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Analysis of the Application of Black Soldier Fly in Sustainable Agriculture and Carbon Emission Reduction Potential

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Abstract:

Facing the dual challenges of global protein resource shortages and carbon neutrality goals, developing new sustainable protein sources has become an urgent need. The black soldier fly, due to its high efficiency in converting organic waste, is gradually becoming an important alternative to traditional feed proteins. This paper systematically reviews the practical applications of black soldier fly in areas such as poultry and aquaculture feed from an application perspective and focuses on analyzing its potential in organic waste recycling and carbon emission reduction. Research indicates that black soldier fly larvae (BSFL) are rich in nutrients, possess great potential for replacing fishmeal and soybean meal in poultry and aquaculture feed, and can significantly improve animal growth performance and gut health. Its industry chain, through methods such as waste conversion, efficient bioconversion, and low-carbon processing, holds significant advantages in reducing greenhouse gas emissions; for example, converting aquaculture sludge can avoid methane emissions and achieve a high waste conversion rate. Finally, the paper proposes recommendations regarding policy support, technological optimization, and market-oriented promotion to foster the sustainable development of the black soldier fly industry chain.

Keywords: Black soldier fly; Insect protein; Carbon reduction; Sustainable feed; Organic waste recycling.

1. Introduction

Global protein supply faces severe challenges. China's import dependence on high-protein feed ingredients such as soybeans and fishmeal remains high, and their prices continue to rise. It is projected that by 2025, the consumption of meat and aquatic products will further increase, intensifying the pressure on protein demand [1]. Simultaneously, global carbon neutrality goals require all industries to advance emission reduction. Although the direct greenhouse gas emissions from the aquaculture industry account

for a relatively small proportion, its feed supply chain contributes 70% to 90% of the carbon footprint, making it a key focus for emission reduction [2].
Regarding international policies, the European Union has opened the application of insect protein in livestock and aquaculture feed starting in 2025, and China's "Action for Saving Grain in Animal Husbandry" also explicitly proposes promoting the utilization of alternative protein resources and the construction of "Zero-Waste Cities," indicating a gradually clarifying policy environment [3].
However,current research mostly focuses on single application areas of the black soldier fly, and there is still a lack of systematic review and comprehensive analysis of its various applications, including replacement in poultry and aquaculture feed, organic waste conversion, and carbon emission reduction contributions, hindering a comprehensive assessment of its industry chain's overall value and synergistic effects. Against this background, the black soldier fly, as a scalable and promising insect protein source, deserves in-depth exploration regarding its application and carbon emission reduction value.
This study aims to systematically analyze the current application status of black soldier fly in aquaculture and poultry feed, evaluate its carbon emission reduction potential, and propose recommendations for advancement from policy, technological, and market perspectives, providing a theoretical reference for related industries.

2. Characteristics, Farming and Processing of Black Soldier Fly

The black soldier fly is characterized by rapid reproduction, a broad diet, and strong adaptability, enabling it to efficiently convert organic waste such as kitchen waste and agricultural residues into high-value insect protein [4]. Compared to other feed insects (such as yellow mealworms, crickets), the black soldier fly holds greater advantages in terms of policy compliance and existing evidence-based research data.
In terms of policy compliance, the black soldier fly is a feed insect that gained policy recognition earlier in major farming countries/regions. The European Union has explicitly included insect-derived proteins like black soldier fly in the permitted ingredient list for livestock and aquaculture feed through relevant regulations and has stipulated safety standards for farming substrates; the US FDA has also promoted the application of black soldier fly in poultry feed and detailed product processing specifications; although China has not yet issued nationwide unified standards, the "Action for Saving Grain in Animal Husbandry" lists black soldier fly as one of the key alternative proteins to explore, and some regions have issued local farming technical specifications. In contrast, policy recognition for insects like yellow mealworms and crickets is still limited to a few countries and has not formed a global compliance framework.
Regarding evidence-based data,the nutritional characteristics, animal application effects, and waste conversion efficiency of black soldier fly have been extensively studied and quantified, with data covering the entire industry chain, whose depth and breadth far surpass that of other feed insects. For major farmed species such as broilers and Nile tilapia, databases on growth performance and physiological indicators at different inclusion levels have been established; in terms of waste conversion, conversion efficiency, larval yield, and nutrient retention rates have been quantified for different substrates. In comparison, research on other insects mostly focuses on nutritional analysis of single substrates, lacking systematic data support for full-cycle and multi-scenario applications.
During the farming of black soldier fly, raw materials require pre-treatment such as sorting and crushing to meet feeding requirements. Intensive farming requires controlling the ambient temperature between 25–30°C and employing automated feeding systems. Temperature control is the most energy-intensive aspect, accounting for approximately 60% of the total energy consumption in farming, while automated equipment can significantly reduce labor costs [5].
The processing stages primarily include sterilization, drying, and crushing. The processing standards for feed-grade black soldier fly protein powder are relatively more lenient compared to food-grade, but relevant regulations domestically and internationally are still being continuously improved. The drying process in the production line has high energy consumption, which can be optimized through low-carbon technologies like waste heat recovery and solar drying. Studies have shown that solar-assisted drying can reduce the energy consumption of the drying process by 30% to 40% while also reducing carbon emissions [6].

3. Application of Black Soldier Fly in Poultry Feed

3.1 Nutritional Value and Digestibility

Black soldier fly larvae (BSFL) are rich in protein (32% to 53%) and fat (18% to 33%), with a balanced amino acid profile, particularly rich in lysine and methionine, making it an ideal substitute for fishmeal and soybean meal in poultry feed [1].

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Studies have shown that the lysine content in BSFL can reach 2.81% to 3.38% (dry matter basis), and the methionine content ranges from 0.41% to 0.82%, which is close to that of fishmeal, and the amino acid digestibility is as high as 73% to 97%, comparable or even superior to soybean meal [1]. Furthermore, BSFL fat has a high lauric acid (12:0) content (17.89% to 37.18%), which possesses antimicrobial potential and promotes gut health, capable of reducing the number of pathogens such as E. coli and Salmonella in the poultry intestine [3].

3.2 Effects on Poultry Growth Performance

Studies have shown that the application of black soldier fly larvae in broiler feed offers significant advantages; low inclusion rates (5% to 10%) usually have no negative impact on broiler weight gain and feed conversion ratio, and can even improve growth performance. For example, a trial on Improved Indigenous Chicken (IIC) in Kenya found that the group with a 10% BSFL inclusion achieved an average daily weight gain (ADWG) of 12.1 g at 8 weeks of age, significantly higher than the 0% inclusion group (9.3 g/d), and the feed conversion ratio (FCR) was optimized to 3.3, lower than the control group (4.5) [7]. Other research indicated that the body weight at 21 days of age in the 6% BSFL inclusion group showed no significant difference from the control group, and the feed cost was reduced by 8% to 10% [1]. From a meat quality perspective, appropriate inclusion of BSFL can improve meat color and flavor, and its fatty acid profile can be optimized through dietary formulation adjustments.

It should be noted that when the BSFL inclusion rate exceeds 15%, it may lead to reduced feed intake and weight gain in broilers. Therefore, in practical applications, the inclusion rate should be controlled within 15%, or defatted BSFL should be used to enhance the suitability of higher inclusion levels.

3.3 Effects on Poultry Immune Response

Components in BSFL, such as chitin and antimicrobial peptides, have the effect of enhancing the immune response in poultry. Studies have indicated that appropriate dietary inclusion of BSFL can increase the secretion of intestinal mucin (MUC2) in broilers; simultaneously, BSFL can elevate the level of secretory immunoglobulin A (sIgA) in serum. One trial showed that the serum sIgA content in broilers from the 10% BSFL inclusion group reached 1.8 mg/mL, significantly higher than that of the control group (1.2 mg/mL) [3].

Furthermore, BSFL can activate the innate immune pathways in broilers, increase lysozyme activity, and enhance the body's resistance to bacterial diseases. It is important to note that the immune-activating effect of chitin is dose-dependent; excessively high inclusion may trigger excessive intestinal inflammatory responses. Therefore, the immunomodulatory effects need to be optimized by considering the inclusion rate.

3.4 Economic Advantages

Multiple studies have indicated that the inclusion of BSFL can significantly reduce feed costs, improve the Cost-Benefit Ratio (CBR) and Return on Investment (RoI), offering greater economic advantages, particularly in the context of high fishmeal prices. Research has shown that the 20% BSFL inclusion group had the lowest feed cost, with the feed consumption cost per chicken during the starter phase reduced by 24% compared to the control group; the CBR reached 2.12 and the RoI was 112.06%, significantly higher than those of the control group [7].

In broiler farming,the economic benefit of BSFL is also reflected in its efficiency in replacing fishmeal. A broiler trial in Kenya found that replacing 50% of fishmeal with BSFL reduced the feed cost per kilogram from 120 KES to 98 KES, and increased profit per bird by 15% within the rearing cycle [8]. Furthermore, localized production of BSFL can reduce the transportation costs associated with imported fishmeal, thereby further amplifying the economic advantages.

4. Application Potential of Black Soldier Fly in Aquafeed

4.1 Nutritional Value and Suitability

Black soldier fly larvae meal (BSFLM) has a crude protein content of 29.9% to 48.2%, a fat content of 25.69% to 28.43%, and is rich in essential amino acids, minerals, and vitamins [9]. Its nutritional composition highly matches the physiological requirements of Nile tilapia, enabling it to effectively replace fishmeal in providing core nutritional support.

In terms of amino acid value, the essential amino acid profile of BSFLM is similar to that of fishmeal, particularly rich in lysine (1.91% to 7.03%), leucine (2.52% to 8.80%), and valine (2.29% to 5.80%) — Lysine is a key limiting amino acid for protein synthesis in Nile tilapia, promoting skeletal muscle development in juvenile fish and increasing the weight gain rate; Leucine regulates muscle protein deposition and reduces muscle loss during the later stages of farming by activating the mTOR signaling pathway; Valine is involved in branched-chain amino acid metabolism, alleviating stress responses in fish under high-density farming conditions. Research indicates that when BSFLM replaces 50% of the fishmeal, the total essential amino acid content in the muscle of Nile tilapia reaches 38.2% (dry matter basis), showing no significant difference from the full fishmeal group (39.5%) [9].

Regarding vitamin value, the contents of vitamin B2 (1.62-24.74 mg/100g), B5 (3.85 mg/100g), B9 (0.27 mg/100g), and choline (110 mg/100g) in BSFLM are significantly higher than the requirements for Nile tilapia (B2 requires 1 mg/100g, B5 requires 1 mg/100g, B9 requires 0.05 mg/100g, choline requires 100 mg/100g): Vitamin B2 participates in energy metabolism in fish, reducing liver fat deposition; B5 promotes coenzyme A synthesis,improving the utilization of dietary fat; Choline supports the synthesis of the neurotransmitter acetylcholine, improving fish locomotor ability and stress resistance. Although vitamins C (0.19-0.37 mg/100g) and E (0.62-1.30 mg/100g) require additional supplementation (tilapia requirements are 5-42 mg/100g and 5-10 mg/100g, respectively), this can be compensated for by adding vitamin premixes (such as coated vitamin C), thus not affecting the overall nutritional suitability of BSFLM (see Table 1).

Table 1. Comparison of Major Vitamin Contents in BSFLM and the Requirements of Nile Tilapia [9]

Vitamin	BSFLM Contents (mg/100g)	Nile Tilapia Requirements (mg/100g)
Vitamin B1 (Thiamine)	0.24–2.00	0.4
Vitamin B2 (Riboflavin)	1.62–24.74	1
Vitamin C (Ascorbic Acid)	0.19–0.37	5–42
Vitamin E	0.62–1.30	5–10

4.2 Effects on Fish Growth Performance

Multiple studies have shown that BSFLM can replace 50% to 75% of fishmeal without negatively affecting the weight gain rate, feed conversion ratio (FCR), and survival rate of Nile tilapia and it demonstrates good adaptability across different culture systems [10]. The effects are most pronounced in semi-open systems (e.g., hapas in ponds), where research indicates that with 50% fishmeal replacement, the specific growth rate (SGR) of Nile tilapia can reach 3.74%/day, FCR is optimized to 1.70, and survival rate is 93.33%, significantly outperforming closed systems like glass tanks [11]. This is because, in semi-open systems, tilapia can consume natural plankton, which complements the nutrition provided by BSFLM and compensates for potential micronutrient deficiencies associated with high replacement rates.

In cage systems (cages in earthen ponds), a 75% replacement rate can still maintain good performance: one study found that at this replacement level, the tilapia achieved an SGR of 0.52%/day, an FCR of 2.13, and a survival rate of 95.83%, and the muscle protein content reached 18.2% (wet weight), showing no significant difference from the full fishmeal group (18.5%) [12]. Even at a 100%replacement rate, a survival rate of 98.30% was still achieved, although the SGR decreased to 1.10%/day (see Table 2), indicating that BSFLM can serve as a sole protein source to support tilapia survival, and growth performance can be further enhanced by supplementing with fish oil and amino acid premixes [10].

Table 2. T Effects of Replacing Fishmeal with BSFLM on the Growth Performance of Nile Tilapia in Different Culture Systems

Culture System	Fishmeal Replacement Rate	Specific Growth Rate (SGR, %/day)	Feed Conversion Ratio (FCR)	Survival Rate (%)	References
Hapas in ponds	100%	1.10	1.10	98.30	[10]
Hapas in ponds	50%	3.74	1.70	93.33	[11]
Cages in earthen ponds	75%	0.52	2.13	95.83	[12]
Glass tanks	100%	1.30	2.23	100	[13]

4.3 Fatty Acid Composition and Regulation

The fatty acid composition of BSFLM has distinct characteristics: on one hand, its high lauric acid content confers broad-spectrum antibacterial and anti-inflammatory effects; on the other hand, its n-3/n-6 polyunsaturated fatty acid ratio is relatively low, and long-term exclusive use may lead to n-3 PUFA deficiency in fish.

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To address these characteristics, defatting treatment can significantly reduce the fat content and increase the n-3/n-6 ratio; alternatively, the fatty acid profile can be optimized through dietary formulation adjustments or substrate modulation. Furthermore, the contribution of BSFLM to the dietary fat content needs to be controlled to avoid hepatic steatosis caused by excessively high saturated fat.

4.4 Economic and Environmental Benefits

The use of BSFLM can significantly reduce aquafeed costs and decrease dependence on imported fishmeal, while also lowering the feed carbon footprint.

From a cost perspective, the current market price of fishmeal is approximately 12,000-15,000 CNY/ton, whereas the large-scale production cost of BSFLM can be controlled within 8,000-10,000 CNY/ton,demonstrating a significant price advantage. Field studies in Kenya have shown that using BSFLM to replace 50% of fishmeal in tilapia feed reduces cost per ton by approximately 14% and increases farming profit by about 15%.

In terms of environmental benefits, the carbon footprint of BSFLM is only 1/4 to 1/2 that of fishmeal. Furthermore, BSFLM production enables the “reduction in volume” of organic waste, while also reducing methane emissions from sludge landfilling. Within the circular economy framework, the frass produced during BSFLM processing can be used as organic fertilizer, further reducing agricultural non-point source pollution.

5. Application of Black Soldier Fly in Carbon Emission Reduction and Waste Treatment

5.1 Carbon Emission Reduction Mechanism

BSFL can efficiently convert various organic wastes, and the conversion efficiency is significantly influenced by the substrate type and ratio.

In aquaculture waste treatment, its conversion rate for Aquaculture Solid Waste (ASW, containing fish feces, residual feed, etc.) can reach 86.2%, far exceeding traditional composting (30%-40%). Processing 1 ton of ASW can reduce the waste volume by approximately 60% to 70%, while simultaneously producing 180-220 kg of BSFL [14]. Further research found that black soldier fly larvae can effectively convert fresh aquaculture sludge. When sludge was mixed with chicken feed at a 75:25 ratio (balancing nutrition and palatability), larval yield was highest (average final weight 176.30 mg/larva), and the waste reduction rate reached 35.68%, and nutrient retention rates were optimal (N: 22.14%; C: 15.29%; S: 15.40%) [15]. This is because the carbohydrates provided by the chicken feed promote larval gut microbial activity, enhancing the decomposition efficiency of organic carbon in the sludge.

In agricultural/food waste treatment,the conversion efficiency of black soldier fly is equally prominent: processing 1 ton of kitchen waste can produce 120-150 kg of BSFL, with a waste reduction rate of 70%-80%, and methane emissions are reduced by over 90% compared to landfilling [16].When processing a mixed substrate of rice straw and pig manure (3:7), the larval degradation rate of crude fiber reached 25%-30%, significantly higher than that of yellow mealworms (15%-20%), demonstrating a stronger ability to convert complex organic matter. Furthermore, black soldier flies have broad substrate adaptability and can process special wastes such as slaughterhouse wastewater and Chinese herbal medicine residues, and the heavy metal content (e.g., Cd, Pb) in the larvae post-conversion can be controlled within safe limits (<0.1 mg/kg), enabling potential for multi-scenario waste treatment.

5.2 Waste Conversion Efficiency

Black soldier fly larvae can efficiently convert various organic wastes. Studies indicate that their conversion rate for Aquaculture Solid Waste (ASW) can reach 86.2% [14]. Research has found that black soldier fly larvae can effectively convert fresh aquaculture sludge. When sludge is mixed with chicken feed at a 75:25 ratio, larval yield is the highest (average final weight 176.30 mg), the waste reduction rate can reach 35.68%, and nutrient retention rates are also optimal (N: 22.14%; C: 15.29%; S: 15.40%) [15].

Attention must be paid to the accumulation of heavy metals (such as Cd, Ni, Pb) in the larval bodies, especially when reared on contaminated substrates like sludge. Although the heavy metal content in BSFL reared on aquaculture sludge increases, it can be controlled within safe limits through substrate pre-treatment and management of the rearing cycle [15]. Recommendation: pre-treatment or screening of substrates; establish monitoring standards for heavy metals in larvae; and prioritize the use of agricultural or food processing wastes as substrates.

6. Challenges and Recommendations for Advancement

6.1 Technical Challenges

The industrialization of black soldier fly still faces multiple technical bottlenecks that require targeted breakthroughs.

Firstly, energy consumption in large-scale farming is high. In intensive farming, temperature control accounts for 60% of the total energy consumption, particularly in temperate regions during winter, maintaining an environment at 25–30°C consumes substantial electricity (approximately 50 kWh per ton of larvae) [5]. Currently, optimization can be achieved through technologies like waste heat recovery and ground-source heat pumps, waste heat recovery systems can reduce temperature control energy consumption by 30%–40% [6].In the future, solar-assisted temperature control systems need to be developed to further reduce reliance on fossil fuels.

Secondly, there is insufficient energy efficiency in processing and inconsistent product quality. The drying stage (e.g., hot-air drying) accounts for 70% of the total energy consumption in processing, and the protein content variation between different batches of BSFLM can reach 10%–15% (due to substrate differences). Supercritical CO_2 drying technology can be promoted, which reduces energy consumption by 25% compared to hot-air drying, and maintains product moisture content stable at 5%–8%; simultaneously,a substrate standardization system should be established. For example, stipulating that kitchen waste used for BSFL farming must meet criteria such as "total sugars >15%, crude fiber <10%" to reduce nutritional fluctuations [4].

Finally, there is the challenge of nutritional balance in aquatic feed. BSFLM is deficient in n-3 PUFAs and lacks vitamins C and E, and high inclusion rates(>75%) may lead to muscle fat deposition in tilapia. There is a need to develop compound formulas such as "defatted BSFLM + fish oil + vitamin premix". For example, defatted BSFLM (70%) + fish oil (5%) + vitamins C/E (0.2%), which can achieve a feed n-3/n-6 ratio of 0.4 and vitamin C content of 30 mg/100g, meeting tilapia requirements; concurrently, research on genetic breeding of BSFL larvae should be conducted to cultivate strains with high n-3 PUFA content [9].

6.2 Lack of Policies and Standards

The current policy and standard system for the insect feed industry remains incomplete, hindering its standardized development.

Firstly, there is a lack of nationally unified standards for raw materials and safety. China has not yet issued official standards for black soldier fly feed ingredients, and different regions have varying regulations on BSFLM inclusion rates (e.g., Guangdong allows ≤15% in broiler feed, Shandong allows ≤10%), hindering cross-regional sales for enterprises. Furthermore, a safety evaluation system is lacking. For instance, detection methods and limits for heavy metals and pathogens (e.g., Salmonella) are not clearly defined. Referencing EU standards, it is urgent to formulate the "General Rules for Insect-Derived Feed Materials", specifying indicator ranges such as protein and fat(protein ≥40%, fat ≤30%) and safety limits (heavy metals, microorganisms).

Secondly, there is a gap in carbon emission reduction measurement and certification mechanisms. The carbon emission reduction benefits of the black soldier fly industry chain have not yet been incorporated into the national carbon trading system, leaving enterprises lacking emission reduction incentives. It is necessary to reference the CCER (China Certified Emission Reduction) methodology to establish a carbon emission reduction measurement model for black soldier flies, such as a dual-module model comprising "waste treatment emission reduction + feed substitution emission reduction". For example, certifying the emission reduction from processing 1 ton of kitchen waste as 0.8 tons of CO_2 equivalent, and promote its inclusion in the carbon trading market [17].

Finally, there are barriers in cross-border trade policies. Different countries have vastly different import quarantine requirements for insect protein (e.g., the EU requires substrate traceability reports, while the US mandates testing for Bt protein). Chinese enterprises exporting BSFLM must undergo multiple tests, increasing costs, necessitating the promotion of international standard harmonization. For example, by participating in the development of insect protein standards within ISO/TC 34 (Food Technology Committee) to unify testing methods and quarantine requirements.

6.3 Market Acceptance

Current market acceptance of black soldier fly protein remains relatively low, and there are shortcomings in cost and supply chain.

From the perspective of consumer acceptance, there is insufficient global awareness of insect-based feed. Particularly in developing countries, consumers generally hold the stereotype that "insect feed is unsafe". A European survey showed that only 30% of poultry farmers are willing to use BSFLM feed, primarily concerned about residual contaminants in the larvae; a Chinese survey also indicated that 58% of aquaculture farmers believe that "insect feed affects the flavor of aquatic products" [3].

In terms of cost competitiveness, the current cost of small-scale BSFLM production (<1000 tons/year) is approximately 10,000-12,000 CNY/ton. While this is lower than fishmeal, it is higher than soybean meal (4,000-5,000 CNY/ton), and the supply chain is underdeveloped — the collection of raw materials (e.g., kitchen waste) lacks

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specialized teams, leading to unstable substrate supply; product storage and transportation require low-temperature conditions(<15°C), increasing logistics costs (approximately 200-300 CNY/ton).

From a market development perspective, the lack of benchmark enterprises and demonstration projects means farmers have little trust in the application effects of BSFLM. Government-led demonstration projects (e.g., the “waste-insects-feed” pilot within the “Zero-Waste Cities” initiative) are needed to showcase the economic and environmental benefits of BSFLM, while simultaneously strengthening industry training to enhance farmers’ understanding of insect protein.

6.4 Recommendations for Advancement

To promote the healthy development of the black soldier fly industry chain, coordinated efforts are needed from technological, policy, and market perspectives.

On the technological front, research, development, and optimization should be strengthened. Breed black soldier fly strains with greater adaptability (e.g., cold-tolerant, high-protein strains) to reduce temperature control energy consumption; promote low-carbon processing technologies (e.g., solar drying, supercritical CO_2 defatting) to reduce processing energy consumption by over 30%; for aquafeed, develop specialized formulas such as “defatted BSFLM + fish oil + coated vitamins” to optimize fatty acid and vitamin balance [6].

On the policy front, the standard system should be improved. Accelerate the establishment of national or industry standards, clarifying BSFLM raw material requirements (e.g., substrate types, nutritional indicators), inclusion specifications (poultry ≤20%, aquaculture ≤75%), and safety testing methods; establish a carbon emission reduction certification system, include black soldier fly farming in the CCER framework, define emission reduction measurement methods, and encourage enterprises to participate in carbon trading [17].

On the market front, demonstration projects and market cultivation should be promoted. Leveraging the “Zero-Waste Cities” initiative, promote the “aquaculture sludge — black soldier fly — aquafeed” model in aquaculture areas (e.g., Pearl River Delta, Yangtze River Delta), and establish 10 to 15 large-scale demonstration projects by 2025; strengthen public outreach through short videos, industry exhibitions, to disseminate the environmental value (e.g., carbon reduction, waste treatment) and safety (e.g., compliance with heavy metal standards) of black soldier flies, thereby enhancing market acceptance.

7. Conclusion

As a novel protein resource, the black soldier fly demonstrates considerable application potential in poultry and aquaculture feed through the recycling and efficient conversion of organic waste and holds unique advantages in carbon emission reduction. Research indicates that black soldier fly can effectively replace traditional protein sources like fishmeal and soybean meal in poultry and aquaculture feed, improving animal growth performance and health while reducing feed costs. Simultaneously, by efficiently converting organic waste, it achieves waste “reduction in quantity” and “resource recovery”, significantly reducing greenhouse gas emissions, thereby demonstrating comprehensive value in sustainable agriculture and carbon emission reduction.

To further promote the sustainable development of the black soldier fly industry chain, future efforts should be guided by the framework of “technological optimization — standard improvement — market cultivation”, focusing on optimizing the fatty acid composition and vitamin supplementation schemes of BSFLM in aquafeed, developing efficient and low-cost processing technologies, and establishing a full life cycle carbon footprint assessment system. At the market level, its economic value should be demonstrated through pilot projects, and public awareness should be enhanced; on the policy front, promoting the certification of carbon reduction benefits and improving the standard system are essential. Future research should also conduct more systematic evaluations based on actual production data across different climate zones and application scenarios, exploring the integrated application of black soldier fly within circular agricultural systems.

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