al.,* 2009). Furthermore, the development of new technologies to improve FMFO production efficiency and reduce environmental impacts can contribute to sustainability efforts (Sarker, 2023; Bohnes and Laurent, 2021). In conclusion, the challenges facing FMFO production must be addressed through a comprehensive approach that considers the environmental, social, and economic dimensions of sustainability. This approach can help ensure the sustainability of small pelagic fish populations and marine ecosystems.

Optimizing FMFO Production for Sustainable Food Security and Biodiversity Conservation

There are several strategies that can be employed to optimize FMFO production and achieve sustainable food security and biodiversity conservation.

Improved fisheries management

Sustainable fisheries management is essential for maintaining the health and productivity of marine ecosystems, as well as for ensuring the long-term viability of FMFO production. Overfishing of small pelagic fish can have significant impacts on marine ecosystems, including changes in the food web, reduced biodiversity, and loss of ecosystem services. By reducing bycatch and implementing quota systems, fisheries managers can help ensure that fish populations are harvested at sustainable levels, promoting the conservation of marine biodiversity and the sustainability of FMFO production. Reducing bycatch is an important strategy for minimizing the impact of FMFO production on non-target species. Bycatch can include endangered or threatened species, as well as juveniles of the target species, which can affect the sustainability of fish populations. By implementing measures to reduce bycatch, such as the use of selective fishing gear, fisheries managers can minimize the impact of FMFO production on non-target species, promoting the long-term sustainability of marine ecosystems (Hall and Mainprize, 2005). Implementing quota systems can also help ensure the sustainability of FMFO production. Quotas can be set based on the biology and ecology of the target species, as well as on the needs of other marine species that depend on them for food. By limiting the number of fish that can be harvested, fisheries managers can help ensure that fish populations are not overexploited, promoting the long-term sustainability of FMFO production (Worm *et al.,* 2009; Belhabib *et al.,* 2014; Hilborn *et al.,* 2020). Overall, sustainable fisheries management practices such as reducing bycatch and implementing quota systems are essential for achieving sustainable FMFO production and promoting the conservation of marine biodiversity.

Sustainable aquaculture practices

Developing sustainable aquaculture practices, such as recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture (IMTA), and biofloc technology (BFT), can help reduce the demand for wild-caught fish and FMFO (Tacon and Metian, 2013). These practices can also help minimize the environmental impact of FMFO production and contribute to the conservation of marine biodiversity. RAS is a closed-loop system that recirculates water within the production unit, reducing the need for water exchange and the risk of disease transmission. Implementing RAS has been shown to improve water quality, increase fish production, and minimize the environmental impact of aquaculture. For example, salmon farmers in Norway have successfully reduced water usage by up to 99% and decreased fish waste released into the environment by using RAS (Badiola *et al.,* 2012; Troell *et al.,* 2014). IMTA involves co-cultivating multiple species in a single production unit, utilizing waste products from one species as a nutrient source for another. This approach can increase production efficiency and reduce the environmental impact of aquaculture. In China, IMTA systems have been effectively implemented, co-cultivating seaweed and shellfish with finfish to improve water quality and nutrient utilization (Chopin *et al.,* 2001). Implementing RAS, IMTA, and BFT can also reduce the demand for wild-caught fish and FM while contributing to marine biodiversity conservation. By promoting sustainable aquaculture practices, we can ensure a thriving aquaculture industry while minimizing its negative impact on the environment.

Alternative protein sources

The use of fishmeal and fish oil (FMFO) in aquafeed has been a longstanding concern due to its environmental impact and contribution to overfishing. To address this issue, alternative protein sources have been developed and implemented in aquafeed. Insect meal and microbial protein are two promising alternative protein sources that have shown potential in reducing the demand for FMFO and mitigating its environmental impact (Naylor *et al.,* 2000; Naylor *et al.,* 2009; Naylor *et al.,* 2021). Insect meal has a similar nutritional profile to fishmeal and has already been used in aquafeed for some species, such as rainbow trout (van Huis *et al.,* 2013). Additionally, microbial protein, derived from microorganisms like bacteria and yeast, has shown promise as a potential replacement for FMFO in aquafeed. Plant-based proteins, such as soybean meal and corn gluten meal, have also been successfully used in aquafeed for various species, including tilapia and common carp. Incorporating plant-based proteins in aquafeed can help reduce the impact of FMFO production on marine ecosystems and biodiversity (Naylor *et al.,* 2021). Implementing alternative protein sources in aquafeed not only contributes to the sustainability of the aquaculture industry but also promotes the conservation of marine ecosystems and biodiversity. By reducing the demand for FMFO, we can mitigate its environmental impact and ensure the long-term viability of the aquaculture industry.

Insect meal

The emergence of insect production as a protein feed source for aquaculture represents a significant advancement in sustainable food systems, addressing the growing demand for protein without competing with human food resources (Sharifinia, 2024). Insects, characterized by their rapid life cycles and adaptability, can thrive on a diverse range of high-efficiency substrates, making them an ideal candidate for aquaculture feed (Berggren *et al.,* 2019; Sharifinia *et al.,* 2023; Sharifinia *et al.,* 2023; Islam *et al.,* 2024). This adaptability not only enhances their growth potential but also allows for the utilization of organic waste, contributing to a circular economy.

Among the various insect species, the black soldier fly (*Hermetia illucens*), common housefly (*Musca domestica*), and yellow mealworm (*Tenebrio molitor*) have garnered particular attention due to their favorable nutritional profiles and growth characteristics. These species typically exhibit crude protein contents ranging from 40% to 63%, with defatted insect meal potentially reaching up to 83% crude protein (Hua *et al.,* 2019). Such high protein levels, combined with their amino acid profiles, position insect meal as a viable alternative to traditional FM in aquaculture diets, which is crucial for meeting the nutritional needs of farmed fish. The amino acid profiles of insects are taxon-dependent, with variations observed among different species. Notably, members of the Diptera group often display amino acid profiles that are similar to those of FM, making them particularly suitable for aquaculture applications (Tran *et al.,* 2015). Furthermore, the crude fat content in insects can vary significantly, ranging from 8.5% to 36%. This variability is influenced by factors such as the insects' growth stages and the substrates used for their cultivation. While insects generally contain lower levels of omega-3 fatty acids, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), they tend to have higher levels of omega-6 fatty acids compared to FM. The quality of lipids in insect meal can be enhanced through strategic substrate selection. For instance, incorporating nutrient-rich substrates, such as fish offal, during insect cultivation can increase the levels of beneficial fatty acids like EPA and DHA. However, this approach may present economic challenges compared to directly feeding fish by-products to aquaculture species. Additionally, the vitamin and mineral content of insect meal is highly dependent on the type of substrate used, underscoring the importance of careful substrate management in optimizing the nutritional value of insect-based feeds (Henry *et al.,* 2015; Islam *et al.,* 2024).

Insects are also characterized by their low carbohydrate content, typically less than 20%, primarily in the form of chitin. While chitin is often regarded as anti-nutritive and indigestible by fish (Rust, 2003), recent studies have indicated that low levels of chitin may act as an immune stimulant, potentially enhancing the health and resilience of aquatic species (Henry *et al.,* 2015). This dual role of chitin highlights the need for further research to fully understand its implications in aquaculture nutrition.

Most studies investigating the replacement of FM with insect meal advocate for partial substitution to optimize growth performance and health outcomes (Table 1). For example, research on Atlantic salmon (*Salmo salar*) demonstrated that insect powder derived from black soldier fly larvae could completely replace FM at a dietary inclusion rate of 14.75% (Belghit *et al.,* 2019). Similarly, yellow mealworm-derived insect meal improved the growth performance of rainbow trout (*Oncorhynchus mykiss*) at graded inclusion levels from 5% to 25%, achieving full replacement of FM (Rema *et al.,* 2019).

Table 1: Studies on using insect meal in aquaculture diets.

Cultured species	Insect species	Substituted values in diet (%)	Suitable amount (%)	Reference
Litopenaeus vannamei	*Tenebrio molitor*	15, 30, 60 and 100	60	(Sharifinia *et al.,* 2023a, b)
Oncorhynchus mykiss	*T. molitor*	100	100	(Terova *et al.,* 2021)
Salmo salar	*Hermetia illucens*	6.25, 12.5 and 25 or 3.7 and 6.7	25	(Weththasinghe *et al.,* 2021)
Lates calcarifer	*H. illucens*	30	30	(Chaklader *et al.,* 2021)
Oreochromis niloticus	*H. illucens*	10, 20, 40, 60, 80 and 100	100	(Tippayadara *et al.,* 2021)
Dicentrarchus labrax	*H. illucens*	6.5, 13, and 19.5	19.5	(Moutinho *et al.,* 2021)
O. mykiss	*H. illucens* and *T. molitor*	50 and 50	50 (YM)	(Melenchón *et al.,* 2022)
Trachinotus ovatus	*H. illucens*	25 and 50	50	(Yu *et al.,* 2023)
Micropterus salmoides	*H. illucens*	1,2, and 4	2	(Peng *et al.,* 2021)
Sparus aurata	*H. illucens*	9.2, 18.4 and 27.6	18.4	(Gai *et al.,* 2023)

Table 1 (continued):

Cyprinus carpio	*H. illucens*	2.6, 5.3, 7.9 and 10.6	5.3	(Li *et al.,* 2017)
Argyrosomus regius	*T. molitor*	10 and 20	10	(Saavedra *et al.,* 2023)
O. mykiss	*T. molitor*	50		(Melenchón *et al.,* 2023)
Acipenser baerii	*H. illucens* and *T. molitor*	15 (BSF) or 15 (YM)		(Józefiak *et al.,* 2019)
C. carpio	Earthworm meal (*Eisenia fetida*) and wormcast	14.5, 14.8, 15.1, and 15.4 (EM) or 1.8, 3.7 and 5.8 (WC)	15.4 (EM) Or 15.1 (EM) + 1.8 (WC)	(Mi *et al.,* 2022)
Channa striata	*H. illucens*	20, 50, 80, and 100	20	(Muslimin *et al.,* 2023)
Cynoglossus semilaevis	*H. illucens*	25, 50, 75 and 100	25	(Li *et al.,* 2022)
Monopterus albus	*H. illucens*	5.26, 10.52 and 15.78	15.78	(Hu *et al.,* 2020)
Lateolabrax japonicus	*H. illucens*	16, 32, 48 and 64	64	(Wang *et al.,* 2019)
Argyrosomus regius	*T. molitor*	10, 20 and 30	10	(Coutinho *et al.,* 2021)
Juvenile channel catfish	Cricket meal (*Gryllus bimaculatus*)	25, 50,75 and 100	100	(Fan *et al.,* 2023)
S. aurata	*H. illucens*	33% and 66%	up to 33%	(Carvalho *et al.,* 2023)

Note: Black soldier fly (BSF), Yellow mealworms (YM), Earthworm meal (EM), Wormcast (WC).

Comparable findings were observed in red sea bream (*Pagrus major*), where the inclusion of defatted yellow mealworm larvae at rates of 25% to 65% significantly enhanced growth performance and disease resistance (Ido *et al.,* 2019).

To further enhance the nutritional value of insect meal, researchers suggest combining it with complementary feed ingredients or manipulating the substrates used to improve fatty acid profiles, digestibility, and palatability. Additionally, defatting the insect source can increase the protein content in the final insect meal, making it even more suitable for aquaculture applications. Utilizing food waste as a substrate for insect cultivation not only improves resource efficiency but also transforms waste streams into valuable protein feeds for aquaculture, provided that local regulations support such practices. As technological advancements continue to drive the production of high-quality insect-based products, the long-term potential of insect meal in aquaculture appears promising. This potential is contingent upon maintaining competitive pricing and establishing a sustainable supply chain, which will ultimately contribute to the resilience and sustainability of global aquaculture systems.

Biofloc meal

Recent research has highlighted the potential of both wet biofloc harvested from natural farming environments and dry microbial meal, also known as biofloc meal (BFM), as viable alternatives in aquaculture feed formulations (Khanjani *et al.,* 2025a; Khanjani *et al.,* 2025b). These bioflocs serve multiple functions: they can lower the protein content of diets, replace fish meal (FM) in aquafeeds, and act as beneficial additives in aquatic nutrition (Shao *et al.,* 2017; Khanjani and Sharifinia, 2020, 2022; Khanjani *et al.,* 2023; Khanjani *et al.,* 2024a; Pérez Rostro *et al.,* 2024; Khanjani and Alizadeh, 2024). Bioflocs are intricate structures that form in the water column through complex interactions involving organic nutrients, physical substrates, and a variety of microorganisms, including phytoplankton, free and attached heterotrophic bacteria, organic particle aggregates, and other organisms such as grazers and cyanobacteria. These interactions are essential for the formation of bioflocs, which play a significant role in maintaining the health and balance of aquatic ecosystems (Abakari *et al.,* 2022; Khanjani *et al.,* 2024b). The utilization of biofloc in aquaculture diets has been summarized in various studies (Table 2), illustrating its potential benefits.

Numerous experiments have explored the incorporation of nutrients from dried bioflocs, particularly BFM, into the diets of shrimp and tilapia (Lee *et al.,* 2017; Binalshikh-Abubkr *et al.,* 2021; Pérez Rostro *et al.,* 2024). This innovative ingredient presents a broader opportunity to replace expensive feed components, thereby enhancing the economic viability of aquaculture (Bauer *et al.,* 2012; Dantas Jr *et al.,* 2016; Shao *et al.,* 2017). Dried microbial particles can be sourced from various origins, significantly influencing their availability and application in aquaculture. One major source includes solid waste or by-products from production ponds or tanks, where the accumulation of organic matter and microbial activity results in nutrient-rich materials that can be harvested and processed into dried microbial particles. These by-products typically contain a diverse range of microorganisms, which can enhance the nutritional quality of the resulting feed. Another critical source of dried microbial particles is ex-situ BFM produced in bioreactors, where controlled conditions facilitate the cultivation of specific microbial communities. In these bioreactors, microorganisms are grown in nutrient-rich media, yielding concentrated biomass that can be harvested, dried, and utilized as a feed ingredient. This method not only guarantees a consistent and high-quality product but also allows for the optimization of microbial strains beneficial for aquatic species. Collectively, these sources of dried microbial particles offer valuable alternatives to conventional feed ingredients, promoting sustainability and efficiency in aquaculture practices.

Table 2: Studies on using biofloc in aquaculture diets.

Cultured species	Sources of biofloc	Substituted values in diet (%)	Suitable amount (%)	Reference
L. vannamei	Microbial floc meal + soy protein concentrate	0-100%	100%	(Bauer *et al.,* 2012)
O. niloticus	Wet biofloc biomass	0-100%	25%	(Caldini *et al.,* 2018)
P. monodon	Biofloc powder	0-100%	100	(Promthale *et al.,* 2019)
L. vannamei	Wet biofloc biomass	33.3- 100%	33.3%	(Khanjani *et al.,* 2020)
O. niloticus	In-situ biofoc	5% and 10%	5% and 10%	(Deng *et al.,* 2021)
L. vannamei	Ex-situ biofloc	5% and 10%	5%	(Uawisetwathana *et al.,* 2021)
F. merguiensis	Wet biofloc biomass	25-100%	25-50%	(Khanjani and Sharifinia, 2022)
O. niloticus	Wet biofloc biomass	0, 15, 30, 45 and 100%	15%	(Aliabad *et al.,* 2022)
C. mrigala	Microfloc meal	0, 30, 40, and 50%	50%	(Rani *et al.,* 2017)
O. niloticus	Dried bioflocs	0-16%	4%	(Binalshikh-Abubkr and Mohd Hanafiah, 2022)
P. vannamei	Biofloc meal	0-40%	30%	(Nethaji *et al.,* 2022)
O. niloticus	Synbiotic and biofloc meal	3 g/ kg feed	-	(Hersi *et al.,* 2023)
O. niloticus	Biofloc meals	5, 10, 15, and 20%	5 to 10%	(Pérez Rostro *et al.,* 2024)
O. niloticus	Wet biofloc biomass	25, 50, 75, and 100%	Up to 25%	Khanjani and Sharifinia, 2024

Several studies have documented the benefits of substituting traditional and costly feed ingredients with dried biofloc or BFM. In various instances, BFM-based diets have shown comparable weight gain, survival rates, and feed efficiency to those fed with FM-based diets (Kuhn *et al.,* 2009). For example, Khatoon *et al.* (2016) reported replacing commercial diets for *L. vannamei* with dried biofloc waste at levels of 25%, 50%, 75%, and 100%, observing that postlarvae (PL) fed with 50% and 75% biofloc exhibited significantly higher specific growth rates and survival compared to other treatments. Similarly, Shao *et al*. (2017) found that substituting 15% of dietary FM with BFM did not adversely affect growth or feed conversion efficiency. Furthermore, Kuhn *et al*. (2009) noted a 50% improvement in weight gain for L. vannamei when a diet containing 16% crude protein was supplemented with concentrated microbial biofloc containing 49% crude protein. For *Penaeus monodon*, Glencross *et al*. (2015) conducted two studies where they supplemented diets with 10% of a low-protein microbial biofloc (~4% protein), resulting in approximately 42% and 50% increases in growth, respectively. Anand *et al*. (2014) concluded that incorporating 4% to 8% BFM into diets improved growth performance and digestive enzyme activity in *P. monodon*.

Promthale *et al*. (2019) indicated that completely replacing FM with BFM did not compromise the growth of *P. monodon*, while also inhibiting the proliferation of *Vibrio parahaemolyticus* in the culture environment and enhancing innate immune responses, such as phenol oxidase activity, phagocytic activities, and total hemocyte counts. Pérez Rostro *et al*. (2024) found that supplementing diets with 5% and 10% BFM resulted in high survival rates and increased growth in Oreochromis niloticus, comparable to control groups. While a 5% replacement may appear minimal, it aligns with the 4% reported by Binalshikh-Abubkr and Mohd Hanafiah (2022) in hybrid red tilapia (*Oreochromis* sp.). In contrast, the maximum level of 10% differs from the 20% reported by Prabu *et al*. (2018) in GIFT tilapia. These variations can be attributed to several factors, including the nutritional composition of the biofloc, the processing methods applied prior to use, and the ability of the cultured species to ingest and digest microbial biofloc (El-Sayed, 2021).

Khanjani *et al*. (2023) effectively illustrated the successful integration of biofloc meal into the feeding regimens of Penaeid shrimp and tilapia, resulting in favorable growth outcomes at various dietary inclusion rates ranging from 4% to 30%. As noted by Ekasari *et al*. (2014), biofloc is recognized as a significant protein source for Nile tilapia, which may help fulfill some of their essential amino acid needs for optimal growth. Conversely, Pérez Rostro *et al.* (2024) found that elevating the levels of biofloc meal (15% and 20%) in the diets led to a reduction in individual weight gain (IWG) and specific growth rate (SGR) in tilapia. This reduction could be attributed to dietary amino acid imbalances, as the biofloc processing aimed at producing heterotrophic biofloc was largely dominated by bacteria (Gallardo-Collí *et al.,* 2019).

It is clear that biofloc lacks essential amino acids, including arginine, lysine, and methionine (Ju *et al.,* 2008). If these deficiencies are not adequately addressed by other components in the diet, particularly FM, they may lead to subclinical deficiencies in tilapia, ultimately resulting in slower growth rates. In the research conducted by Pérez Rostro *et al*. (2024), it was found that the protein content of the native biofloc was reduced due to the methods used in processing it into biofloc meal, which might also influence the levels of specific essential amino acids (Ekasari *et al.,* 2014). In summary, while biofloc offers a promising alternative for aquaculture feed, it is crucial to carefully evaluate its nutritional composition and potential deficiencies to enhance growth performance in aquatic species (Khanjani, 2026).

Plant-based proteins

Plant-based protein sources are increasingly recognized as viable alternatives to FM in aquaculture due to their favorable protein composition, affordability, and consistent availability from diverse agricultural resources. These plant proteins are particularly advantageous for feeding aquatic species, offering numerous benefits for aquafeed formulation (Hussain *et al*., 2024). They can enhance the sustainability of aquaculture by reducing reliance on fish meal, which is often subject to fluctuating prices and availability. However, despite their benefits, plant proteins also present certain challenges when compared to fish meal. For instance, they typically contain a high level of cellulose, which can limit digestibility in aquatic animals (Jannathulla *et al.,* 2019). Additionally, the amino acid profiles of many plant proteins are often imbalanced, lacking some essential amino acids (EAAs) such as lysine, tryptophan, and methionine. This deficiency can hinder optimal growth and health in fish and shrimp. Furthermore, plant proteins may have lower palatability, making them less appealing to some aquatic species, and they often contain anti-nutritional factors (ANFs) like phytic acid and enzyme inhibitors, which can negatively affect nutrient absorption and overall feed efficiency (Liu *et al.,* 2021).

These limitations raise important considerations for feed nutritionists regarding the feasibility of using plant proteins as effective substitutes for fish meal. Various studies have explored the potential of different plant and animal protein sources for either total or partial replacement of fish meal in aquafeed. Among plant proteins, soybean meal stands out as one of the most widely utilized options in fish feed formulations. Its global availability, cost-effectiveness, excellent nutritional profile, and relatively balanced amino acid composition make it a preferred choice for aquaculture (Gatlin III *et al.,* 2007). Additionally, animal by-products such as meat and bone meal, poultry byproduct meal, and tankage meal have been identified as suitable alternatives to fish meal, offering good digestibility, nutritional value, and competitive pricing (Galkanda-Arachchige *et al*., 2020).

Table 3 illustrates the incorporation of plant-based proteins into the diets of various aquatic species, showcasing the extent to which these alternative protein sources can replace traditional fish meal. The table highlights different species of fish and shrimp, detailing the specific types of plant proteins used, their inclusion levels, and the resulting effects on growth performance, feed efficiency, and overall health. This data underscores the potential for plant-based proteins to serve as effective substitutes in aquafeeds, contributing to more sustainable aquaculture practices. By examining the outcomes of these dietary adjustments, researchers and nutritionists can better understand the viability of plant proteins in meeting the nutritional needs of aquatic animals while also addressing the challenges associated with their use.

Byproducts of the aquaculture industry and fishery

Byproducts from the aquaculture and fishery sectors refer to the materials that remain after fish are processed on an industrial scale for human consumption (Hua *et al.,* 2019). It is estimated that between 50% and 70% of these byproducts are classified as "inedible," primarily consisting of trimmings such as viscera, heads, skin, bones, and blood (Stevens *et al.,* 2018).

Table 3: Studies on using plant protein sources in aquaculture diets.

Cultured species	Plant protein sources	Substituted values in diet (%)	Suitable amount (%)	Reference
O. niloticus	*Moringa oleifera*	0, 5, 7, and 9 g/ kg diet	5 g/kg	(El-Son *et al.,* 2022)
C. carpio	*M. oleifera*	0, 10, 20, 30, 40, and 50% of crude protein	30%	(Ibrahim *et al.,* 2018)
O. mossambicus	*M. oleifera*	0, 3, 6, 9, and 12%	9, and 12%	(Mbokane and Moyo, 2018)
Pangasius bocourti	*M. oleifera*	0, 100, 150, and 200 g/kg	100 g/kg	(Puycha *et al.,* 2017)
Labeo rohita	*M. oleifera*	0, 10, 20, and 30%	30%	(Masood *et al.,* 2020)
Cirrhinus mrigala	*M. oleifera*	0, 10, 20, 30, 40, and 50% replacement of FM	10%	(Tabassum *et al.,* 2021)

Table 3(continued):

Cultured species	Plant protein sources	Substituted values in diet (%)	Suitable amount (%)	Reference
Oncorhynchus mykiss	*M. oleifera*	10, 20, 30, and 40% replacement of FM	20%	(Labh, 2020)
Sparus aurata	*M. oleifera*	0. 5, 10, and 15% supplementation	15%	(Jiménez-Monreal *et al.,* 2021)
Dormitator latifron	Soybean meal (Glycine max)	0, 40, 70, and 100%	100%	(Badillo-Zapata *et al.,* 2021)
Seriola dumerili	SBM + inosine	0, 25, 50 & 75% with or without inosine at 0.6%	50–75%	(Hossain *et al.,* 2018)
Monopterus albus	Soy protein concentrate (SPC)	0, 15, 30, 45, 60, and 75%	26%	(Zhang *et al.,* 2019)
Micropterus salmoides	Fermented soybean meal (FSM)	0, 20, 40, 60, and 80%	40%	(Xu, Q. *et al.,* 2022)
Micropterus salmoides	FSM	Control, 75, 150, 225, and 300 g/kg	150 g/kg	(Yang *et al.,* 2022)
M. salmoides	Cottonseed protein concentrate (CPC)	0, 15, 30, 45, and 70%	45%	(Xu, *et al.,* 2022)
Trachinotus ovatus	CSM+ Acidified phytase	0,20,40, and 60%	20%	(Qin *et al.,* 2022)
Acanthopagrus schlegelii	FCM	0, 80, 160, and 240 g/kg	16%	(Sun *et al.,* 2015)
Pseudobagrus ussuriensis	CGM	0, 10, 20, 30, 40, 50 & 60 %	40%	(Bu *et al.,* 2018)
Acipenser baerii	CPC	0, 15, 30, and 45 %	15%	(Taati *et al.,* 2022)
Catla catla	RSM with Probiotic	34% RSM with 0, 1, 2, 3, 4 & 5 g/kg of probiotics	34% RSM with 2 g/kg of probiotics	(Shahzad *et al.,* 2022)
Hemibagrus wyckioides	RSM	0, 11.2, 22.4, 33.6, and 44.8 %	11.2%	(Zhang *et al.,* 2020)
Megalobrama amblycephala	CM	208.2, 279.4, 350.5, 421.4, and 492.8 g/kg	50%	(Zhou *et al.,* 2018)
Huso huso	Hydrolyzed canola protein	0, 300, 400, 500 mg of protein	500 mg	(Ebrahimnezhadarabi *et al.,* 2022)
O. niloticus	PCM	0, 12.5, 25, 37.5, and 50%	25%	(Mohammadi *et al.,* 2020)
O. mykiss	PM	0, 10, 20, and 30%	10%	(Acar and Türker, 2018)
C. carpio	GM	0, 25, 50, 75, and 100%	50%	(SD El-Saidy *et al.,* 2005)
O. niloticus	Guar Sprout Meal	0, 25, 50, 75, and 100%	25–50%	(Priyadarshini *et al.,* 2020)
O. niloticus	SFM	0, 25, 50, 75, and 100%	50%	(Iqbal *et al.,* 2022)

Table 3(continued):

Cultured species	Plant protein sources	Substituted values in diet (%)	Suitable amount (%)	Reference
C. carpio	SFM	0, 25, 50, 75, and 100%	75%	(Rahmdel *et al.,* 2018)
L. rohita	Almond meal	0, 20, 40, 60, 80 and 100%	40%	(Hussain *et al.,* 2021)
Monocirrhus polyacanthu	Almond leaf extract	0.25, 0.50, 0.75, 1.00, and 1.25 g/L	0.75 g/L	(Ramos *et al.,* 2020)
C. carpio	Black seed	Control, 0.25, 0.5 & 1%	-	(Yousefi *et al.,* 2021)
O. niloticus	Black seed meal	0, 25, 50, 75, and 100% of BSM alternative to SBM	50%	(Ahmed *et al.,* 2018)
O. mykiss	Lupin meal	0, 15, 30, 45, and 60%	30%	(Acar *et al.,* 2018)
O. niloticus	Rice protein concentrate	0, 25, 50, and 75%	25%	(Reda *et al.,* 2022)
E. fuscoguttatus ♀× *E. lanceolatus*♂	FRP	10, 30, and 50 %	10%	(He *et al.,* 2021)
L. rohita	De-oiled rice bran	0, 20, 30, 40, 50, and 60%	40%	(Kumar *et al.,* 2018)
Perca flavescens	HP-DDG	25, 50, 75, and 100%	50%	(Von Eschen *et al.,* 2022)

Note: Soybean meal (SBM), Cottonseed meal (CSM), Fermented cottonseed meal (FCM), Corn gluten meal (CGM), Corn protein concentrate (CPC), Rapeseed meal (RSM), Canola meal (CM), Processed canola meal (PCM), Peanut meal (PM), Guar meal (GM), Sunflower meal (SFM), Fermented rice protein (FRP), High-protein distillers dried grains (HP-DDG).

This inedible portion is increasingly being recognized as a practical alternative to FM sourced from reduction fisheries, which are wild-caught fish specifically processed for FM production (Olsen *et al.,* 2014). Currently, approximately 20% of the global FM supply is derived from fishery byproducts (FAO, 2018), while around 10% comes from aquaculture byproducts (Jackson and Newton, 2016). The continuous growth and intensification of the aquaculture industry create opportunities to enhance processing capabilities, allowing for the capture of additional byproducts and increasing their utilization in FM production. This shift towards utilizing byproducts can yield several significant benefits. Firstly, it enhances the perceived environmental sustainability of the aquaculture sector by reducing pressure on natural resources and helping to preserve marine ecosystems. Secondly, it generates economic and social advantages through the valorization of waste materials, which can lead to job creation in local communities and improve livelihoods. Additionally, this approach contributes to the long-term sustainability of aquaculture by relying on more sustainable sources of protein.

The nutritional composition of fish meal is influenced by the types of raw materials and the manufacturing processes employed. High-quality FM made from whole fish typically contains between 66% and 74% crude protein, 8% to 11% crude lipids, and less than 12% ash. In contrast, fish meal derived from byproducts generally has a lower protein content, ranging from 52% to 67%, with crude lipids between 7% and 14%, and ash content varying from 12% to 23%. For instance, white fish meal produced from byproducts contains approximately 60% to 67% crude protein, 7% to 11% crude lipids, and 21% to 23% ash (Ween *et al.,* 2017). Tuna fish meal from byproducts has a protein content of 57% to 60%, with fat levels between 8% and 14%, and ash content ranging from 12% to 21% (Kim *et al.,* 2014; Hua *et al.,* 2019).

These differences in protein and ash content in byproduct fish meals are expected, as the nutrient profiles differ significantly between whole fish, fillets, and other body parts such as viscera and bones. Consequently, the varying proportions of byproducts used in FM production contribute to the nutrient variability of byproduct-derived fish meals. Research has shown that byproduct fish meals possess considerable potential as alternative raw materials. For example, fish meal made from tuna byproducts can replace 25% to 30% of the protein from high-quality FM without negatively impacting the growth performance of spotted rose snapper (*Lutjanus guttatus*) when included at levels of 15.8% to 21.4%. Similarly, for olive flounder (*Paralichthys olivaceus*), up to 30% of FM can be substituted with tuna byproduct meal at a dietary inclusion rate of 21% (Kim *et al.,* 2014). Furthermore, research on Korean rockfish (*Sebastes schlegeli*) indicated that 75% of FM could be replaced with tuna byproduct meal at a dietary inclusion rate of 58.1%, without compromising growth or feed efficiency (Kim *et al.,* 2018).

Despite the less-than-optimal nutritional profile of byproduct fish meals, which poses challenges for completely replacing high-quality FM, they remain a practical and cost-effective alternative. The large-scale production of fish meal and fish oil requires significant capital investment and operational costs (Naylor *et al.,* 2009). To maintain economic viability, a steady supply of raw materials in substantial quantities is essential. These factors create notable challenges regarding the utilization of byproducts (Olsen and Hasan, 2012), especially when raw materials must be sourced from remote fish-processing facilities or when only small quantities are produced daily, making the economic feasibility questionable.

Technology development

Recent developments in technology can significantly enhance FMFO production, while also minimizing its environmental impact. Galanakis (2018) propose that improving processing and extraction methods can increase FMFO yield, decrease waste, and reduce the energy required for production, leading to lower greenhouse gas emissions and a smaller carbon footprint. Additionally, research and development in this area can address food security concerns by providing a sufficient supply of omega-3 fatty acids, crucial for human health. Sustainable FMFO production can also help conserve marine biodiversity and support the economic livelihoods of fishing communities worldwide. Recent studies have explored the potential of using microalgae or waste streams from fish processing to optimize FMFO production (Gheysen *et al.,* 2018; Al Khawli *et al.,* 2019; Rudovica *et al.,* 2021). Through investment in these strategies, we can improve the sustainability and efficiency of FMFO production, benefiting human health, marine ecosystems, and fishing communities globally, while ensuring a reliable source of omega-3 fatty acids for the future.

Case studies or examples of successful FMFO production optimization programs

Several successful FMFO production optimization programs demonstrate the feasibility and importance of optimizing FMFO production sustainably and in an eco-friendly manner. For example, Calanus AS, a Norwegian company, has developed a sustainable method for producing FMFO from *Calanus finmarchicus*, a small crustacean that is abundant in the North Atlantic. This approach has been shown to be a more sustainable and environmentally friendly alternative to traditional FMFO production methods (Pedersen *et al.,* 2014; Prado-Cabrero and Nolan, 2021). Additionally, the use of waste streams from processing farmed fish to produce FMFO has been successfully implemented, contributing to reducing waste and improving the sustainability of FMFO production (Olsen *et al.,* 2014; Šimat *et al.,* 2019). By adopting sustainable approaches to FMFO production, we can help mitigate the negative environmental and social impacts of aquaculture, promote circular economy strategies, and support the United Nations Sustainable Development Goals (Al Khawli *et al.,* 2019; Stentiford *et al.,* 2020; Rudovica *et al.,* 2021). Sustainable FMFO production can reduce the environmental impact of aquaculture, which is a vital source of protein for millions of people worldwide (Tacon and Metian, 2013). Moreover, sustainable FMFO production can contribute to closing the loop in the seafood industry, reducing waste and promoting more efficient use of resources (Al Khawli *et al.,* 2019; Rudovica *et al.,* 2021). In conclusion, successful examples of FMFO production optimization programs provide compelling evidence that it is feasible and essential to optimize FMFO production sustainably and in an eco-friendly manner. By adopting such approaches, we can ensure the continued availability of FMFO as a significant source of omega-3 fatty acids while mitigating the negative environmental and social impacts of its production.

The role of technology and innovation in achieving sustainable FMFO production

Technology and innovation play a critical role in achieving sustainable FMFO production. Advanced technologies and innovative solutions can significantly reduce the negative environmental impacts of FMFO production while improving efficiency and sustainability. One example of technology playing a role in sustainable FMFO production is the use of RAS systems. These systems use advanced filtration and water treatment technologies to recycle and reuse water, reducing the need for freshwater and minimizing wastewater discharge. RAS can also reduce the risk of disease outbreaks, improve the quality and yield of fish produced, and increase production efficiency (Blancheton *et al.,* 2013). Furthermore, RAS can provide an opportunity to integrate fish production with plant production, creating a closed-loop system and reducing waste (Graber and Junge, 2009). In addition, innovative approaches to feed formulation can also contribute to sustainable FMFO production. The use of alternative protein sources, such as insect meal, microbial biomass, or single-cell proteins, can reduce the demand for fishmeal as a feed ingredient and prevent overfishing (Tacon and Metian, 2013). Moreover, the use of precision feeding technologies can reduce overfeeding and nutrient waste, resulting in more efficient use of resources (Kaushik and Seiliez, 2010). Furthermore, digital technologies such as big data analytics, artificial intelligence, and blockchain can improve transparency and traceability in the FMFO supply chain. These technologies can enhance the ability to monitor and manage the environmental impacts of FMFO production and provide consumers with greater assurance that the products they purchase are sustainably produced. For example, blockchain technology can provide a tamper-proof record of the origin and production conditions of FMFO products, improving transparency and accountability in the supply chain (Howson, 2020; Liu *et al.,* 2021; Rahman *et al.,* 2021). Overall, technology and innovation play a crucial role in achieving sustainable FMFO production. Advanced technologies such as RAS, alternative protein sources, precision feeding technologies, and digital technologies can help to reduce negative environmental impacts, promote resource efficiency, and improve transparency and traceability in the FMFO supply chain. By adopting such approaches, we can help ensure the continued availability of FMFO as a significant source of omega-3 fatty acids while mitigating the negative environmental and social impacts of its production.

The importance of stakeholder engagement and collaboration in optimizing FMFO production

Stakeholder engagement and collaboration are critical in optimizing FMFO production sustainably and in an eco-friendly manner. Effective stakeholder engagement can ensure that diverse perspectives are considered and integrated into the decision-making process, while collaboration among stakeholders can help to identify and address common challenges and opportunities. Stakeholders in FMFO production include fish farmers, feed manufacturers, FMFO producers, researchers, conservation organizations, and policymakers. Each of these stakeholders has a vital role to play in promoting sustainable FMFO production. For example, fish farmers can adopt best management practices to reduce the environmental impacts of aquaculture, while feed manufacturers can develop and promote alternative protein sources to reduce the demand for fishmeal as a feed ingredient (Tacon and Metian, 2013). FMFO producers can adopt sustainable production methods, such as closed-loop systems and waste reduction strategies, while researchers can provide scientific evidence and develop innovative solutions to promote sustainability. Collaboration among stakeholders can help to identify and address common challenges and opportunities in FMFO production. For example, partnerships between FMFO producers and conservation organizations can help to promote sustainable sourcing practices and reduce the environmental impacts of FMFO production. Moreover, collaboration among stakeholders can facilitate the sharing of knowledge and expertise, leading to more effective decision-making and problem-solving (FAO, 2018). Effective stakeholder engagement and collaboration can also promote social and economic sustainability in FMFO production. For instance, engagement with local communities can help to ensure that FMFO production benefits local economies and does not have negative social impacts (FAO, 2020). Moreover, collaboration among stakeholders can promote the adoption of circular economy strategies, such as the use of waste streams from fish processing to produce FMFO, creating economic opportunities and reducing waste (Olsen *et al.,* 2014; Šimat *et al.,* 2019). Another example of stakeholder collaboration in FMFO production is the Sustainable Fisheries Partnership's (SFP) Fishery Improvement Projects (FIPs) in Peru. The FIPs bring together FMFO producers, fishmeal and fish oil buyers, and government representatives to improve the sustainability of the Peruvian anchovy fishery, a crucial source of FMFO. The FIPs address issues such as overfishing, bycatch, and ecosystem impacts, and promote the adoption of more sustainable fishing practices. Overall, stakeholder engagement and collaboration are critical in optimizing FMFO production sustainably and in an eco-friendly manner. Effective engagement and collaboration among diverse stakeholders can help to identify and address common challenges and opportunities, promote social and economic sustainability, and ensure that FMFO production is environmentally sustainable and economically viable in the long term.

Potential future developments and trends in FMFO production and their impact on sustainability and conservation efforts

The future of FMFO production is expected to be influenced by various technological, market, and consumer trends that could have implications for sustainability and conservation efforts. These trends include the increased use of alternative protein sources in fish feed, the adoption of precision feeding technologies, changes in consumer preferences, and shifts in global markets.

One potential future development is the greater adoption of alternative protein sources in fish feed. As demand for FMFO continues to increase, there is a growing need for alternative protein sources to reduce the pressure on wild fish stocks. Microbial protein, insect meal, and single-cell protein are among the possible alternative protein sources that could replace or reduce the use of FMFO in fish feed (Tacon and Metian, 2013). By lowering the demand for wild fish stocks, these alternative protein sources could help to reduce the environmental impact of FMFO production and contribute to a more sustainable and efficient use of resources. Another potential future development is the adoption of precision feeding technologies. Precision feeding involves the use of realtime monitoring and control systems to adjust feed delivery based on the nutritional needs of individual fish. Precision feeding can reduce overfeeding and nutrient waste, resulting in more efficient use of resources and improved environmental sustainability (Kaushik and Seiliez, 2010). Moreover, the use of new technologies such as blockchain could enhance the transparency and traceability of the FMFO supply chain, improving sustainability and conservation efforts. Blockchain technology can provide a tamper-proof record of the origin and production conditions of FMFO products, allowing consumers to make informed choices and ensuring that sustainable sourcing practices are followed (Howson, 2020; Liu *et al.,* 2021). Changes in consumer preferences and shifts in global markets could also impact sustainability and conservation efforts in FMFO production. For example, the growing demand for plant-based and vegetarian diets could reduce the demand for FMFO, leading to reduced pressure on fish stocks and promoting more sustainable practices in FMFO production (Tacon and Metian, 2013). Additionally, shifts in global markets could affect the sustainability of FMFO production, as changes in demand could lead to overfishing or unsustainable sourcing practices. Another potential trend that could impact FMFO production sustainability is the adoption of circular economy models. For instance, the use of waste streams from fish processing to produce FMFO could create economic opportunities and reduce waste (Olsen *et al.,* 2014; Šimat *et al.,* 2019). Furthermore, the development of IMTA systems, where fish farming is integrated with the cultivation of other species such as seaweed or shellfish, could create more sustainable and efficient production systems that minimize environmental impacts (Neori *et al.,* 2004). Overall, the future of FMFO production will be shaped by various technological, market, and consumer trends that could affect sustainability and conservation efforts. The adoption of alternative protein sources, precision feeding technologies, blockchain, circular economy models, and IMTA systems could all contribute to more sustainable and efficient FMFO production. These developments could help to ensure the continued availability of FMFO as a significant source of omega-3 fatty acids while mitigating the negative environmental and social impacts of its production.

Conclusion

Ensuring sustainable production of FMFO is crucial for maintaining food security without compromising marine biodiversity. To achieve this balance, a comprehensive approach that considers all aspects of the aquaculture industry is necessary. One crucial aspect is the development and implementation of alternative protein sources, such as insect meal, microbial protein, and plant-based proteins, in aquafeed to reduce the demand for FMFO and mitigate its environmental impact (Naylor *et al.,* 2021). Insect meal, for instance, has a comparable nutritional profile to fishmeal and is already being used in aquafeed for some species like rainbow trout (van Huis *et al.,* 2013). Microbial protein, derived from microorganisms like bacteria and yeast, is another promising alternative protein source, while plant-based proteins like soybean meal and corn gluten meal have also been successfully incorporated in aquafeed for various species like tilapia and common carp (Naylor *et al.,* 2021).

Another critical aspect is the promotion of sustainable aquaculture practices that minimize environmental impact, such as RAS and IMTA (Chopin *et al.,* 2001). Implementing RAS can reduce water usage and minimize waste production, while IMTA can reduce nutrient discharge and promote ecosystem health. Furthermore, increasing public awareness of the importance of sustainable seafood production and consumption is crucial. Consumers can drive demand for sustainably produced seafood and influence industry practices, while governments can incentivize the adoption of sustainable aquaculture practices and support research and development of alternative protein sources. In summary, striking a balance between sustainable FMFO production, food security, and biodiversity conservation requires a multi-faceted approach that involves developing and implementing alternative protein sources, promoting sustainable aquaculture practices, and increasing public awareness of sustainable seafood production and consumption.

Ensuring long-term food security while conserving marine biodiversity is incompatible with the continued extraction of fishmeal and fish oil from wild stocks and natural ecosystems. This dependency has created an unsustainable structural link between aquaculture growth and marine ecosystem degradation. To achieve sustainable intensification, aquaculture must be decoupled from wild fish exploitation. This transition requires the development and large-scale adoption of alternative, sustainable protein sources such as insect meal, single-cell proteins, microbial proteins, microbial biomass, and plant-based proteins. Current research must move beyond experimental validation to industrial-scale applications that can meet the nutritional demands of a rapidly expanding aquaculture sector.

A parallel transformation involves integrating the principles of a circular economy into aquaculture feed production. Policies should aim to maximize the upcycling of seafood processing by-products into high-value feed ingredients, creating a closed-loop system that enhances the value of existing capture fisheries without further depleting marine resources. At the production level, applying precision aquaculture technologies including RAS, BFT, and IMTA, together with improving infrastructure and strategic species selection, can significantly reduce environmental pressure while maintaining productivity.

Filter-feeding bivalves, seaweeds, and omnivorous or herbivorous fish species are essential within this framework, as they rely on zero or minimal external feed inputs and contribute to restorative production models. At the policy level, instruments such as imposing taxes on wild fish catch for fishmeal and fish oil production can internalize environmental costs and correct current market externalities. Strengthening transparency across seafood supply chains through full traceability and labeling would empower consumers to make informed choices and favor species produced with reduced dependence on marine-based ingredients. Establishing public-private partnerships among governments, industries, universities, and research institutions to co-invest in sustainable aquafeed production facilities can further mitigate financial risks and accelerate technology implementation.

The path to a sustainable future lies not in extending the exploitation of finite wild resources but in technological innovation beyond them. Strategically replacing capture-based raw materials with environmentally aligned alternatives can build a resilient food system that sustains a growing population while enabling marine ecosystems to recover and thrive. Increasing seafood supply through sustainable aquaculture, while proportionally decreasing extraction from wild aquatic ecosystems, represents a practical and essential balance for protecting aquatic resources and securing intergenerational food equity.

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Conflicts of interest

The authors have declared no conflict of interest.

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