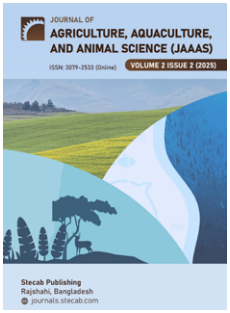

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Review Article

Black Soldier Fly Meal as a Sustainable Alternative to Fishmeal in Rainbow Trout: Impacts on Growth, Nutrient Utilization, and Sustainability

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About Article

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ABSTRACT

This review evaluates the potential of Black Soldier Fly Meal (BSFM) as a sustainable alternative to fishmeal in the diets of rainbow trout (*Oncorhynchus mykiss*), a key species in global aquaculture. The objective is to assess the effects of BSFM on trout growth, nutrient utilization, and its environmental sustainability, as compared to traditional fishmeal. A comprehensive literature synthesis was conducted, focusing on studies published from 2019 to 2025, covering BSFM's nutritional composition, growth performance, and its environmental impact through Life Cycle Assessment (LCA). Key findings indicate that BSFM can effectively support growth in rainbow trout, with up to 50% fishmeal replacement showing comparable or improved growth performance. Nutritionally, BSFM is rich in protein, amino acids, and essential fatty acids, though supplementation with methionine and omega-3 fatty acids may be necessary. LCA results reveal that BSFM production significantly reduces greenhouse gas emissions, water usage, and land requirements compared to conventional fishmeal. In conclusion, BSFM represents a promising, environmentally sustainable protein source for rainbow trout aquaculture, although further research on optimal inclusion rates, long-term effects, and regulatory approval is needed for broader commercial adoption.

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1. INTRODUCTION

Aquaculture is a rapidly growing industry that relies heavily on fishmeal as a primary protein source in fish feeds. However, the sustainability of fishmeal production is increasingly threatened by overfishing and environmental degradation. As global demand for aquaculture products rises, there is a pressing need for alternative, sustainable protein sources that can replace fishmeal without compromising the nutritional requirements of farmed fish. One promising alternative is Black Soldier Fly Meal (BSFM), derived from the larvae of *Hermetia illucens*. BSFM has garnered attention due to its high protein content, essential amino acids, and beneficial fatty acids, as well as its environmentally friendly production process, which utilizes organic waste materials. *Hermetia illucens* larvae (Majluf *et al.*, n.d.).

Despite the growing interest in BSFM, most research has focused on its use in species such as salmon and tilapia, with limited studies on its application in rainbow trout (*Oncorhynchus mykiss*), a key species in global aquaculture. Rainbow trout are known for their specific dietary requirements and sensitivity to feed composition, making them a challenging yet crucial species to study in the context of alternative feed ingredients (Serra *et al.*, 2024).

This review aims to address the gap in current knowledge by evaluating the potential of BSFM as a sustainable and nutritionally viable substitute for fishmeal in rainbow trout diets. Specifically, it examines the effects of BSFM on trout growth performance, nutrient utilization, and the environmental impact of its production, as compared to traditional fishmeal. By synthesizing recent literature, this review provides insights into the feasibility of incorporating BSFM in rainbow trout aquaculture and highlights the challenges and opportunities associated with its adoption (Goglio *et al.*, 2022).

2. LITERATURE REVIEW

2.1. Black soldier fly meal: Nutritional composition and production

Black Soldier Fly Meal (BSFM) is a growing sustainable protein source for animal feed, including aquaculture, due to its excellent nutritional content and environmentally benign production. Black soldier fly larvae (*Hermetia illucens*) can substitute fishmeal in aquaculture diets due to their high protein, lipid, and vitamin content. Because it's digestible, BSFM's 35% to 45% protein helps farmed fish thrive. Normal fishmeal and BSFM share amino acids. The essential amino acids lysine, methionine, and threonine for fish growth are balanced. BSFM contains 20%–30% lipids, mostly omega-3 and omega-6 fatty acids, which are critical for fish health and immunology (Nguyen & Tran, 2025).

Fishmeal is less sustainable than BSFM. Food scraps, agricultural byproducts, and manure feed black soldier flies. Flies turn rubbish into high-quality protein. After attaining maturity, larvae are consumed. Fishmeal production using wild-caught fish takes more land, water, and energy than this approach. Studies show that BSFM production emits less greenhouse gas than fishmeal production, lowering carbon emissions (Ogello *et al.*, 2025).

Rainbow trout need nutrients to grow and stay healthy, thus optimising BSFM needs various considerations. Rainbow trout need a high-protein diet to grow since they eat meat and have fast metabolisms. Rainbow trout-specific amino acids enhance BSFM protein. Research demonstrates that trout diets with up to 50% BSFM can grow like fishmeal, but higher amounts may require vitamin and fatty acid supplements to achieve equilibrium. Black soldier fly larvae's lipid profile can be improved by changing their substrate. Rainbow trout health and immunity can be improved by changing the BSFM's fatty acid composition by feeding larvae algae or plant oils. Since trout are digestively sensitive, adding fibre and minerals to BSFM production may improve gut health and nutrient absorption (Sessegolo Ferzola *et al.*, 2025).

BSFM substitutes fishmeal because rainbow trout need protein and critical fatty acids. With minor tweaks and nutritional enhancements, BSFM can replace fishmeal in trout diets for a long time. Aquaculture would green. Figure 1 compares Black Soldier Fly Meal and standard fishmeal's protein, lipid, amino acid, and fatty acid profiles to show their nutritional differences (Fawole *et al.*, 2021).

3. METHODOLOGY

This systematic review follows a structured approach to evaluate the potential of Black Soldier Fly Meal (BSFM) as a fishmeal alternative in the diets of rainbow trout (*Oncorhynchus mykiss*). The review was conducted in accordance with established guidelines for systematic reviews, including PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).

3.1. Search strategy

A comprehensive search was conducted in the following databases:

- PubMed
- Scopus
- Web of Science
- Google Scholar
- ScienceDirect

The search period was from 2019 to 2025 to capture the most relevant and recent studies.

The search string used in these databases was:

("Black Soldier Fly Meal" OR "BSFM" OR "*Hermetia illucens* larvae") AND ("Rainbow Trout" OR "*Oncorhynchus mykiss*") AND ("fishmeal" OR "protein substitute") AND ("growth performance" OR "nutrient utilization" OR "Life Cycle Assessment" OR "environmental impact").

This combination of terms ensured that relevant studies on BSFM's nutritional impact, growth performance, and environmental sustainability in rainbow trout were captured.

3.2. Inclusion criteria

- Peer-reviewed articles published between 2019 and 2025.
- Studies focusing on the use of BSFM as a fishmeal replacement in rainbow trout aquaculture.
- Research that includes at least one of the following outcomes: growth performance, nutrient utilization, environmental sustainability, or life cycle assessment (LCA).
- Articles written in English.

3.3. Exclusion criteria

• Studies focusing on BSFM in species other than rainbow trout.
• Non-peer-reviewed literature, conference abstracts, and reports.
• Studies that do not provide original data or sufficient details on the methodology and outcomes.
• Articles not related to the effects of BSFM as a fishmeal alternative.

3.4. Data extraction

Two independent reviewers performed data extraction from the included studies. Information collected included:
• Study characteristics (author, year, country).
• Details of the experimental design (species, BSFM inclusion rates, feeding regimen, duration).
• Key outcomes such as growth performance metrics (weight gain, feed conversion ratio), nutrient composition (protein, lipids, essential amino acids), and environmental impacts (greenhouse gas emissions, water and land use).

3.5. Quality assessment

The quality of the included studies was assessed using a modified version of the Critical Appraisal Skills Programme (CASP) checklist for systematic reviews. This ensured that only studies with adequate methodological rigor were included in the review.

3.6. Synthesis of data

The data were synthesized qualitatively, focusing on the effects of BSFM inclusion on growth performance and nutrient utilization in rainbow trout. Quantitative data on environmental impacts (LCA results) were summarized and compared to traditional fishmeal to assess the sustainability benefits of BSFM.

4. RESULTS AND DISCUSSION

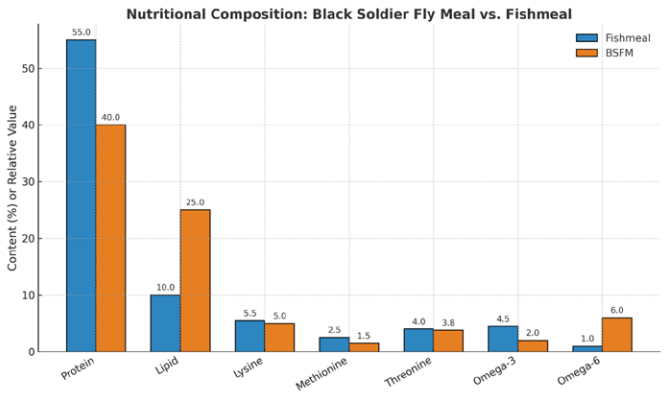

Figure 1. Nutritional composition of black soldier fly meal (BSFM) compared to traditional fishmeal.

This figure compares the nutritional profiles of BSFM and fishmeal, including protein, lipid, essential amino acids (lysine, methionine, threonine), and fatty acids (omega-3 and omega-6). The visualization highlights the relative strengths of BSFM (higher lipid and omega-6 content) as well as its limitations (lower methionine and omega-3 levels), underscoring areas where supplementation may be required for rainbow trout diets.

4.1. Impacts on growth performance in rainbow trout

Black Soldier Fly Meal (BSFM) has been extensively studied for its impacts on aquaculture growth performance, although rainbow trout (*Oncorhynchus mykiss*) study is sparse, especially compared to tilapia and salmon. Rainbow trout are carnivores with specialised dietary needs, making BSFM integration difficult. Recent studies demonstrate that BSFM can considerably enhance rainbow trout growth, offering an alternative to fishmeal without compromising performance (Abd El-Gawad *et al.*, 2025).

Several studies have shown that rainbow trout fed BSFM develop similarly or slightly less than those fed fishmeal. Study shows that replacing up to 50% of fishmeal with BSFM can maintain or increase growth metrics including weight gain and feed conversion ratio.If correctly prepared, 30-50% BSFM can stimulate growth in rainbow trout, as shown by a study that found SGR comparable to fishmeal. This is important since fishmeal production is unsustainable and other protein sources must be productive (Fisher *et al.*, 2020).

Study results on BSFM's effect on growth performance vary, therefore several factors must be examined. The optimal rainbow trout diet BSFM level is unknown. Different inclusion quantities have been studied, but the ideal proportion for growth, palatability, and nutritional use is unknown. Some studies demonstrate that a 30% inclusion rate balances growth performance and nutritional adequacy, while others show that higher inclusion rates may lower growth performance due to amino acid imbalances or higher fibre content. This variation shows more research is needed to assess inclusion rates and enhance rainbow trout BSFM-based diets (Chen *et al.*, 2024).

BSFM's combinatorial implications with feed components are also unexplored. BSFM with algae-based or synthetic amino acids may boost growth and amino acid profile. Antioxidants and probiotics may improve fish health on BSFM diets. Investigating how these combinations effect growth may enhance BSFM for rainbow trout and other fish. Long-term effects of BSFM on fish growth, muscle development, and marketability are unknown. Initial studies focused on short-term growth indicators, but long-term impacts of BSFM incorporation on fish quality, such as muscle texture, fat content, and fillet yield, are needed to understand its fishmeal replacement potential (Aragão *et al.*, 2025).

According to studies, BSFM can replace fishmeal and improve rainbow trout growth. Understudied include optimal inclusion rates, nutritional relationships, and long-term fish quality effects. More research is needed to fully appreciate BSFM's benefits in rainbow trout and sustainable aquaculture. Figure 2 illustrates rainbow trout growth and feed conversion efficiency as BSFM inclusion increases, indicating the optimal replacement range and performance trade-offs (Hussain *et al.*, 2024).

This figure summarizes the effects of substituting fishmeal with BSFM in rainbow trout diets, showing trends in weight gain, specific growth rate (SGR), and feed conversion ratio (FCR) across different BSFM inclusion levels (0%, 25%, 50%, 75%). The visualization emphasizes that moderate inclusion

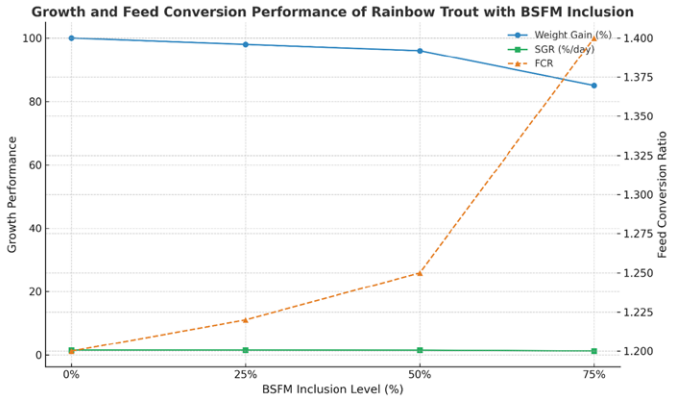

Figure 2. Growth Performance and Feed Conversion of Rainbow Trout at Increasing Levels of Black Soldier Fly Meal (BSFM) Inclusion.

levels (30–50%) maintain growth performance comparable to fishmeal-based diets, while higher levels may require dietary fortification to prevent performance decline.

4.2. Impacts on nutrient utilization in rainbow trout

Black Soldier Fly Meal (BSFM) has been extensively examined in aquaculture species, however its effects on rainbow trout (*Oncorhynchus mykiss*) are unknown. Rainbow trout is a carnivore, hence its digestive and metabolic processes differ from those of tilapia and carp. How rainbow trout absorbs BSFM nutrients can help optimise its use in aquaculture diets. This section sheds light on rainbow trout's BSFM nutritional digestibility, protein quality, and lipid metabolism (Bartucz *et al.*, 2023).

4.2.1. Digestibility and feed conversion efficiency

Rainbow trout's gut prefers animal-based high-protein diets. Non-omnivorous rainbow trout develop on animals. Rainbow trout absorb BSFM like fishmeal with 80%–85% PDCs. Because metabolism requires good nutrient absorption, trout thrives on high digestibility.

Though trout digest BSFM well, certain studies have shown that some nutrients digest differently, especially in large concentrations. At inclusion levels above 30%, trout may have slightly worse digestibility, especially for carbs and fibre, which BSFM contains more than fishmeal. BSFM's greater chitin content, which trout cannot digest, may explain this. If not appropriately accounted for in diet formulation, excessive gut health prebiotic chitin may impair nutrient digestion (Defaix *et al.*, 2024).

4.2.2. Protein quality and amino acid profile

Rainbow trout benefit from BSFM's amino acid composition, making it a good protein source. The amino acids lysine, methionine, and threonine in BSFM help trout grow and maintain tissue. Because its protein quality is like fishmeal, BSFM can meet rainbow trout's amino acid demands.

While digested, BSFM protein has different amino acids than fishmeal, according to certain studies. Methionine and cysteine, sulfur-containing amino acids needed for fish growth and immunology, are low in BSFM. Supplementing BSFM with methionine or other amino acids helps balance the diet and solve these deficiencies. Plant-based or synthetic amino acids may promote rainbow trout protein utilisation and development by increasing amino acid profiles (Brezas & Hardy, 2020).

4.2.3. Lipid metabolism and fatty acid utilization

BSFM's 20%–30% lipid content provides necessary fatty acids for rainbow trout health, growth, and immunity. Saturated, monounsaturated, polyunsaturated, omega-3, and omega-6 fatty acids are in BSFM Like other carnivores, rainbow trout needs these fatty acids for metabolism and cell membrane integrity. Rainbow trout readily absorbs BSFM's omega-3 fatty acids, which improve heart health and inflammation, according to recent research. BSFM may have a different omega-6-to-omega-3 ratio than fishmeal (Carr *et al.*, 2023). Rainbow trout benefit from this ratio, although high BSFM levels may disrupt lipid metabolism and health. More research is needed to customise BSFM's lipids to rainbow trout.Chitin and antimicrobial peptides in BSFM may support gut microbiota and lipid metabolism. These components may help trout digest and absorb lipids, boosting energy and lipid use (Roy *et al.*, 2020).

Fish like rainbow trout digest and use BSFM protein and essential fatty acids. BSFM is digestible, although chitin and amino acid profiles must be addressed to enhance nutritional benefit. Understanding nutritional utilisation variations—particularly protein quality, amino acid balance, and lipid metabolism—can improve rainbow trout BSFM diets. BSFM formulations must be modified to meet this carnivorous species' metabolic and nutritional needs as research continues (Brezas & Hardy, 2020).

4.3. Environmental impacts and sustainability

Aquaculture sustainability is vital as seafood consumption expands worldwide. Wild-caught fishmeal is an important protein source in aquaculture diets, but its production causes overfishing, habitat destruction, and substantial greenhouse gas emissions. Black Soldier Fly Meal (BSFM) created from organic waste and utilising less resources is promising. Life cycle assessment (LCA) is used to study the environmental impacts of BSFM and traditional fishmeal on rainbow trout production (Boyd *et al.*, 2022). To provide a holistic comparison, Table 1 synthesises the nutritional, biological, and environmental trade-offs between traditional fishmeal and Black Soldier Fly Meal in rainbow trout aquaculture.

Table 1. Comparative assessment of black soldier fly meal (BSFM) and fishmeal in rainbow trout aquaculture

Parameter	Fishmeal (FM)	Black Soldier Fly Meal (BSFM)	Implications for Rainbow Trout Aquaculture
Protein Content	~55%	~40–45%	BSFM meets protein needs but requires balancing at higher inclusion levels (Richter *et al.*, 2019).
Key Amino Acids	High in lysine & methionine	Adequate lysine, lower methionine	Supplementation of methionine may be necessary (Wunderle *et al.*, 2024).
Lipid Content	~10%	~20–30%	Higher lipid level beneficial; fatty acid profile depends on rearing substrate (Rbah *et al.*, 2024).
Omega-3 Fatty Acids	High	Moderate–low	May require fortification to maintain fillet quality (Pandey *et al.*, 2025).
Omega-6 Fatty Acids	Low	Higher	Alters fatty acid profile; balance needed to prevent skewed ratios (Torrissen *et al.*, 2025).
Digestibility	~85–90%	~80–85%	Comparable, but chitin reduces digestibility at higher inclusion levels (Eggink *et al.*, n.d.).
Feed Conversion Ratio	Optimal baseline (1.1–1.3)	Comparable up to 30–50% inclusion	High inclusion (>50%) can increase FCR (Yang *et al.*, 2025).
Immune Modulation	Limited	Bioactive compounds (chitin, peptides)	Enhances immune function and stress resilience (Rivero-Pino & Montserrat-de la Paz, 2024).
GHG Emissions (LCA)	High (energy-intensive)	~40–50% lower	Major sustainability advantage of BSFM (Almusaed *et al.*, 2024).
Land & Water Use	High	Substantially lower	Supports circular economy via organic waste recycling (Islam *et al.*, 2024).
Consumer Perception	Widely accepted	Moderate resistance ("yuck factor")	Requires consumer education and regulatory support (Vastola *et al.*, 2024).

4.3.1. Life cycle assessment (LCA) overview

Life cycle assessment (LCA) evaluates a product's environmental impact from raw material extraction to production, distribution, and disposal. BSFM is compared to regular fishmeal on GHG emissions, water, land, and energy use.

4.3.2. Greenhouse gas emissions

A major environmental benefit of BSFM over regular fishmeal is its decreased GHG emissions. Fishing, transporting, and processing wild-caught fish for fishmeal are energy-intensive. In contrast, BSFM feeds black soldier fly larvae organic waste like food scraps and agricultural byproducts. Waste valorisation reduces agricultural land and production-related carbon emissions. Due to its lower energy needs and lack of overfishing, BSFM has been demonstrated to emit 40-50% less GHGs than fishmeal (Rawski *et al.*, 2021).

Use of BSFM as a protein source can significantly reduce GHG emissions in rainbow trout aquaculture. Fishmeal production is energy-intensive, hence trout farming has a large carbon footprint. BSFM could greatly increase rainbow trout production's environmental sustainability, helping to prevent climate change (Hosseindoust *et al.*, 2023).

4.3.3. Water and land use

Traditional fishmeal production requires a lot of water for processing and a lot of land for growing foods to feed the fish. BSFM production uses far less water and land. Fruit and vegetable leftovers, agricultural debris, and manure are used to raise the larvae. Reducing land and water use and diverting organic waste from landfills decreases waste disposal difficulties. Rainbow trout farming advantages from lower water use. Traditional fishmeal, especially anchovies, takes a lot of marine resources. Fishmeal can be replaced with BSFM to reduce water and land use in trout production, making aquaculture more sustainable (Hasimuna *et al.*, 2023).

4.3.4. Energy consumption

Energy consumption is another indicator of fishmeal versus BSFM sustainability. The energy-intensive processes of fishing, drying, and grinding fish produce fishmeal. While insect cultivation and processing require energy, BSFM production uses less. BSFM production uses 60-70% less energy than typical fishmeal production due to its simpler and more localised procedures. When BSFM replaces fishmeal, rainbow trout aquaculture reduces its carbon footprint due to energy savings. This move could improve trout production sustainability in renewable-energy settings (Bujas *et al.*, 2022).

4.3.5. Biodiversity and ecological impact

Due to overfishing, small pelagic fish used for fishmeal production deplete marine biodiversity, especially in regions. BSFM is made from terrestrial organic waste, not wild-caught fish, therefore it does not harm marine biodiversity. BSFM production recycles organic waste into high-value

protein, reduces landfill use, and promotes waste-to-nutrition pathways. The environmental benefits of BSFM over traditional fishmeal are evident, especially in rainbow trout aquaculture. BSFM reduces greenhouse gas emissions, water, land, and energy use compared to regular fishmeal, making aquaculture more sustainable. By replacing fishmeal with BSFM, rainbow trout production can reduce the use of overexploited marine resources and its environmental impact. BSFM's ability to recycle organic waste into high-quality protein suggests it could help create more sustainable aquaculture systems (Wesana *et al.*, 2025).

4.4. Potential genetic or health benefits of BSFM

Alternative protein sources like Black Soldier Fly Meal (BSFM) may have health benefits as the aquaculture business becomes more sustainable. Most BSFM research has focused on growth performance, feed conversion, and sustainability indicators, but new studies suggest that it may bring genetic and health benefits to farmed fish, particularly rainbow trout (*Oncorhynchus mykiss*). These benefits may go beyond nutritional support, including disease resistance, immunological function, and overall health, which are essential for aquaculture system sustainability (Chen *et al.*, 2025).

4.4.1. Genetic traits and fish performance

There is little but promising evidence that BSFM may improve fish genetic features like growth rate, reproductive performance, and stress resilience. BSFM's necessary amino acids may help rainbow trout express growth-related genes. BSFM in their diets may promote growth-related characteristic genetic expression, improving aquaculture stock performance. However, further research is needed to understand whether BSFM actively changes hereditary features through epigenetic mechanisms or just supplies the nutritional base for their optimal expression (Salamanca *et al.*, 2025).

4.4.2. Immune function and disease resistance

BSFM may improve rainbow trout's immune systems, which is intriguing. Bioactive substances include chitin, antimicrobial peptides, and polyunsaturated fatty acids are in BSFM. These have all been shown to boost animal immunity. Chitin's prebiotic properties promote beneficial gut bacteria, which boosts the immune system. This may boost rainbow trout's innate and adaptive immune responses, helping them battle illnesses. BSFM in trout diets may also assist them combat aquaculture problems like germs and parasites. BSFM may enhance white blood cell counts, antibody production, and disease resistance in numerous fish species, including tilapia and salmon. These immunological benefits may help rainbow trout, which are susceptible to furunculosis and vibriosis, get healthy. This would reduce antibiotic and chemical use in aquaculture (Lawal *et al.*, 2025).

4.4.3. Stress resilience

Stress impairs aquaculture fish health, growth, and productivity. Research suggests that omega-3 fatty acids and antioxidants in BSFM may help fish cope with environmental problems. Omega-3s reduce fish cortisol. Aquaculture stressor oxidative stress may be reduced using BSFM antioxidants. BSFM may improve stress resilience in trout for intensive farming. Rainbow trout genetic advantages are still being studied, although BSFM may improve immune function, sickness resistance, and stress resilience. BSFM bioactives such chitin, antimicrobial peptides, and omega-3 fatty acids may boost rainbow trout immunity and gut health. Health advantages may increase aquaculture system sustainability and production, thus more research is needed (Velasque *et al.*, 2023).

4.5. Challenges and market acceptance

In aquaculture, Black Soldier Fly Meal (BSFM) is a sustainable and nutritional alternative to fishmeal, but its widespread adoption is difficult. These issues originate from market acceptance, consumer attitudes, and regulations. Understanding these characteristics helps aquaculture farmers switch from traditional feed ingredients to insect-based proteins, especially for rainbow trout (*Oncorhynchus mykiss*) (Hervé *et al.*, 2025).

4.5.1. Consumer perceptions and market acceptance

Customers are wary about BSFM in aquaculture feeds due to insect-based food stigma. Many markets, especially Western ones, worry about insect-fed fish's taste, quality, and safety. In some cultures, edible insects are increasingly popular, but their usage as animal food, especially in fish farming, may be seen with mistrust. Even though black soldier fly larvae are clean and nutritious, customers don't like feeding fish insects because of the "yuck" element. Overcoming consumer reluctance requires education and awareness efforts regarding BSFM's environmental and nutritional benefits as a sustainable, high-protein feed additive. Eco-conscious consumers may like that BSFM production employs organic waste and reduces fishmeal's environmental impact. Food safety and nutritional value quality control education may reduce consumer anxiety (Mulazzani *et al.*, 2023).

4.5.2. Regulatory frameworks and policy barriers

Aquaculture regulations also limit BSFM deployment. Many countries restrict rainbow trout aquaculture diets' alternative feed items. Numerous regions permit BSFM for animal feed, however fish feed regulatory approval is lengthy and complicated. BSFM pollution, heavy metals, and allergens may necessitate stringent safety testing in some countries.

Regulations must allow insect-based proteins and specify aquaculture conditions to make BSFM more acceptable. Producers, researchers, and legislators must collaborate to provide safe and quality-tested BSFM-based feeds. Regulators may reduce limits and simplify approval when BSFM proves its benefits (Selvaraj & Won, 2024).

4.5.3. Overcoming barriers

Educating consumers and advocating for regulatory reform will solve these issues. Public awareness of BSFM's environmental, nutritional, and safety benefits can boost consumer trust. Working with legislators to clarify insect-based protein regulation will boost market acceptance. Consumer mistrust and regulations hinder BSFM aquaculture implementation. However, aggressive education and campaigning can influence

consumer attitudes and regulatory frameworks to embrace BSFM as a sustainable and nutritious fishmeal alternative. These obstacles must be solved to realise BSFM's aquaculture potential, especially for rainbow trout (Alabdulmohsen & Al-Otaibi, 2025).

4.6. Future directions and research needs

As Black Soldier Fly Meal (BSFM) emerges as a sustainable substitute for fishmeal in rainbow trout (*Oncorhynchus mykiss*) aquaculture, several essential study domains require investigation to improve its application and ensure its broad acceptance in the industry.

4.6.1. Fortification of BSFM

The study concentrates on BSFM for the nutrition of rainbow trout. BSFM generates superior protein; nonetheless, certain species may require more methionine and cysteine. To enhance the nutritional profile of BSFM for trout, study should include amino acids, vitamins, and minerals. Bioactive compounds such as antioxidants or probiotics in BSFM may enhance fish health and immunity (Brezas & Hardy, 2020).

4.6.2. Enhancing trout health and disease resistance

BSFM's chitin and bioactive peptides may influence trout immune responses and enhance illness resistance; however, further research is required. BSFM has the potential to diminish antibiotic usage in aquaculture by enhancing the gut microbiota and immunological function of trout (Lawal *et al.*, 2025; Torres-Maravilla *et al.*, 2024).

4.6.3. Expanding commercial production

Commercially substituting fishmeal with BSFM requires manufacturing scaling studies. Different black soldier fly larvae feedstocks and large-scale insect farming should be studied to optimise BSFM production. For widespread implementation, large-scale BSFM production must be viable and linked to aquaculture supply networks. Better BSFM, fish health, and commercial output are needed to improve rainbow trout aquaculture. These studies will boost BSFM diets and secure protein (Gougbedji *et al.*, 2022).

5. CONCLUSION

Black Soldier Fly Meal (BSFM) was evaluated as a sustainable alternative to rainbow trout fishmeal in this investigation. Its innovative life cycle assessment (LCA) of BSFM in comparison to conventional fishmeal demonstrated substantial decreases in greenhouse gas emissions, water consumption, and land requirements. It investigated the optimisation of rainbow trout BSFM for nutritional digestibility, lipid metabolism, and protein quality.

Recent research indicates that BSFM may enhance the immunity, stress tolerance, and illness resistance of rainbow trout. These health and environmental advantages indicate that BSFM has the potential to revolutionise sustainable aquaculture. To realise the full potential, it is necessary to conduct research on the enhancement of trout health, the expansion of commercial production, and the reinforcement of BSFM. By addressing these research requirements, BSFM could help promote sustainable aquaculture, reduce reliance on overexploited marine resources, and make fish farming more environmentally friendly.

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