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Alternative Feeds for Sustainable Aquaculture: A Comprehensive Structured Review

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Abstract

The rising demand for sustainable aquaculture has prompted extensive research into alternative feed ingredients to replace traditional Fish Meal (FM) and Fish Oil (FO), which are linked to environmental and economic challenges. This comprehensive, structured review synthesizes recent advancements in plant and algae-based feeds, probiotics, insect meals, and other novel protein sources for aquaculture. The primary problem addressed is the need for sustainable, cost-effective, and nutritionally adequate alternatives to FM and FO to support the growing aquaculture industry while mitigating ecological impacts. Methodologically, the review encompasses a systematic analysis of peer-reviewed studies published between 2023 and 2024, evaluating the efficacy of various alternative feeds across different fish species. The flow of the study is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Analyzing a comprehensive selection using advanced searching approaches on Scopus and Web of Science discovered (n = 34) final primary data, which were then examined. The findings were divided into three themes: 1) insect-based feeds, 2) plant and algae-based feeds, and 3) alternative protein sources. Key findings reveal that many alternative feeds, including fermented plant meals, microalgae, and insect-based ingredients, promise to maintain or enhance growth performance, improve fish health, and ensure high nutritional quality. *Spirulina platensis* and *Schizochytrium* sp. inclusion in aquafeed has been illustrated to be able to enhance growth and antioxidant capacity effectively. At the same time, Black Soldier Fly Meal (BSFM) effectively supports gut health and immune response. The review concludes that while alternative feeds offer substantial benefits, species-specific responses necessitate tailored formulations. Future research should optimize these alternative ingredients, assess long-term effects, and evaluate economic feasibility to fully integrate them into sustainable aquaculture practices. This review highlights the potential of alternative feeds to transform aquaculture into a more sustainable industry, contributing to global food security and environmental conservation.

Keywords: Alternative protein, insect-based feeds, plant-algae based feeds

■ 1.0 INTRODUCTION

Aquaculture is basically the culture of aquatic animals like fish, crustaceans, mollusks, and aquatic plants; this has become an integral component of the food producing systems in the world. It is espoused not only because of its perceived role it plays in helping to meet seafood demand on a global scale but also in bringing about food security and economic development. In fact, according to the Food Agriculture Organization (FAO), it is one of the fastest-growing sectors of the world and is growing even faster than traditional capture fisheries (Costa-Pierce, 2022; Verdegem *et al*., 2023). Such rapid growth causes many important sustainability issues; most of them relate to feed resources, at the heart of the environmental and economic viability of this industry. Besides, the sources and kinds of feed applied have a very big impact on aquaculture sustainability. There is an economic risk with the changing availability and prices of FM and FO, hence underlining the urgent need for sustainable and economically viable alternatives (Bridson et al., 2020; Idenyi et al., 2022; Jiang et al., 2022; Rector et al., 2023). Recently, alternatives to aquaculture feed have received much attention for their probable contributions toward reduction of the sector's dependence on FM and FO as stated by studies from Bandara and Tharindu Bandara, 2018; Dam et al., 2020; Midhun and Arun, 2023 and Ro et al., 2022.

■ 2.0 ALTERNATIVE FEEDS

There are many alternatives studied and used; plant proteins probably remain the most prevalent. These include the use of soy, corn, wheat and peas. These plant proteins also often contain ANFs, which can impede nutrient digestion and absorption by fish. Insect-based proteins are another promising alternative that has received considerable interest, particularly black soldier fly larvae and mealworms.

They have a very interesting amino acid profile and are well accepted by the majority of fish species. In the meantime, microbial biomass and single-cell proteins consist of algae, yeast, and bacteria that represent new and more environmentally feasible alternatives to aquaculture feed. Algae are especially rich in omega-3 fatty acids, which are so crucial for the growth and health of fish and traditionally come from FO. Moreover, products from yeasts in general from *Saccharomyces cerevisiae*, have additional merits in respect of their acting as immunostimulants, thus enhancing the health and disease resistance of fish.

The industry, however, remains highly dependent on consumer acceptance of insect-based feed alternatives for aquaculture feeding. A recent work by Roccatello et al. (2024) researched the attitude of European consumers toward fish fed with insect-based feed. The results of such findings showed that gender, age and dietary habits were important socio-demographic determinant factors in relation to perceived attitude towards the sustainability of insect-based feed and climate change. More importantly, it proved that those consumers who were better informed on food sustainability issues actually demonstrated increased acceptance of insect-fed fish. Of course, this again means that effective information campaigns can be used to enhance consumer acceptance of such feeds and therefore promote their adoption in aquaculture. Besides, several literatures have also pinpointed insect meal as one of the efficient alternative protein sources in aquaculture. In a study by Linh et al. (2024) find out BSFLM as a substitute for FM when feeding Koi carp, Cyprinus carpio var. koi. Weight gain and SGR were significantly higher in diets with up to 200 g/kg−1 BSFLM without depressed FCR or survival rate. BSFLM inclusion up-regulated the expression of immune-related genes, indicating an enhancement of immune responses. The results thus indicated that BSFLM could be a good alternative to FM with added benefits for growth and immunity. The review Sogari et al. (2023) established the increasing amount of studies regarding insect-based feed applications in aquaculture. Nutrient content, sustainability of the insect meals, and performance comparable to the conventional fish feeds were discussed. Results from such a review also showed that insect meals support growth rates comparable in, if not superior to, a large number of fish species. The discussion also touched on the economic viability and ecological friendliness of insect-based feeds in aquaculture, saying they can be key solutions to FM scarcity and environmental degradation challenges.

Meanwhile, in 2024, a study by Jones et al. (2024) focused on determining the effects of alternative protein diets on the Nile tilapia, *Oreochromis niloticus* raised in a Recirculating Aquaculture System. Tests were conducted to see how various sources of proteins such as BSFM, poultry by-product meal and traditional fishmeal can affect the nutrient composition of the resultant wastewater used in hydroponic cultivation for lettuce and basil. The wastewater generated by BSFM had the most essential nutrients and gave the highest yields for the plants. In this regard, BSFM was identified as a promising valuable feed ingredient which could provide a suitable and nutrient-laden input for integrated aquaculture-agriculture systems. Jones et al. (2024) conducted a similar study on GCM substitution to FM in the diets of the Nile Tilapia. These results indicated that partial replacement, only up to 164 g/kg, improved growth parameters and FCRs, while total replacement exhibited negative performance.

In the present study, Zhang et al. (2024) discuss the effects of dietary supplementing *Spirulina platensis* powder and *Spirulina platensis* polysaccharides on growth performance, health and gut microbiota in largemouth bass, *Micropterus salmoides.* Growth performance, protein efficiency ratio, liver antioxidant capacity and gut microbiota diversity improved after *Spirulina* administration. Another alternative that looks very promising includes microalgae. Further, Neylan et al. (2024) assessed a microalga, *Schizochytrium* sp., rich in omega-3 Polyunsaturated Fatty Acids for its ability to replace the use of FO in sablefish diets. It was observed that high inclusion microalgal diets had equal performance compared to standard fishmeal and FO-based diets based on their influence on fish growth performance. Meanwhile, Pant et al. (2024) observed during the same period an expanded review of the GIFT program in Timor-Leste, placing emphasis on sustainability and local feed production. The intervention described included hatchery establishment, Better Management Practices (BMPs), farmer training and markedly increased yields of fish from the interventions described promoting sustainable intensification.

Among these, insect meals, plant-based proteins, and low-trophic level organisms have been a few alternatives tested for their use. Moroni et al. (2024)) studied FM substitution with 10% bacterial protein and FO was performed with a blend of poultry oil and DHA-rich microalgae oil in European sea bass. The bacterial protein had no effect on fish growth. In addition, insect meal has proved to be one of the very potential alternatives to FM because of its high protein content with a quite good amino acid profile. Rodríguez-Rodríguez et al. (2024) investigated in vitro digestibility of protein coming from seven species of insects and observed that protein digestibility related to FM

falls within the same range as for *Tenebrio molitor*. At the same time, *Acheta domestica* and *Hermetia illucens* were similar to Soybean Meal (SB). Bullon et al. (2024), on the other hand, were also in a position to demonstrate that insect meal and grape marc at replacement levels against FM in abalone diets did not compromise nutritional quality, hence attesting to the versatility of insect meal across different aquaculture species. A study by Mounes et al. (2024) on substitution of SB with pumpkin seed cake in the diets of Nile tilapia follows. Accordingly, their results showed significant enhancements of growth performance, feed conversion and health of fish, further strengthening with increasing inclusion levels. Other low-trophic organisms such as polychaetes constitute another alternative to FM. In that respect, Monteiro et al. (2024) studied the use of polychaete meal on diets of the European sea bass. Results indicated that up to 40% FM substitution with polychaete meal did not affect growth and nutrient utilization.Baldi et al. (2024) targeted the acceptability of the insect-fed fish among mature consumers in Italy.

Meanwhile, biofloc technology-a technology using microbial flocs as a source of protein-has emerged promising too. Gallardo-Collí et al. (2024) have presented the protocol for the production of biofloc meals and determined its chemical composition. With appropriate processing protocols, the biofloc meals maintain the nutrients and become a sustainable protein feed ingredient in aquaculture production. More lately, aquaponically grown duckweed is also found to be an alternative for sustainable feed ingredients. For instance, Alkhamis (2024) assessed the effect of supplementing duckweed in the feeding of Nile tilapia about water quality and growth performance of fish. In a somewhat different but related context, Begho and Irabor (2024) examined economic and behavioral drivers of feed protein sources decisions by fish farmers in Nigeria. Evidence for the efficiency of alternative additives to improve fish health and disease resistance, such as IgY by Zhang et al. (2024) and SM extract by Chaklader et al. (2024), respectively. On the other hand, Begho and Irabor (2024) further emphasized that there is a need to understand and address those economic and behavioral factors driving feed choices among fish farmers. Aquaculture, in that respect, can therefore move through the diversities in angles toward greener and healthier concepts, ensuring the long-term viability and productivity of fish farming.

The seeking of alternative ingredients to feed and their utilization, therefore, are very instrumental towards attaining sustainable development in aquaculture. Such alternatives should hence lead to a reduction in the use of FM and FO, lessening the environmental impacts and contributing to economic resilience while supporting growth in a sustainable manner. In this regard, more research, innovation and collaboration by the stakeholders are so crucial if the existing challenges are to be surmounted and the full potential of alternative feeds realized in aquaculture. Thus, the future sustainability of aquaculture rests upon our capability to develop and utilize environmentally friendly feed products that can be economically viable

3.0 RESEARCH METHODOLOGY

3.1 Identification

Three fundamental stages of the systematic review approach were employed to choose many pertinent papers for this investigation. The initial step is to identify keywords and search similar terms using dictionaries, thesaurus, encyclopedias, and previous research. Search strings for the databases Scopus and Web of Science (refer to Table 1) have been constructed after all relevant phrases have been selected. In the first phase of the systematic review procedure, 1,076 papers were successfully retrieved from both databases for the current study project. The research questions are as follows:

i. How do insect-based feeds affect various aquaculture species' growth, health, and sustainability?
ii. What are the impacts of plant and algae-based feeds on the growth, health, and environmental sustainability of aquaculture species?
iii. How do alternative protein sources compare to traditional Fish Meal (FM) in terms of growth performance, health benefits, and economic feasibility in aquaculture?

3.2 Screening

During the screening process, research items are evaluated for relevance to the predefined research questions, focusing on alternative feeds for sustainable aquaculture. Duplicate papers are removed at this stage. The first screening phase excluded 878 publications, leaving 198 papers for further examination based on specific inclusion and exclusion criteria (see Table 2). The primary focus was on research literature, including reviews, meta-syntheses, meta-analyses, books, chapters and conference proceedings not covered in the latest study. The review was limited to English-language publications from 2023-2024 with 98 papers rejected due to duplication.

Table 1 The search strings

Database	Search strings
Scopus	TITLE-ABS-KEY ((alternative OR subtitute) AND (feeds OR meal) AND (sustainable OR viable) AND aquaculture) AND (LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2024)) AND (LIMIT-TO (SUBJAREA, "AGRI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final")) Date of Access: June 2024
Web of Science	(alternative OR subtitute) AND (feeds OR meal) AND (sustainable OR viable) AND aquaculture (Topic) and 2024 or 2023 (Publication Years) and Article (DocumentTypes) and English (Languages) Date of Access: June 2024

Table 2 The selection criterion of searching

0.4	Inclusion	Exclusion
Language	English	Non-English
Timeline/Years	2023- 2024	< 2023
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject Area	Agriculture and Biological Science	Besides Agriculture and Biological Science

3.3 Eligibility

The final review sample is established after applying all inclusion and exclusion criteria. A full list of the research items in this sample is disclosed to ensure transparency and allow readers to understand the basis of the study's findings. In the eligibility stage, 100 articles were initially considered. Each article's title and significant content were carefully reviewed to ensure relevance to the study's research aims. However, 66 publications were excluded due to insufficient alignment with the study's purpose. Ultimately, 34 papers were selected for evaluation.

3.4 Data abstraction and analysis

An integrative analysis was used in this study to examine and synthesize different research designs (quantitative, qualitative, and mixed methods). The goal was to identify relevant topics and subtopics. Data collection was the first step in developing themes with Figure 1 showing how the authors carefully analyzed 34 publications for relevant content. The authors then assessed key studies on alternative feeds for sustainable aquaculture, reviewing methodologies and results. The authors collaborated to develop themes based on the evidence, maintaining a log to record observations and interpretations. The authors compared results to resolve any inconsistencies in the theme development process. The themes were refined for consistency and two experts in aquaculture technology and nutrition reviewed them to ensure clarity, relevance and adequacy. Adjustments were made based on their feedback (see Figure 1).

4.0 FINDINGS AND RESULTS

Table 3 presents the findings on insect-based feeds as a sustainable alternative for aquaculture. Table 4 presents the findings on the use of plant-algae-based feed for sustainable aquaculture. The findings for alternative protein sources are detailed in Table 5.

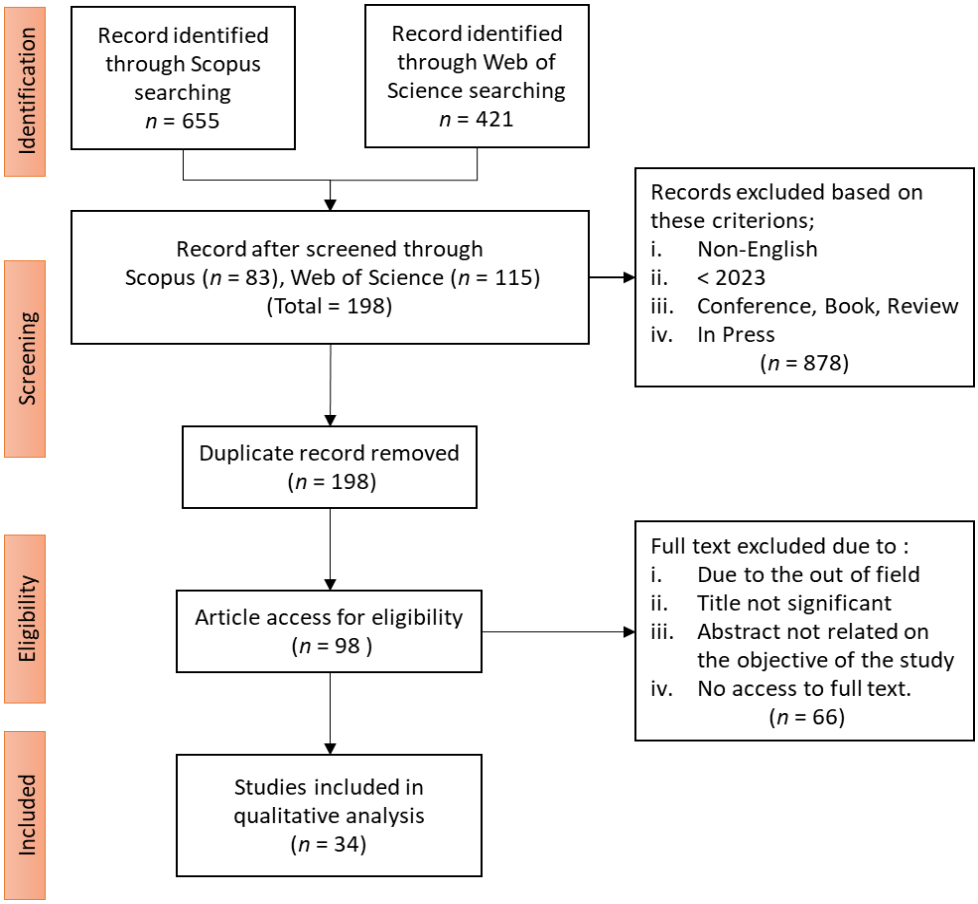

Figure 1 Flow diagram of the proposed search study adapted from Alias et al., 2022; Moher et al., 2010

Table 3 Insect-based feeds

No	Author and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
1	Linh et al., 2024	Evaluate BSFLM as a replacement for FM in Koi carp diets.	Diet formulation, growth metrics analysis, immune response assays.	BSFLM enhanced growth metrics and SGR at higher inclusion levels, improved weight gain, and upregulated immune-related gene expressions.	BSFLM is a viable substitute for FM, supporting growth and immune function. Future research should focus on optimizing inclusion levels and long-term health impacts.
2	Yıldırım-Aksoy et al., 2023	Assess the benefits of using frass in channel catfish diets.	Diet formulation, hematological analysis, survival rate assessment.	Improved hematological parameters and increased survival rates against bacterial infection.	Frass is a beneficial feed additive for health improvements. Further studies should explore optimal frass inclusion rates and their effects on different fish species.
3	Prachom et al., 2023	Explore the use of two-spotted cricket meals (CM) in striped snakehead diets.	Diet formulation, growth performance analysis, protein retention study.	CM could replace FM without compromising growth, enhanced protein retention, and reduced environmental waste outputs.	CM is ecologically advantageous. Future research could investigate cricket meal effects on different life stages and long-term sustainability impacts.
4	Eide et al., 2024	Conduct a large-scale trial on the use of	Large-scale diet trial, growth	BSFLM supported growth performance	BSFLM is commercially viable.

No	Author and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
		BSFLM in Atlantic salmon diets.	performance, gut health assessment.	and did not adversely affect gut health.	Future research should address long-term economic impacts and consumer acceptance.
5	Khieokhajonkhet et al., 2024	Evaluate the dietary inclusion of Giant Cricket Meals (GCM)in Nile tilapia diets.	Diet formulation, growth and FCR analysis, health assessment.	Improved growth, FCRs and moderate inclusion levels were beneficial without adverse health effects.	GCM demonstrates the potential for scaling up. Future research should focus on large-scale implementation and nutritional optimization.
6	Rimoldi et al., 2023	Investigate the use of shrimp waste meal and insect exuviae rich in chitin as feed components.	Diet formulation, gut microbiota analysis, short-chain fatty acid production.	Positively modulated gut microbiota enhanced bacterial diversity and short-chain fatty acid production.	Shrimp waste meal and insect exuviae are effective, sustainable components. Further research should explore their effects on different fish species and long-term health benefits.

Table 4 Plant-algae-based feeds

No	Author and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
1	Nandi et al., 2023	To investigate the use of Fermented Water spinach Meal (FWM) as an FM replacement in the diets of female stinging catfish.	Feeding trials with varying levels of FWM inclusion.	Significant improvements in growth, reproductive performance, and health with 50% FWM, higher fatty acid profiles and improved gut morphology.	FWM at 50% inclusion is viable as an alternative protein source. Future research could explore long-term effects and optimize FWM inclusion levels.
2	Zhang et al., 2024	To assess the partial replacement of fishmeal with *Spirulina platensis* (SP) powder and the addition of *Spirulina platensis* PSP in largemouth bass diets.	Feeding trials with SP and PSP supplementation.	Improved growth performance, protein efficiency, muscle amino acid composition, antioxidant capacity, and digestive enzyme activities.	Spirulina is a sustainable and beneficial alternative to traditional fishmeal. Future research could focus on economic viability and large-scale applications.
3	Ratti et al., 2023	To examine the use of black soldier fly prepupae reared on Spirulina-enriched substrates as an alternative ingredient for rainbow trout.	Inclusion of insect meal in fish diets and analysis of growth, health, and immune response.	No compromise in growth, gut and liver health, or marketable traits; enhanced immune-related gene expression.	Insect meal is a sustainable alternative to fishmeal, promoting a circular economy. Future studies could explore the optimization of rearing conditions and cost-effectiveness.
4	Barreto et al., 2024	To explore the incorporation of *Salicornia ramosissima* biomass as a partial replacement for wheat meal in European sea bass diets.	Feeding trials comparing experimental and control diets.	No significant differences in growth performance or nutrient digestibility; modulated biochemical profiles of fish muscle.	*Salicornia* biomass can valorize agricultural residues in fish feed. Future research could focus on scaling up production and assessing long-term health impacts.
5	Neylan et al., 2024	To evaluate *Schizochytrium* sp. as	Feeding trials with varying levels of	High microalga inclusion performed comparably to fish-	Microalgae is a viable, sustainable lipid source. Future research

No	Author and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
		an alternative to FO in sablefish diets.	microalga inclusion.	ingredient control diets; improved fillet PUFA concentrations.	could explore economic implications and potential for other fish species.
6	Filipa-Silva et al., 2023	To assess the replacement of FO with alternative marine lipid sources, including algal oil and salmon by-product oil, in European sea bass diets.	Comparative analysis of fish muscle EPA and DHA levels, freshness, and nutritional quality.	Alternative lipids-maintained EPA and DHA levels and ensured fish freshness and nutritional quality during storage.	Alternative marine lipids reduce reliance on FO and enhance sustainability. Future studies could investigate long-term consumer health benefits and environmental impacts.
7	Zatti et al., 2023	To evaluate the full replacement of FO with algae oil in farmed Atlantic salmon.	Feeding trials assessing omega-3 fatty acid levels, growth performance, and product quality.	Algae oil maintained omega-3 levels, growth performance, and product quality while reducing contaminants.	Algae oil is a promising solution to FO availability and contamination issues. Future research could optimize algae oil production and assess its impact on different fish species.

Table 5 Alternative Protein Sources

No	Author and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
1	Baumgärtner et al., 2024	To evaluate the efficacy of probiotics (*Bacillus subtilis* and *Bacillus indicus*) as alternatives to astaxanthin in mirror carp.	Feeding trials comparing probiotics and astaxanthin.	Probiotics enhanced microbial diversity and immune response without significantly affecting growth, while astaxanthin improved growth.	Probiotics offer health benefits but are species-specific. Future research should focus on tailored probiotic formulations for different fish species.
2	Ciriminna et al., 2024	To investigate the use of food processing discards in feeds for Mediterranean Sea urchins (*Paracentrotus lividus*).	Feeding trials with various animal-source ingredients and food discards.	Lettuce-based feeds with krill and mussels significantly enhanced caviar production and quality.	Food discards are viable, eco-friendly feed alternatives. Future studies could explore other types of food discards and their impacts on different aquaculture species.
3	Desouky et al., 2023	To explore the replacement of fishmeal with pea peels in diets for Nile tilapia (*Oreochromis niloticus*).	Feeding trials with varying levels of pea peel inclusion.	Pea peels at 15% and 25% improved growth performance and feed efficiency without affecting water quality or fish health.	Pea peels are effective partial fish meal replacements. Future research might investigate the long-term effects and cost-benefit analysis of large-scale use.
4	Vijayan et al., 2024	To evaluate watermelon rind as an alternative protein source in diets for *Labeo rohita*.	Feeding trials with different replacement levels of watermelon rind.	Significant improvements in nutritional indices, digestive enzyme activity, reduced tissue damage, and enhanced amino acid and fatty acid profiles at 50% replacement.	Watermelon rind is a cost-effective and sustainable fishmeal alternative. Future research could explore its use in other fish species and optimize inclusion levels.
5	Moroni et al., 2024	To examine the effects of substituting	Feeding trials assessing	No adverse impact on growth; genetic	Single-cell proteins and alternative lipids

No	Author and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
		fishmeal with bacterial protein and FO with a blend of poultry oil and microalgae oil in European sea bass.	growth and feed conversion efficiency.	selection enhanced feed conversion efficiency.	are viable for reducing reliance on marine-based ingredients. Future studies could focus on optimizing these formulations for different aquaculture species.
6	Mounes et al., 2024	To assess the substitution of soybean with pumpkin seed cake in Nile tilapia diets.	Feeding trials with varying levels of pumpkin seed cake inclusion.	Significant improvements in growth performance, antioxidant capacity, and immune response at higher substitution levels.	Pumpkin seed cake is an effective alternative protein source. Future research might investigate its effects on other fish species and long-term health impacts.
7	Monteiro et al., 2024	To explore polyhaeta meal (PM) as a fishmeal alternative in European sea bass diets.	Feeding trials with different levels of PM inclusion.	PM replaced up to 40% of fishmeal without compromising growth, nutrient utilization, or fillet quality; lower inclusion levels enhanced intestinal absorption and lipid metabolism.	Low-trophic organisms like PM are promising for sustainable aquaculture feeds. Future studies could explore their use in other aquaculture species and optimal inclusion levels.
8	Toledo-Solís et al., 2023	To highlight the potential of red vetchling (*Lathyrus cicera*) as an soybean replacement.	Comparative analysis of nutritional adequacy and environmental impact.	Red vetchling reduced the carbon footprint of aquafeeds while maintaining nutritional adequacy.	Red vetchling promote sustainable aquaculture. Future research should focus on the large-scale feasibility and economic viability of these alternatives.

■ 6.0 DISCUSSION

The integration of insect-based feeds into aquaculture particularly BSFLM and cricket meal has demonstrated considerable promise as a sustainable alternative to traditional FM, addressing critical ecological and economic issues in the sector. Studies indicate that BSFLM maintains and enhances growth metrics and SGRs in fish such as Koi carp while upregulating immune-related gene expressions suggesting robust immune responses. Additionally, frass, a by-product of the BSFL industry has been proven to improve haematological parameters and increase survival rates against bacterial infections in channel catfish. In addition, complementary research on two-spotted cricket meals in striped snakehead diets reveals it can replace FM without compromising growth performance, enhancing protein retention and reducing environmental waste. Large-scale trials on Atlantic salmon further validate the commercial viability of BSFLM indicating it supports growth performance without adversely affecting gut health. Moreover, GCM has benefited Nile tilapia, improving growth and FCR at moderate inclusion levels. The use of shrimp waste meal and insect exuviae rich in chitin has also been found to positively modulate gut microbiota in rainbow trout, enhancing bacterial diversity and short-chain fatty acid production. Collectively, these findings highlight the efficacy of insect-based feeds in aquaculture, offering sustainable alternatives that support fish growth, enhance immune responses and improve feed utilization while reducing environmental impacts, positioning insect meals as a promising solution for the future of sustainable aquaculture.

Besides, the exploration of plant and algae-based feeds for aquaculture exhibits significant potential in replacing traditional FM and FO addressing sustainability concerns while maintaining or enhancing fish health and growth performance. Studies have demonstrated the efficacy of various alternative ingredients across different fish species. For instance, fermented water spinach meal (FWM) in the diets of female stinging catfish improved growth, reproductive performance and health. *Spirulina platensis* powder and PSP in largemouth bass diets enhanced growth performance, protein efficiency and health status. The use of black soldier fly prepupae reared on Spirulina-enriched substrates for rainbow trout supported the growth and immune function while promoting a circular economy by utilizing organic waste. *Salicornia ramosissima* biomass partially replaced wheat meal in European seabass diets without affecting growth performance suggesting health-promoting effects. *Schizochytrium* sp., a microalga, was effective as an alternative to FO in sablefish diets, enriching fillet PUFA concentrations. Notably, the replacement of FO with alternative marine lipid sources in European sea bass-maintained EPA and DHA levels, ensuring nutritional quality and consumer health. Algae oil fully replaced FO in farmed Atlantic salmon,

maintaining omega-3 fatty acid levels and product quality while reducing contaminants. Accordingly, these findings collectively highlight the potential of plant and algae-based ingredients to support fish health, growth and sustainability in aquaculture, advocating for further research to optimize these sustainable feed options.

Alternative protein sources in aquaculture are increasingly essential due to sustainability concerns and the rising cost of traditional fishmeal. Various studies have explored different protein substitutes, revealing both challenges and potential benefits. In cyprinid aquaculture, probiotics like *Bacillus subtilis* and *Bacillus indicus* were discovered to enhance microbial diversity and immune response in mirror carp without significantly affecting growth, suggesting species-specific benefits of probiotics. The use of food processing discards such as krill and mussel-enriched lettuce-based feeds significantly improved caviar production and quality in Mediterranean Sea urchins, promoting sustainability. Hence, replacing FM with pea peels in Nile tilapia diets improved growth performance and feed efficiency indicating the effectiveness of plant-based proteins. As a protein source for *Labeo rohita*, watermelon rind demonstrated improvements in nutritional indices and digestive enzyme activity, underscoring its cost-effectiveness and sustainability. Substituting FM with bacterial protein and FO with poultry and microalgae oils in European sea bass diets-maintained growth and enhanced feed conversion efficiency, supporting the viability of single-cell proteins and alternative lipids. Meanwhile, pumpkin seed cake in Nile tilapia diets improved growth performance, antioxidant capacity and immune response, highlighting its potential as an effective alternative protein source. Polychaeta meal for European sea bass replaced up to 40% of FM without compromising performance, advocating for low-trophic organisms in aquaculture feeds. At the same time, red vetchling as a soybean replacement reduces the carbon footprint of aquafeeds while maintaining nutritional adequacy. These studies collectively demonstrate that alternative protein sources can enhance growth, health and environmental sustainability in aquaculture emphasizing the need for species-specific responses and tailored formulations.

■ 7.0 IMPLICATIONS AND CONCLUSIONS

Taken together, these findings underpin the potential for insect-based, plant, and algae-based feeds and alternative protein sources to play key roles in aquaculture. Such results are indicative of the realization of growth potentials, improved immune responses and better feed utilization with reduced environmental impacts by fish. These results turn out to be promising signs for these sustainable feed options regarding the future of aquaculture but further require research in the area and the need for species-specific formulation to fully exploit their potentials.

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