LITERATURE REVIEWS

Evaluation of the Effect of Black Soldier Fly Larvae Meal on the Growth of Aquatic Species: A Literature Review

Evaluación del efecto de la harina de larva de mosca soldado negro en el crecimiento de especies acuícolas: Revisión de la literatura

Avaliação do efeito da refeição de larvas de mosca do soldado negro no crescimento de espécies aquáticas: Uma revisão da literatura

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Abstract

Background: Given the growing need to feed a projected global population of 9.6 billion by 2050, it is crucial to explore protein sources for the aquaculture industry. **Objective:** The objective of this article was to identify the nutritional and growth effects observed in aquatic species fed black soldier fly larvae meal (BSFLM) through a literature review. **Methods:** A systematic literature review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The search for studies was conducted using the Scopus, ScienceDirect, Google Scholar, SciELO, and MDPI databases. **Results:** The results indicate that the inclusion of BSFLM in aquaculture diets can replace up to 100% of soybean meal in species such as juvenile grass carp (*Ctenopharyngodon idellus*) without significantly affecting final body weight or specific growth rate (SGR). In Nile tilapia (*Oreochromis niloticus*), the inclusion of 20% BSFLM resulted in a significant increase in daily weight gain and an improvement in the biosynthesis of fatty acids and amino acids. In Pacific white shrimp (*Litopenaeus vannamei*), the inclusion of up to 22.5% BSFLM had no negative impact on specific growth rate or feed efficiency. In Atlantic salmon (*Salmo salar*), the inclusion of up to 8% BSFLM did not adversely affect growth or feed performance. **Conclusion:** BSFLM can replace up to 61.3% of fishmeal and 95.4% of fish oil, using fewer resources and reducing greenhouse gas emissions by 1.2–2.7 kg per kg of live weight gain. However, it is essential to optimize inclusion levels to maximize benefits without compromising fish health.

Keywords: *animal nutrition; aquatic animals; aquatic environment; green chemistry; insects; pisciculture; proteins; sustainable development.*

Resumen

Antecedentes: Dada la creciente necesidad de alimentar a una población proyectada de 9600 millones para 2050 es crucial explorar fuentes proteicas para la industria acuícola. **Objetivo:** El objetivo del presento artículo fue identificar los efectos nutricionales y de crecimiento observados en especies acuícolas alimentadas con harina de larva de mosca soldado negro

(BSFLM) mediante una revisión bibliográfica. **Métodos:** Se realizó una revisión bibliográfica sistemática siguiendo las directrices PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). La investigación para los estudios se realizó utilizando bases de datos como ScienceDirect, Google Scholar, SciELO y MDPI. **Resultados:** Los resultados indican que la inclusión de BSFLM en dietas acuícolas puede reemplazar hasta el 100% de la harina de soja en especies como la carpa herbívora juvenil (*Ctenopharyngodon idellus*) sin afectar significativamente el peso corporal final ni la tasa de crecimiento específico (SGR). En tilapias (*Oreochromis niloticus*), la inclusión del 20% de BSFLM resultó en un incremento significativo en la ganancia de peso diario, mejorando la biosíntesis de ácidos grasos y aminoácidos. Para los camarones blancos (*Litopenaeus vannamei*), una inclusión de hasta el 22.5% de BSFLM no tuvo un impacto negativo en la tasa de crecimiento específico ni en la eficiencia alimentaria. En salmones del Atlántico (*Salmo salar*), la inclusión de hasta el 8% de BSFLM no afectó negativamente el crecimiento ni el rendimiento alimenticio. **Conclusión:** La BSFLM puede reemplazar hasta el 61.3% de la harina de pescado y el 95.4% del aceite de pescado, utilizando menos recursos y reduciendo las emisiones de gases de efecto invernadero en 1.2-2.7 kg por kg de ganancia de peso vivo. Sin embargo, es esencial optimizar los niveles de inclusión para maximizar los beneficios sin comprometer la salud de los peces.

Palabras claves: *animales acuáticos; desarrollo sostenible; insectos; medio ambiente acuático; nutrición animal; piscicultura; proteínas; química verde.*

Resumo

Antecedentes: Dada a necessidade crescente de alimentar uma população projectada de 9,6 mil milhões de pessoas até 2050, é crucial explorar fontes de proteína para a indústria da aquacultura. **Objectivo:** O objectivo deste artigo foi identificar os efeitos nutricionais e de crescimento observados em espécies de aquacultura alimentadas com farinha de larva de mosca soldado negra (BSFLM) através de uma revisão bibliográfica. **Métodos:** Foi realizada uma revisão sistemática da literatura seguindo as diretrizes PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). A pesquisa para os estudos foi conduzida utilizando bases de dados como o ScienceDirect, Google Scholar, SciELO e MDPI. **Resultados:** Os resultados indicam que a inclusão de BSFLM em dietas de aquacultura pode substituir até 100% do bagaço de soja em espécies como a carpa-relva juvenil (*Ctenopharyngodon idellus*) sem afetar significativamente o peso corporal final ou a taxa de crescimento específico (SGR) . Na tilápia (*Oreochromis niloticus*), a inclusão de 20% de BSFLM resultou num aumento significativo do ganho de peso diário, melhorando a biossíntese de ácidos gordos e aminoácidos. Para o camarão branco (*Litopenaeus vannamei*), uma inclusão de até 22,5% de BSFLM não teve impacto negativo na taxa de crescimento específica ou na eficiência alimentar. No salmão do Atlântico (*Salmo salar*), a inclusão de até 8% de BSFLM não afetou negativamente o crescimento ou o desempenho alimentar. **Conclusão:** O BSFLM pode substituir até 61,3% da farinha de peixe e 95,4% do óleo de peixe, utilizando menos recursos e reduzindo as emissões de gases com efeito de estufa em 1,2-2,7 kg por kg de ganho de peso vivo. No entanto, é essencial otimizar os níveis de inclusão para maximizar os benefícios sem comprometer a saúde dos peixes.

Palavras-chave: *animais aquáticos; desenvolvimento sustentável; insetos; meio aquático; nutrição animal; piscicultura; proteínas; química verde.*

1 Introduction

In 2022, aquaculture accounted for approximately 15.3% of animal-based protein intended for human consumption (Boyd et al., 2022). In the same year, global aquaculture production reached 82.1 million tons, valued at $250.1 billion, with fish representing the most cultivated group, accounting for $139.7 billion (Rocha et al., 2022). The annual per capita consumption of fish in Ecuador is 13.5 kg, Brazil 9.45 kg (35 kg in the Amazon), Chile 5.7 kg and Colombia 6.86 kg (Guzman-Pincheira et al., 2024).

The growing demand for aquatic products, combined with the need to feed a projected population of 9.6 billion by 2050, is placing significant pressure on natural resources (Rogers, 2023). To ensure food security, it is essential to increase the sustainable production of food, including alternative protein sources for aquafeeds (Aragão et al., 2022). Aquaculture, which depends largely on fishmeal (FML) and fish oil, is at risk due to the overexploitation of marine resources (Glencross et al., 2020). Although plant-based proteins offer an alternative, they may lead to health issues in fish, such as enteritis in salmonids when soybean meal exceeds 10% of their diet (Hardy, 2010; Krogdahl et al., 2010).

The use of insects such as the black soldier fly (BSF), *Hermetia illucens* (Diptera: Stratiomyidae), as a feed source for fish represents a sustainable strategy. It reduces dependence on traditional marine-derived ingredients, e.g., FML and fish oil, while contributing to making the global food system resilient and to nutritional security (Berenbaum et al., 2021). BSF larvae demonstrate high biodegradation efficiency, reducing between 65.5 and 78.9% of organic matter per day (Suryati et al., 2023). A group of 15,000 larvae can process up to 2 kg of organic waste within 24 hours (Diener et al., 2011), reinforcing their role in waste reduction within sustainable aquaculture systems. Insect-based diets, such as black soldier fly larvae meal (BSFLM), are essential for sustainable aquaculture due to their nutritional efficiency, waste reduction capacity, and potential to replace conventional FML (Verma et al., 2024).

Ahmad et al. (2024), highlight various insects used as feed in aquaculture, with the most commonly utilized being BSF, *Tenebrio molitor* (Coleoptera: Tenebrionidae), *Musca domestica* (Diptera: Muscidae), *Melanoplus differentialis* (Orthoptera: Acrididae), and *Gryllodes sigillatus* (Orthoptera: Gryllidae). Among these, BSF is the most promising option due to its ability to reduce the feed conversion ratio (Limbu et al., 2022).

Based on these premises, the objective of this article was to identify the nutritional and growth effects observed in aquatic species fed with BSFLM through a literature review.

2 Methodology

2.1 Design of the literature review

A systematic literature review was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Page et al., 2021). A protocol was established that included a clear definition of the research question, the selection of databases, inclusion and exclusion criteria, and the strategy for analyzing the extracted data. The objective of this review was to evaluate the effect of BSFLM on the growth and health of various aquatic species.

The research question that guided this review was: *How does the inclusion of BSFLM in the diet of aquatic species affect their growth, feed efficiency, and health?* This question was broken down into specific components that guided the search and selection of relevant scientific literature.

2.2 Search strategy

The scientific literature search was conducted on June 10, 2024, using the Scopus bibliographic database (https://www.scopus.com/) as the primary reference source. In addition, ScienceDirect (https://www.sciencedirect.com/), Google Scholar (https://scholar.google.com/), SciELO (https://scielo.org/es/), and MDPI (https://www.mdpi.com/) were consulted to broaden the thematic and geographical scope. To optimize the search, specific search terms were used, such as (*black soldier fly OR Hermetia* *illucens OR insect meal*) *AND* (*aquaculture OR fish OR growth OR health*) *AND* (*diet OR supplementation OR feed*). Boolean operators (AND, OR, NOT) were employed to refine the results and ensure the inclusion of relevant studies. Relevance was defined based on the presence of original experimental data evaluating the effects of BSFLM on the growth, feed efficiency, or health of aquatic species. Only peer-reviewed articles that met these criteria and aligned with the research question were considered eligible for inclusion.

2.3 Eligibility criteria

2.3.1 Inclusion criteria

Only articles published in English or Spanish between 2008 and 2024 and available in full text were considered. In addition, only peer-reviewed scientific publications reporting original and quantifiable data were included.

2.3.2 Exclusion criteria

Brief communications or technical reports without original data, studies that did not use BSFLM, studies focused on non-aquatic species, and duplicate articles or those not available in full text were excluded.

2.4 Systematic article selection process

The article selection process was carried out in three phases. In the first phase, the titles of the studies identified in the literature search were screened to exclude those that did not meet the inclusion criteria. This included studies lacking original data, studies focused on non-aquatic species, articles that did not use BSFLM, publications without full-text availability, and those corresponding to brief technical reports.
In the second phase, the abstracts of the remaining articles were evaluated using the same inclusion and exclusion criteria. Finally, in the third phase, the articles that passed the previous two stages were reviewed in full to confirm their eligibility based on the criteria defined in Section 2.3.1. Agreement between assessments conducted at each stage was measured using the kappa coefficient, ensuring the reliability of the selection process.

2.4.1 Application of the PRISMA methodology

After applying the filters according to the PRISMA approach, 417 documents were processed. The articles included in the final analysis were those that addressed aquaculture nutrition and the inclusion of alternative ingredients, such as insect meals, and were published between 2008 and 2024. This process resulted in the elimination of 123 articles, resulting in 294 documents analyzed (Figure 1).

In the third phase of the PRISMA process, which focused on verifying the eligibility of the documents, the 294 selected articles were meticulously evaluated. This analysis centered on titles and abstracts to determine the relevance of each article concerning key aspects such as nutritional composition, the impact on growth and health of aquatic species, and the economic viability of using BSFLM. After removing duplicate documents and those that did not align with the study's objectives, 157 articles met all the criteria for relevance, publication date, and methodological quality.

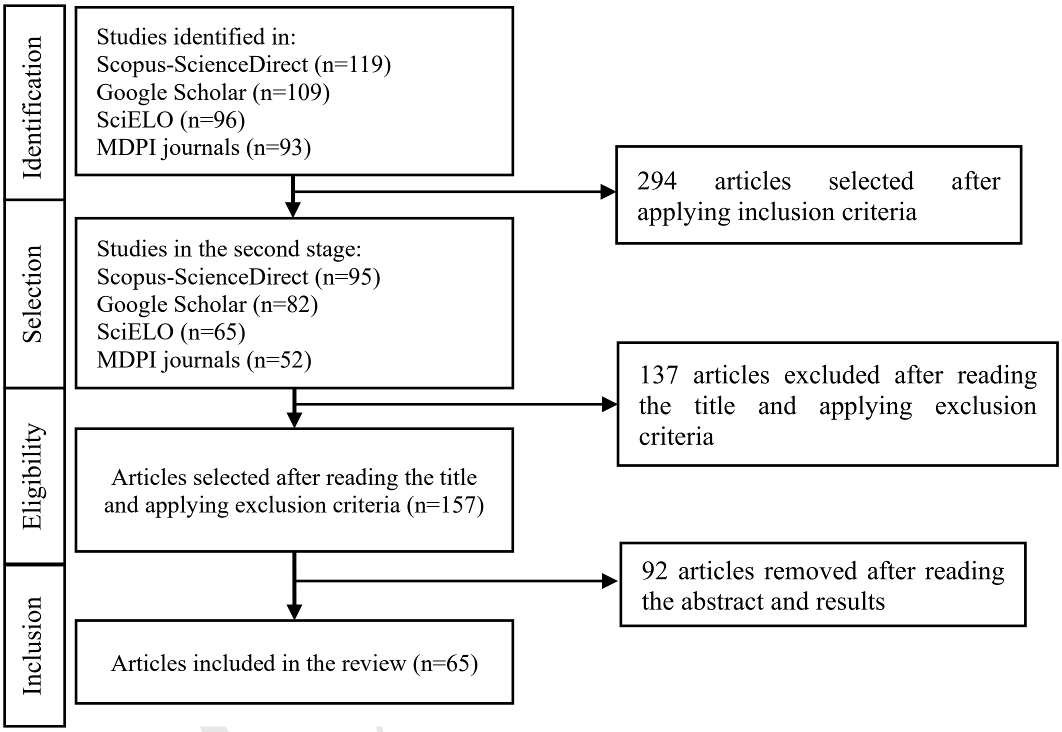

Figure 1. PRISMA methodology applied to the study.

In the final stage of the process, an additional 92 documents were removed, leaving a final database of 65 articles. The analysis of these articles enabled the identification of emerging trends and patterns in the use of insect meal in aquaculture, leading to informed discussions that reflected existing knowledge and highlighted areas of uncertainty and opportunities for future research. These findings made a significant contribution to the body of knowledge on the use of alternative ingredients in aquaculture feed.

2.4.2 Analysis of the trend of selected articles

The analysis of the literature on the use of BSFLM in aquaculture shows a growing interest in this protein alternative, particularly in recent years. The review indicates that the largest number of publications is concentrated in the years 2023 and 2024, with 12 each, demonstrating a significant increase in scientific production in this area (Figure 2). This increase may be related to the growing concern for sustainability in aquaculture and the search for alternatives to the use of FML and soybean meal in the feeding of aquatic species, aligning with the UN's Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 14 (Life Below Water), which promote the use of sustainable resources and the reduction of environmental impact on aquatic ecosystems, respectively (Kerton, 2023).

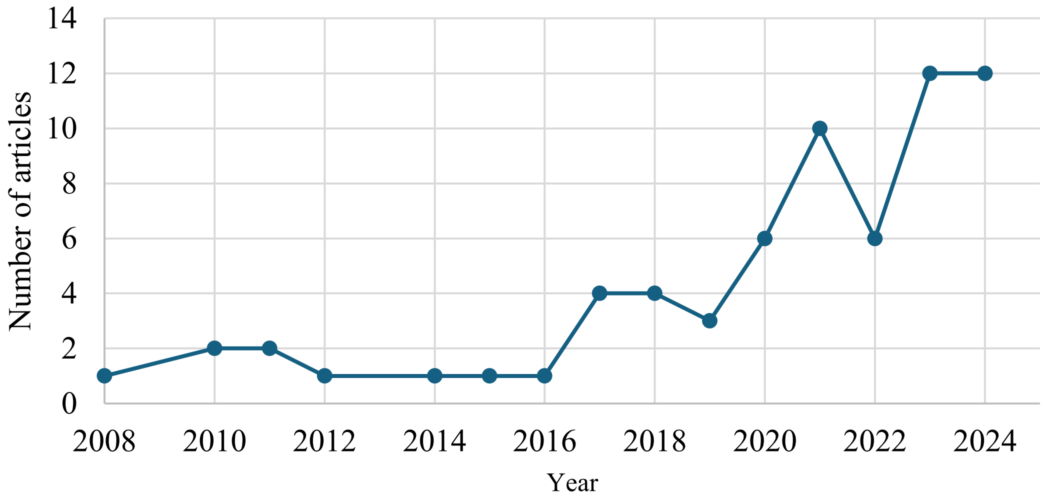

Figure 2. Temporal trend of selected articles.

Regarding the distribution of articles by year, it is observed that between 2008 and 2016, scientific production was relatively low, with only 1 or 2 articles published annually. Then, from 2017 onward, production began to increase significantly, rising to 4 articles in 2017 and 6 in 2020. The use of insects in aquaculture feed has emerged as a sustainable and promising alternative, as noted by Knorr and Augustin (2024), by offering an efficient protein source that can reduce dependence on FML.

2.5 Data extraction and statistical analysis

Data extraction was performed using a standardized form that included variables such as the aquatic species, diet composition (percentage inclusion of BSFLM), experiment duration, and specific outcomes in terms of growth, feed efficiency, and health. The data were organized and synthesized for subsequent analysis and discussion within the context of the review.

2.6 Synthesis of results

The results of the included studies were synthesized and presented in tables that summarize the effects of BSFLM on the evaluated aquatic species. The discussion of the results focused on comparing the findings with existing literature, identifying knowledge gaps, and suggesting areas for future research.

3 Results

3.1 Carp fed with *Hermetia illucens* larvae meal

Lu et al. (2020) evaluated replacement levels of 25, 50, 75, and 100% of soybean meal (SM) with BSFLM, reporting SGR values ranging from 5.55 ± 0.01 to 5.57 ± 0.04 %/day, feed conversion ratio (FCR) values between 1.55 and 1.56, and 100% survival. Additionally, positive effects were observed on antioxidant enzyme activity, such as catalase (CAT), which reached 5.51 ± 1.14 U/mL in the 25% replacement (BSFLM25) group, significantly higher than the control. Similarly, Hu et al. (2023) reported improvements in carp muscle quality by increasing the levels of EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) in muscle tissue when more than 15% of soybean meal was replaced with BSFLM, suggesting relevant nutritional and functional benefits.

Linh et al. (2024) demonstrated that diets containing up to 200 g/kg of BSFLM significantly promoted the expression of immune-related genes such as TNF-α, IL1, IL10, and hsp70, with increases of up to 2.89-fold in the intestine and 2.8-fold in the spleen compared to the control (T1), confirming an immunostimulatory effect. Li et al. (2017) highlighted that the inclusion of BSFLM in the diet of Jian carp (*Cyprinus carpio* var. Jian) enhanced CAT antioxidant enzyme activity in the 75% replacement (BSFLM75) and 100% replacement (BSFLM100) groups without significantly altering total protein, albumin, or globulin levels, which suggests hepatic and immune stability. These results provide complementary evidence to the growth performance analysis, demonstrating the positive impact of BSFLM on physiological functions critical for aquaculture productivity.

Table 1. Diets and study conditions for carp.

Species name	Amount of feed	Study duration	Initial weight	Reference
Ctenopharyngodon idellus	0% SM (360 g/kg), 25% BSFLM (270 g/kg), 50% BSFLM (180 g/kg), 75%	56 days; initial age: 14 days.	10.10 ± 0.28 g.	(Lu et al., 2020)

	BSFLM (90 g/kg), and 100% BSFLM (0 g/kg)			
Ctenopharyngodon idellus	1 to 3% of body weight, 7 different diets with substitutions from 0 to 100% soybean meal with BSFLM.	90 days.	299.93 ± 0.85 g	(Hu et al., 2023)
***Cyprinus carpio* var. koi**	0, 50, 100, 150, and 200 g/kg BSFLM.	8 weeks.	20.0 ± 0.2 g	(Linh et al., 2024)
***Cyprinus carpio* var. Jian**	BSFLM replacing 0, 25, 50, 75, and 100% of FML protein (2.6, 5.3, 7.9, and 10.6% of the total diet).	59 days; juveniles.	34.78 g	(Li et al., 2017)

Note: Lu et al. (2020) partially or completely replaced soybean meal with BSFLM at inclusion levels of 25, 50, 75, and 100%, corresponding to 270, 180, 90, and 0 g/kg of soybean meal, respectively. As the replacement level increased, the inclusion of soybean meal decreased while that of BSFLM increased in the overall diet formulation, maintaining nutritional balance across treatments.

3.2 Tilapias fed with *Hermetia illucens* larvae meal

Ye et al. (2022) evaluated the inclusion of BSFLM as a partial replacement for soybean meal in Nile tilapia (*Oreochromis niloticus*) diets, using levels of 5, 10, and 20%. The average daily weight gain values observed were 1.97 ± 0.10, 3.21 ± 0.12, and 5.03 ± 0.18 g/day, respectively, compared to the control group (1.23 ± 0.04 g/day). Moreover, improvements were reported in tricarboxylic acid (TCA) cycle activity and in the biosynthesis of amino acids and unsaturated fatty acids. Kariuki et al. (2024) used inclusion levels of 25, 50, and 75% as a partial replacement for FML, observing the highest weight gain with the 50% inclusion (52.16 g) and the lowest with the 75% level (46.00 g), with no significant differences in feed intake or hematological parameters.

Tippayadara et al. (2021) used FML replacement levels with BSFLM ranging from 10 to 100% over a 12-week period, without finding significant differences ($p > 0.05$) in growth, survival, or feed intake. Hematological values remained stable, while lysozyme and peroxidase activities in skin mucus increased in the BSFLM treatments. Odhiambo et al. (2023) analyzed the length-weight relationship in tilapia fed BSFLM at 0, 25, 50, 75, and 100% inclusion levels, observing isometric growth (B coefficient of 3.230 to 3.635) and condition factors (K) ranging from 0.907 to 1.002, indicating good body condition across all groups.

Table 2. Diets and study conditions for tilapia.

Species name	Amount of feed	Study duration	Initial weight	Reference
Oreochromis niloticus	BSFLM (50, 100, and 200 g/kg) was used to replace 5, 10, and 20% of FM, respectively	30 days	60 ± 5.35 g	(Ye et al., 2022)
	0, 25, 50, and 75% BSFLM	26 weeks; fingerlings	approximately 20–30 grams	(Kariuki et al., 2024)
	0% (100 g FM, 0 g BSFLM), 10% (90 g FM, 10 g BSFLM), 20% (80 g FM, 20 g BSFLM), 40% (60 g FM, 40 g BSFLM), 60% (40 g FM, 60 g BSFLM), 80% (20 g FM, 80 g BSFLM), and 100% (0 g FM, 100 g BSFLM)	12 weeks; 420 fish	14.77 ± 2.09 g	(Tippayadara et al., 2021)
	0, 25, 50, 75, and 100% BSFLM	12 weeks	15 ± 0.06 g	(Odhiambo et al., 2023)

3.3 Shrimp fed with *Hermetia illucens* larvae meal

Usman et al. (2021) analyzed the viability of using BSFLM as a substitute for FML in the diet of Pacific white shrimp (*Litopenaeus vannamei*). Experiments were conducted to evaluate the growth performance, feed efficiency, and survival of shrimp fed different levels of BSFLM inclusion in their diet. In contrast, Nunes et al. (2023) studied the replacement of FML with BSFLM in diets for post-larval (PL) whiteleg shrimp (*Penaeus vannamei*), focusing on growth performance (Table 3).

Chen et al. (2021) evaluated the effects of BSFLM in the diet of Pacific white shrimp, focusing on growth performance, gut health, and disease resistance against *Vibrio parahaemolyticus*. The study used different percentages of FML replacement with BSFLM (10, 20, and 30%), measuring various health and growth parameters over a period of 7 weeks. Novriadi et al. (2024) investigated the incorporation of BSFLM and *H. illucens* larvae oil (BSFLO) in the diet of juvenile *L. vannamei*. The study evaluated growth, feed efficiency, and resistance to *Vibrio harveyi* infections, using BSFLM inclusion levels ranging from 0.5 to 5% over a 90-day period.

Table 3. Diets and study conditions for shrimp.

Species name	Amount of feed	Study duration	Initial weight	Reference
Litopenaeus vannamei	8–3% BW/day (body weight per day)	49 days; juveniles	1.20 ± 0.07 g	(Usman et al., 2021)
Penaeus vannamei	0, 25, 50, 75, and 100% BSFLM	42 days; PL15 (15 days post-larval)	2.7 ± 0.2 mg	(Nunes et al., 2023)
Litopenaeus vannamei	25% of FML was replaced with 10, 20, and 30% BSFLM	7 weeks; juveniles	~0.88 g	(Chen et al., 2021)
Litopenaeus vannamei	0.5–5% BSFLM	90 days; juveniles	0.97 ± 0.01 g	(Novriadi et al., 2024)

3.4 Salmon fed with *Hermetia illucens* larvae meal

Eide et al. (2024) conducted a large-scale trial on the use of BSFLM as an alternative protein source for Atlantic salmon (*Salmo salar*), evaluating its impact on growth performance and health during the fattening phase in seawater under commercial conditions. The study, carried out in Vestland, Norway, spanned 21 weeks and involved a total of 18,1046 salmon distributed across six sea cages (Table 4). Furthermore, Belghit et al. (2019) investigated the use of BSFLM as a replacement for FML in Atlantic salmon diets during their seawater phase, evaluating effects on growth, nutrient utilization, liver health, and the sensory quality of salmon fillets.

Fisher et al. (2020) also analyzed the use of BSFLM as a protein source in low-fishmeal diets for Atlantic salmon, focusing on digestibility and growth performance with different inclusion levels (0, 100, 200, and 300 g/kg). This experiment was conducted at Dalhousie University and the Verschuren Centre for Sustainability in Energy and the Environment at Cape Breton University in Canada. Meanwhile, Radhakrishnan et al. (2023) used BSFLM as a functional ingredient in the diet of Atlantic salmon in sea cages under farm-like conditions in a 13-month study, employing inclusion levels of 5 and 10% as a replacement for plant-based ingredients.

Table 4. Diets and study conditions for salmon.

Species name	Amount of feed	Study duration	Initial weight	Reference
Salmo salar	4 and 8% BSFLM included in the total diet as partial replacement of conventional protein sources	21 weeks; post-smolt	420g	(Eide et al., 2024)
	50, 100, and 150 g/kg BSFLM	16 weeks; post-smolt stage	1398 g	(Belghit et al., 2019)
	0, 100, 200, and 300 g kg^{-1}	112 days	2.8 ± 0.1 g	(Fisher et al., 2020)
	5 and 10% BSFLM	13 months	~173 g to ~4 kg	(Radhakrishnan et al., 2023)

3.5 Trout fed with *Hermetia illucens* larvae meal

Bruni et al. (2020) investigated the effects of including BSFLM in commercial-type diets for rainbow trout (*Oncorhynchus mykiss*), focusing on lipid metabolism and fillet quality. They used three experimental diets with increasing levels of BSFLM inclusion (0, 25, and 50%) and analyzed parameters such as gene expression related to lipid metabolism, liver histology, and fatty acid composition in fillets over a period of 98 days (Table 5). Meanwhile, Dumas et al. (2018) analyzed the effects of BSFLO and partially defatted BSFLM on growth performance, feed efficiency, nutrient deposition, blood glucose, and lipid digestibility in rainbow trout, evaluating various inclusion levels in experimental diets over three months.
For their part, Elia et al. (2018) explored the effects of BSFLM inclusion in the diet of rainbow trout, evaluating histological characteristics, intestinal mucin composition, and oxidative stress biomarkers in the fish. Lastly, Borgogno et al. (2017) analyzed the inclusion of BSFLM in the diet of rainbow trout, focusing on the sensory profiles and physicochemical properties of the fillets. They evaluated diets with 0, 25, and 50% replacement of FML with BSFLM using descriptive analysis.

Table 5. Diets and study conditions in trout.

Species name	Amount of feed	Study duration	Initial weight	Reference
Oncorhynchus mykiss	0, 25, and 50%	98 days	137.3 ± 10.5 g	(Bruni et al., 2020)
	0, 6.6, 13.2, and 26.4% BSFLM; 2.5, 5.0, and 10% BSFLO	84 days	45.7 ± 1.4 g	(Dumas et al., 2018)
	0, 25, and 50% BSFLM	78 days	178.9 ± 9.8 g	(Elia et al., 2018)
	0, 25, and 50% BSFLM	92 days	178.9 ± 9.81 g	(Borgogno et al., 2017)

3.6 Sea bass fed with *Hermetia illucens* larvae meal

Abdel-Tawwab et al. (2020) analyzed the impact of using BSFLM as a partial replacement for FML in the diet of European sea bass (*Dicentrarchus labrax*), evaluating growth performance, somatic indices, body composition, and hematobiometric variables. They also conducted an economic analysis of feed costs. Magalhães et al. (2017), investigated the inclusion of BSFLM as a replacement for FML in diets for juvenile European sea bass, formulating diets with different percentages of insect meal and evaluating growth parameters, feed utilization, and digestibility.

Wang et al. (2019) studied the use of BSFLM as an alternative protein ingredient in diets for juvenile Japanese sea bass (*Lateolabrax japonicus*). This study, conducted over 56 days, evaluated growth performance, body composition, blood metabolites, digestive enzyme activities, hepatic and intestinal histomorphology, and the expression of genes related to lipid metabolism (Table 6). Moutinho et al. (2021) examined the effects of BSFLM inclusion in diets for juvenile European sea bass (*Dicentrarchus labrax*), focusing on liver oxidative status and fillet quality during shelf life. They used diets with different levels of FML replacement (0, 15, 30, and 45%) and evaluated parameters such as hepatic lipid oxidation, antioxidant enzyme activities, and fatty acid composition in the fillets during a 3-day refrigerated storage period.

Table 6. Diets and study conditions in sea bass.

Species name	Amount of feed	Study duration	Initial weight	Reference
Dicentrarchus labrax	45% crude protein, with 25, 35, and 50% BSFLM replacing FML protein	8 weeks	12.1 ± 0.21 g	(Abdel-Tawwab et al., 2020)
Dicentrarchus labrax	Different diets with 0, 6.5, 13, and 19.5% BSFLM, replacing 15, 30, and 45% of FML respectively	62 days; juveniles	50 g	(Magalhães et al., 2017)
Lateolabrax japonicus	16, 32, 48, and 64% BSFLM	56 days; juveniles	14.14 ± 0.17 g	(Wang et al., 2019)
Dicentrarchus labrax	0, 15, 30, and 45% BSFLM	62 days; juveniles	50 g	(Moutinho et al., 2021)

4 Discussions

4.1 Analysis of the selected articles on carp

The studies by Lu et al. (2020) and Hu et al. (2023) concur in reporting that replacing SM with BSFLM does not significantly affect growth performance in juvenile grass carp when low to moderate inclusion levels are used. Lu et al. (2020) found no significant differences in final body weight between the control group (36.89 ± 1.02 g) and the 100% BSFLM group (37.11 ± 1.00 g), with a similar SGR (SM: 5.55 ± 0.04 %/day; BSFLM100: 5.56 ± 0.04 %/day). However, Hu et al. (2023) reported a decrease in SGR in diets with 75 and 100% BSFLM (0.98 and 0.95% per day, respectively) compared to the control group (1.07%) ($p<0.05$). This discrepancy could be due to the difference in the duration of the studies (56 days vs. 90 days) and the experimental conditions. Macusi et al. (2023) state that exposure time is a critical factor in evaluating the viability of BSFLM as a total substitute for SM since longer feeding durations allow for a more accurate assessment of physiological adaptation, nutrient utilization, and cumulative effects on growth and health parameters.

Li et al. (2017) and Linh et al. (2024) evaluated the effects of BSFLM in different carp species, obtaining varied results. Linh et al. (2024) observed that the inclusion of 200 g/kg of BSFLM in the diet of Koi carp significantly improved SGR and weight gain (WG), with a high linear correlation ($r = 0.917$ and 0.912, respectively) ($p<0.05$). These results suggest that koi are able to adapt to BSFLM well. Conversely, Li et al. (2017) found no significant differences in SGR between groups treated with different levels of BSFLM and the control group in Jian carp, which could reflect variations in nutritional needs and digestive capacity among different carp species.

Regarding liver and intestinal health, both Lu et al. (2020) and Li et al. (2017) reported potential adverse effects at high BSFLM inclusion levels in carp. Lu et al. (2020) found a significant increase in the hepatosomatic index (HSI) in the group with 50% BSFLM ($2.30 \pm 0.42\%$) compared to the control group ($1.79 \pm 0.38\%$) ($p<0.05$), as well as a reduction in villi length and intestinal wall thickness in groups with more than 50% BSFLM inclusion. These results are consistent with the findings of Cheng et al. (2021), who suggest that high levels of BSFLM can induce liver and intestinal stress due to the presence of indigestible compounds like chitin.

These findings highlight the need to balance nutritional efficiency with long-term fish health in diets that include BSFLM. Although BSFLM is a viable alternative to soybean and FML, it is essential to monitor potential adverse effects at high inclusion levels. Future research should focus on identifying the specific components of BSFLM that cause these negative effects and developing processing strategies to minimize their impact, as proposed by Leeper et al. (2022). Tailoring diets to specific species and optimizing BSFLM inclusion levels are key to maximizing the benefits of this ingredient in aquaculture.

4.2 Analysis of the selected articles on tilapia

Ye et al. (2022) demonstrate that the inclusion of BSFLM significantly improves growth performance in *Oreochromis niloticus*, with a notable increase in daily weight gain (5.03 ± 0.18 g/day) and metabolic efficiency ($p < 0.05$). In particular, the group fed with 20% BSFLM reached a final weight of 211 g, showing improvements in the biosynthesis of fatty acids and amino acids. These findings are consistent with those reported by Nogales-Mérida et al. (2019), who also observed growth improvements in tilapia when using alternative protein sources, underscoring the viability of BSFLM as an efficient alternative to soybean meal. However, Kariuki et al. (2024), observed variations in their results, with the highest WG (52.16 g) achieved with a diet containing 50% BSFLM without significant differences in daily feed intake ($p>0.05$). These differences suggest that the optimal amount of BSFLM may depend on the experimental context and study duration, as proposed by Roccatello et al. (2024), who emphasize the importance of adjusting diets based on specific farming conditions.

The study by Tippayadara et al. (2021) maintains that the complete replacement of FML with BSFLM did not adversely affect the growth of Nile tilapia, maintaining stability in feed efficiency indices and hematological parameters ($p>0.05$). In contrast, Ye et al. (2022) documented an increase in enzymatic activity and ATP production with the inclusion of BSFLM, suggesting a positive impact on energy efficiency and fish health. Additionally, Tippayadara et al. (2021) reported improvements in immunity, especially in the groups fed with 40 and 60% BSFLM, where an SGR of 1.41 and 1.38% per day, respectively, was recorded ($p<0.05$). These results are supported by Gasco et al. (2016), who found that the inclusion of insect proteins in aquaculture diets not only improves growth but also enhances immune response, highlighting the potential of BSFLM as a functional ingredient in aquaculture.

Odhiambo et al. (2023) reported that the inclusion of BSFLM resulted in isometric growth, as indicated by the regression coefficients (β) that ranged between 3.230 and 3.635. These results are consistent with the findings of Luo et al. (2011), who also observed isometric growth in tilapia fed with betaine-enriched diets. Moreover, the condition factor (K), which ranged between 0.907 and 1.002, suggested that the fish maintained good overall health throughout the study. This supports the observation of Tacon and Metian (2008) that a stable condition factor is a key indicator of well-being in farmed fish ($p<0.05$).

While improvements in growth performance and feed efficiency have been observed, it is essential to also consider practical applications and future projections. Kariuki et al. (2024) emphasize the feasibility of replacing up to 50% of FML with BSFLM without compromising growth, a critical aspect for the sustainability of aquaculture given the high cost and demand for FML. Ye et al. (2022) and Tippayadara et al. (2021) highlight the metabolic and immunity benefits, projecting a promising use of BSFLM in the aquaculture industry. However, more research is needed to determine the optimal proportions of BSFLM inclusion by also taking into account variations in farming conditions in order to maximize economic and environmental benefits. Lange and Nakamura (2023) recommend this as well as specific approaches to optimize the use of alternative ingredients in aquaculture diets.

4.3 Analysis of the selected articles on shrimp

Usman et al. (2021) and Nunes et al. (2023) agree that BSFLM can replace a significant percentage of FML in shrimp diets without negatively impacting growth performance. Usman et al. (2021) found that up to 22.5% inclusion of BSFLM did not have a significant impact on SGR, weight gain, survival rate, or feed efficiency in juvenile *Litopenaeus vannamei* ($p>0.05$). These results are consistent with the findings of Cummins et al. (2017), who also observed that BSFLM could partially replace FML without compromising growth or health in fish. Shrimp fed with BSFLM achieved a final weight of 9.2–10.1 g, with an average SGR of 4.2–4.32%/day, demonstrating that BSFLM can be a viable alternative at moderate inclusion levels.

Nunes et al. (2023) indicate that BSFLM is economically competitive at a price of up to 3.04 USD/kg, underscoring its viability in the aquaculture industry. They also demonstrated that replacing 50 and 75% of FML with BSFLM in *Penaeus vannamei* resulted in favorable WG performance, yielding biomass gains of 791 ± 52 g/m³ and 776 ± 38 g/m³**,** respectively. They also found a lower FCR, particularly in the group with 50% replacement (1.16 ± 0.06) compared to the groups with 0% (1.25 ± 0.04) and 100% replacement (1.24 ± 0.08) ($p<0.05$). These results indicate that BSFLM can improve feed efficiency, which is consistent with the findings of Henry et al. (2015), who observed improvements in FCR and system sustainability when alternative ingredients were used in aquaculture diets.

In contrast, Chen et al. (2021) observed variations in results when higher levels of BSFLM inclusion were used in diets. While replacing 10 and 20% of FML with BSFLM did not show significant changes in growth performance ($p>0.05$), a 30% replacement resulted in a notable decrease in SGR and WG, as well as an increase in FCR ($p<0.05$). This indicates that high BSFLM inclusion levels may have adverse effects on growth performance, which aligns with the observations of Wang et al. (2021), who also reported a decrease in feed efficiency and growth in fish with high BSFLM diets. Moreover, Chen et al. (2021) reported negative impacts on intestinal histology and the expression of immunity-related genes in shrimp fed with 20 and 30% BSFLM, indicating reduced gut health and increased signs of apoptosis.

Novriadi et al. (2024) contribute significantly to this discussion by demonstrating that the inclusion of BSFLM and BSFLO in diets for juvenile *Litopenaeus vannamei* not only maintains healthy growth but also improves resistance to *Vibrio harveyi* infections. Shrimp fed with diets including up to 5% BSFLM and BSFLO showed an increase in growth performance to 14.55 g and higher survival rates, with survival rates ranging from 80 to 90% compared to the control group. These results are consistent with the findings of Van Der Fels-Klerx et al. (2018), who demonstrated that BSFLM can effectively replace FML and also provide additional benefits in terms of immunity and health in aquatic species.

The comparison of these studies shows that while BSFLM is a promising alternative to FML, the inclusion level must be carefully calibrated to avoid negative effects on shrimp health and growth. It is crucial to continue investigations to determine the optimal BSFLM inclusion levels that maximize both growth performance and shrimp health while evaluating its economic viability in different production scenarios. Integrating BSFLM into aquaculture diets has the potential to reduce dependence on FML and improve the sustainability of the sector, provided thorough analyses are conducted to ensure its effective implementation.

4.4 Analysis of the selected articles on salmon

Eide et al. (2024) and Belghit et al. (2019) concur in reporting that the inclusion of BSFLM does not significantly affect the growth and feed performance of *Salmo salar*.

According to the findings of Eide et al. (2024), salmon reached final weights of 4.747 and 4.651 g with diets including 4 and 8% BSFLM, respectively, compared to 4.556 g in the control group ($p<0.05$). Similarly, Belghit et al. (2019) reported comparable growth in salmon fed with up to 100% BSFLM, reaching an average final weight of 3.686 g ($p>0.05$). However, Fisher et al. (2020) observed that a higher inclusion of 300 g/kg BSFLM significantly reduced growth performance, with a WG of only 6.8 g ($p<0.05$). This discrepancy may be due to the inclusion levels of BSFLM, suggesting that while moderate levels can be beneficial, very high levels might be detrimental to growth.

Radhakrishnan et al. (2023) and Eide et al. (2024) also presented similar findings in terms of intestinal and hematological health. Both studies reported that the inclusion of BSFLM did not result in significant adverse effects on the health of salmon ($p>0.05$). In particular, Radhakrishnan et al. (2023) found that salmon fed with diets containing 5% BSFLM (based on total feed weight) showed higher DNA concentration in the skin mucosa and increased levels of red blood cells and hemoglobin, suggesting lower stress compared to the control groups. Eide et al. (2024) also reported an increase in the beta diversity of the gut microbiota and a higher abundance of *Lactobacillaceae* and *Bacillaceae*, suggesting a possible prebiotic effect of BSFLM. These findings align with the results of Sørensen et al. (2020), who demonstrated that the inclusion of insects in the diet can improve gut microbiota and promote overall fish health. However, further research is needed to confirm these benefits and better understand the underlying mechanisms.

In terms of practical applications, BSFLM shows great potential as a sustainable alternative to FML in salmon diets. However, Fisher et al. (2020) caution against the limits of its inclusion, highlighting that excessive levels may compromise growth performance, a concern also raised by Moutinho et al. (2024), who warned of the risks of including excessive amounts of alternative ingredients in fish diets. Future projections should focus on optimizing BSFLM proportions to maximize benefits without compromising growth while investigating the mechanisms behind the observed positive effects on intestinal and hematological health. The adoption of BSFLM could significantly reduce dependence on FML, promoting more sustainable and cost-effective aquaculture, as also suggested by Macusi et al. (2023), who emphasized the need for sustainable nutritional strategies in modern aquaculture.

4.5 Analysis of the selected articles on trout

Bruni et al. (2020) and Elia et al. (2018) state that the inclusion of BSFLM in the diet of rainbow trout does not negatively affect weight gain. Although no severe histopathological alterations were found, both studies revealed the presence of adverse metabolic effects. Elia et al. (2018) detected an imbalance in several oxidative stress biomarkers, along with a reduction in glutathione peroxidase activity in the liver and kidneys ($p < 0.05$), suggesting a disruption of oxidative homeostasis. Similarly, Bruni et al. (2020) reported a significant increase in fat accumulation in the liver of fish fed diets containing BSFLM, which could be associated with the oxidative disturbances observed by Elia et al. (2018). These findings are consistent with those of Renna et al. (2017), who also observed lipid accumulation in the liver when using diets high in BSFLM, highlighting the need for a balanced approach in the inclusion of black soldier fly larvae meal to avoid long-term adverse effects.

Dumas et al. (2018) showed that the inclusion of partially defatted BSFLM and BSFLO resulted in high growth performance and low FCR values (≤ 0.91) ($p<0.05$). However, thermal-unit growth coefficient significantly decreased with the highest inclusion diet (26.4%) ($p<0.05$), and the length of intestinal villi was reduced at higher BSFLM levels. Additionally, a negative relationship was observed between blood glucose and the level of BSFLO ($p<0.05$), suggesting possible adverse metabolic effects. Despite these effects, the WG was notable, with the trout multiplying their body weight by at least sixfold in 84 days. In comparison, Borgogno et al. (2017) found that the inclusion of BSFLM significantly affected the sensory profile of trout fillets, improving juiciness and tenderness but also increasing the perception of metallic flavors and altering the fatty acid profile by decreasing polyunsaturated fatty acids omega-3 (PUFA ω-3) ($p<0.05$). This indicates that while BSFLM inclusion can enhance certain sensory aspects, it is crucial to consider the potential adverse effects on the metabolic and antioxidant health of the fish, as also highlighted by Renna et al. (2017) in their review concerning the use of alternative ingredients in aquaculture diets.

In terms of practical applications, these studies indicate that insect meal can be a viable protein source in aquaculture, but it is essential to adjust inclusion levels to optimize benefits without compromising fish health. Moderate inclusions of BSFLM, as suggested by Bruni et al. (2020) and Elia et al. (2018), can maintain fillet quality and avoid severe metabolic disturbances. Future research should focus on determining the optimal inclusion levels that maximize growth and product quality without negatively affecting fish health. Additionally, it is crucial to develop balanced diets that mitigate the observed adverse effects, such as increased liver fat and imbalances in oxidative stress biomarkers, to ensure sustainable and high-quality aquaculture production.

4.6 Analysis of the selected articles on sea bass

Abdel-Tawwab et al. (2020) and Magalhães et al. (2017) concur that the inclusion of BSFLM does not significantly affect the growth of European sea bass or the digestibility of essential nutrients. Abdel-Tawwab et al. (2020) demonstrated that up to 50% BSFLM can replace FML protein without compromising growth performance, achieving a WG of 52.6 g and an FCR of 1.42 ($p<0.05$). Similarly, Magalhães et al. (2017) reported comparable SGR, ranging from 2.09 to 2.28% per day, with an FCR of 0.61 to 0.62 ($p<0.05$). However, the feed efficiency observed by Magalhães et al. (2017) was superior to that reported by Abdel-Tawwab et al. (2020), who suggested that the proportion and type of FML replacement with BSFLM may require specific adjustments to maximize benefits in different farming contexts. These findings are consistent with those of Pulido-Rodriguez et al. (2024), who also emphasized the need to adjust BSFLM proportions in diets for different aquatic species to optimize feed efficiency.

Wang et al. (2019) presented results showing significant variations in feed intake and ash retention (AR) when up to 64% BSFLM was included in the diet of juvenile Japanese sea bass. Unlike Abdel-Tawwab et al. (2020), who did not observe significant changes in body composition or somatic indices, Wang et al. (2019) reported lower ash accumulation in fish fed with higher levels of BSFLM ($p<0.05$). This difference could be attributed to variations in the species studied and the specific composition of the diets, suggesting that BSFLM may influence mineral absorption, a critical aspect to consider in diet formulation in order to maintain nutritional balance. These results highlight the need for a careful evaluation of the specific nutritional impacts of BSFLM on different species, as shown by Bingqian et al. (2024), who emphasized differences in nutrient absorption when using alternative ingredients in aquaculture diets.

Moutinho et al. (2021) provide further evidence on the effects of BSFLM on fish health and quality, maintaining that the inclusion of up to 45% BSFLM in the diet of juvenile European sea bass is not only viable but also improves liver oxidative stability and fillet quality during refrigerated storage. However, an increase in lipid oxidation was also observed at higher inclusion levels, underscoring the importance of balancing the amount of BSFLM in the diet to avoid adverse effects on the final product quality ($p<0.05$). This aligns with the findings of Zarantoniello et al. (2023), who emphasized the need to monitor lipid oxidation in fish fillets when using alternative ingredients in aquaculture diets.

The comparison of these studies has significant practical implications for aquaculture. The cost reduction in feed reported by Abdel-Tawwab et al. (2020), saving 15.6% by using BSFLM, along with the high digestibility and feed efficiency observed by Magalhães et al. (2017), indicates strong economic and sustainable potential for BSFLM. However, the differences in AR observed by Wang et al. (2019) and the impact on oxidative stability and fillet quality reported by Moutinho et al. (2021) show the need for a more careful approach in formulating species-specific diets for different farming scenarios. Future studies should focus on optimizing BSFLM proportions and evaluating their long-term effects on fish health and quality, ensuring a practical and beneficial implementation in the aquaculture industry.

4.7 Economic and environmental aspects of *Hermetia illucens* larvae meal

BSFLM offers a range of significant economic and environmental benefits, as highlighted by various studies. According to Chaix-Bar et al. (2023), the production of these larvae requires significantly less land and water than soy (57 and 10 times less, respectively) and emits fewer greenhouse gases (1.7 times less). Moreover, operational costs for a small production unit in Ethiopia amount to ETB 312,000 ($5,700) annually, with potential revenues of ETB 339,480 ($6,190) from selling dehydrated larvae and frass (organic fertilizer). Environmentally, these larvae help reduce waste biomass by 55–76%, transforming organic waste into valuable products such as proteins and fertilizers, which contribute to mitigating pollution and improving agricultural sustainability.

Studies like those by Munthali et al. (2023), Rawski et al. (2021), Sumbule et al. (2021), and Chaix-Bar et al. (2023) also draw attention to the economic and environmental benefits of BSFLM. Sumbule et al. (2021) note that this meal is more cost-effective than FML, reducing feed costs by up to $0.53 per kilogram and generating a positive gross profit margin of $0.83, with a return on investment of 16.05%. Rawski et al. (2021) emphasize that in Siberian sturgeon aquaculture, the incorporation of BSFLM can replace up to 61.3% of FML and 95.4% of fish oil, improving efficiency and economic profitability. Munthali et al. (2023) state that in Malawi, both small-scale farmers and large commercial producers can generate significant income with the production of these larvae. In environmental terms, BSFLM production uses fewer resources (50–90% less land and 40–80% less feed per kg of protein) and reduces greenhouse gas emissions by 1.2–2.7 kg per kg of live weight gain. These studies underscore that BSFLM is not only economically viable but also a sustainable option for animal feed.

In conclusion, the literature review identified several aquatic species, such as carp (*Ctenopharyngodon idellus* and *Cyprinus carpio*), tilapia *(Oreochromis niloticus*), shrimp (*Litopenaeus vannamei* and *Penaeus vannamei*), salmon (*Salmo salar*), and trout (*Oncorhynchus mykiss*), that were fed BSFLM, with dosages ranging from 5 to 100% and trial durations between 30 and 98 days. The inclusion of BSFLM in their diets showed positive effects on growth performance and feed efficiency. In carp, replacing up to 100% of soybean meals with BSFLM did not significantly impact final body weight or SGR, while in tilapia, a 20% inclusion improved daily WG and the biosynthesis of fatty and amino acids. In shrimp, up to 22.5% BSFLM inclusion did not affect SGR, WG, or feed efficiency, and in salmon, up to 8% BSFLM did not negatively influence growth or feed performance. Additionally, BSFLM presents significant economic and environmental advantages, requiring 57 times less land and 10 times less water than soy, while emitting 1.7 times fewer greenhouse gases. A small production unit in Ethiopia can operate annually at $5,700, generating $6,190 in revenue and reducing feed costs by up to $0.53 per kilogram, with a profit margin of $0.83 and a 16.05% return on investment. In aquaculture, BSFLM can replace up to 61.3% of FML and 95.4% of fish oil, reducing resource use and lowering greenhouse gas emissions by 1.2 to 2.7 kg per kilogram of live weight gain.

Declarations

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Conflicts of interest

The authors declare they have no conflicts of interest regarding the work presented in this report.

Author contributions

David Agapito Zambrano Vera and Reni Danilo Vinocunga-Pillajo were involved in the study design and data analysis; Martha Cecilia Alcívar Bazurto was responsible for editing and proofreading; Susy Natalia Gómez Zurita, Aida Salomé Romero Vistín, and Carlos Alfonso Sánchez Vallejo contributed to writing the manuscript.

Use of artificial intelligence (AI)

No AI or AI-assisted thnologies were used during the preparation of this work.

Data availability

The data sets used in the current study are available from the corresponding author on request.

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