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Simple Summary: Black soldier fly larvae meal (BSFLM) is a sustainable ingredient that could replace traditional animal feed sources. However, to ensure it is safe for animal consumption, producers must carefully control quality and hygiene. This study applied a food safety plan called HACCP to identify and manage possible risks during production, such as bacteria, moulds, heavy metals, or pesticide residues. By using practices like heat treatment, good hygiene, and careful selection of raw materials, we identified the key steps where safety can be ensured. Our findings show that applying these controls can make BSFLM a reliable and safe feed ingredient. This contributes to more sustainable farming and reduces reliance on conventional feed sources.

Abstract: Black soldier fly (*Hermetia illucens*) larvae meal (BSFLM) offers a promising solution for sustainable animal feed. However, its safe adoption requires robust quality assurance systems. This study applies the Hazard Analysis and Critical Control Points (HACCP) plan to identify and evaluate biological, chemical, and physical hazards throughout the BSFLM production process. Key risks included microbial contamination, allergens, and chemical contaminants. Preventive strategies and specific processing steps were defined to mitigate these risks. Critical control points (CCPs), along with their associated limits, monitoring protocols, and corrective actions, were established to ensure product safety. The results underscore the importance of structured risk management to enable the safe integration of insect meals into animal nutrition and support the development of a sustainable insect-based feed sector.

Keywords: insect-based feed; risk assessment; food safety; critical control points (CCPs); insect farming; sustainable animal nutrition; good manufacturing practices (GMPs)

1. Introduction

Insect production as a protein source for animal and human consumption has gained increasing attention over the past decade due to its potential to meet global food demand while reducing pressure on conventional agricultural systems [1]. Insect farming offers several advantages, including high feed conversion efficiency, minimal space and water requirements, and a substantially lower environmental footprint compared to traditional livestock production [2,3]. Among the most promising species is the black soldier fly (*Hermetia illucens*), whose larvae are rich in protein, lipids, and essential minerals, making them a sustainable and functional alternative for animal feed [4].

However, using insects for food and feed presents significant challenges regarding product safety and quality. Insects are typically reared on substrates composed of agro-industrial residues, organic by-products, and recycled materials, which can introduce microbiological and chemical contamination risks [5,6]. Common hazards include pathogenic microorganisms (e.g. *Salmonella*,

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Listeria monocytogenes), heavy metal accumulation (lead, cadmium, arsenic), mycotoxins, pesticides, and allergens from chitin and other natural compounds [2,7]. These risks may be exacerbated in artisanal or small-scale systems with less stringent substrate and process control [8].

In response, regulatory bodies have begun to establish frameworks to ensure safety in insect production. In 2015, the European Food Safety Authority (EFSA) published a technical report on the risks of using insects for food and feed, emphasizing the need for specific industry regulations [9]. The European Commission authorized the use of insect protein in aquaculture feed in 2017, followed by approval for poultry and pig feed [8]. According to the International Platform of Insects for Food and Feed (IPIFF), European insect producers have marketed over 5,000 tonnes of insect-derived products since 2017, and the market is expected to reach 3 million tonnes by 2030 [8]. In contrast, Latin America still lacks robust regulation in this area, underscoring the need for targeted scientific data and policy frameworks to support local control measures and facilitate insect use as feed and food ingredients [10].

To address these risks and ensure product safety, the Hazard Analysis and Critical Control Points (HACCP) system has been widely adopted in the food industry [11] and is increasingly recommended for insect production [10,12,13]. HACCP enables the identification and assessment of physical, chemical, and biological hazards along the production chain, defining critical control points (CCPs) and parameters to mitigate risks [7]. Structured into 12 steps and 7 principles, HACCP provides a preventive framework that includes operational practices, control measures, and evidence-based verification, as recommended by the Codex Alimentarius Commission [11].

Producers and processors are strongly encouraged to address these hazards through good agricultural practices (GAP), good manufacturing practices (GMP), and preventive approaches based on HACCP, thus promoting safety management across the supply chain, in line with IPIFF guidance [8]. This methodology is particularly relevant for facilities involved in processing, transforming, and marketing insects beyond primary production, for both human and animal nutrition [13].

This study aims to explore the application of the HACCP plan to black soldier fly (*Hermetia illucens*) larvae meal (BSFLM) production, drawing on the literature and on previous and ongoing research at the Centre for Terrestrial Arthropod Research (CINAT), Universidad Nacional de Colombia. Biological, chemical, and physical hazards were assessed along the production chain, and CCPs were identified to ensure product safety. The analysis includes preventive strategies, control parameters, and corrective actions aimed at improving production and minimizing risk. A similar approach was previously applied to *Tenebrio molitor* meal, where HACCP was used to identify critical hazards and recommend control strategies to processors [10]. That experience provided a useful framework to strengthen food safety practices for *Hermetia illucens* and to extend these methods to other insect-based products.

2. Materials and Methods

2.1. Study Context and Data Sources

This study was conducted at the Centre for Terrestrial Arthropod Research (CINAT), Universidad Nacional de Colombia. The insect meal to be used as animal feed was produced from *Hermetia illucens* larvae reared on a mixed organic waste diet. Some processing steps differed slightly from those described in the literature, reflecting specific conditions applied at CTAR. This work does not present the details of BSFLM production but only the information relevant to the application of HACCP. The hazard analysis incorporated microbiological and toxicological data obtained in the meal produced.

2.2. HACCP Team Formation

The team was established in accordance with Codex Alimentarius recommendations [11,13,14]. It was multidisciplinary, including professionals in animal production (specifically *Hermetia illucens*

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farming), veterinary medicine, food science and technology, and quality management systems. All members contributed to each stage of analysis and recommendations.

2.3. Review of HACCP Prerequisites

The CINAT laboratory currently meets more than 50% of the Good Manufacturing Practices for Animal Feed (GMPAF), which are considered prerequisite programs (PRPs). These PRPs were assessed based on the Colombian Resolution 061252 of 2020, which establishes national guidelines for GMPAF [15].

2.4. Product Identification, Intended Use, and Process Description

A technical specification sheet was developed for black soldier fly larvae meal (BSFLM), detailing expected quality control parameters. Laboratory analyses were performed to obtain information on the compositional, microbiological and toxicological characteristics of the BSFLM. Information on the intended use was compiled, considering the target sector (animal feed), potential forms of commercialization, recommended labelling instructions, and guidelines for preparation or pre-processing. Relevant regulatory frameworks were consulted [13]. Additionally, a process flow diagram for BSFLM production at CINAT was also constructed. Each stage of the production process was defined, and key control variables were identified.

2.5. Hazard Identification, Risk Analysis, and Preventive Measures

Hazard analysis was carried out for each stage of the production process, based on an extensive literature review and data from ongoing research at CINAT BioInsectonomy Project (unpublished data). Hazard evaluations (i.e. cause and likelihood of occurrence) were informed by the HACCP team's expertise, while severity (i.e. potential consequence) was determined using literature reports for each hazard. A five-level risk matrix was used to estimate hazard relevance by multiplying the probability of occurrence by the assigned severity score, reflecting potential impacts on product safety or animal health. Control measures were defined through team discussions, aiming to minimise the occurrence of each hazard through the application of GAP, GMP, PRPs, and risk management strategies, following Codex Alimentarius recommendations [10,11,16].

2.6. Identification of Critical Control Points, Critical Limits, Monitoring System, and Corrective Actions

Critical control points (CCPs) were identified using the Codex Alimentarius decision tree approach [8,10,16]. For each CCP, critical limits were established alongside a monitoring system. Then, corrective actions were defined to address deviations from control, following international recommendations [11,13,16].

2.7. Validation of Control Measures and Verification of the HACCP System

The HACCP team developed a proposal outlining how processors can implement these activities when applying a HACCP plan. These recommendations were formulated in line with guidance from the Codex Alimentarius [17] and the Food Safety and Inspection Service [18].

2.8. Documentation and Record-Keeping

Finally, the HACCP team developed a list of the minimum documents and records that should be maintained to support decisions made under the HACCP plan in accordance with Codex Alimentarius and Food Safety and Inspection Service (FSIS) recommendations [18].

3. Results

3.1. Final Product Description

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(Table 1) provides a comprehensive technical overview of BSFLM, incorporating data generated under the BioInsectonomy Project.

Table 1. General product description and inputs used in the production of BSFLM.

Item	Description
Product name	Black Soldier Fly Larvae Meal (*Hermetia illucens*)
Raw materials (origin)	Final-instar larvae and prepupae of *H. illucens* provided by Insect Farming Technologies – EntoPro (La Miel Farm, Ibague municipality, Tolima, Colombia), reared on a substrate of cassava waste, carrot waste, guava flour, wheat bran, and coffee cherry.
Ingredients and additives	Citric acid (5%) added as an antioxidant during the blending stage. No other additives were used. IPIFF has not yet approved specific additives for insect feed.
Inputs	Food-grade plastic packaging.
Proximate composition (% dry matter)	Moisture (%): 7.0 ± 1.7 Dry matter (%): 93.0 ± 0.1 Gross energy: 5966.7 ± 1 kcal/kg Crude protein: 40.7 ± 0.8 Non-protein nitrogen (NPN): 6.5 ± 0.8 Ether extract: 32.7 ± 1.2 Crude fibre: 7.2 ± 4 Ash: 8.4 ± 5
Heavy metal (mg/kg)	Lead (Pb): Not detected * Chromium (Cr) <1.0 Mercury (Hg) <0.02
Microbiological characteristics	Aerobic mesophiles (CFU/g): 15,000 Moulds and yeasts (CFU/g): <100 Sulphite-reducing Clostridium (CFU/g): <10 Coagulase-positive S. aureus (CFU/g): <100 Total coliforms (CFU/g): 340 *Escherichia coli* (CFU/g): <10 *Salmonella* spp: Absent
Processing and Packaging	Produced via separation, washing, inactivation, blanching, emulsification, laminating, drying, and packaging. These steps enhance physicochemical properties, reduce compaction, and limit microbial contamination. See flow diagram for details.
Shelf Life	Under good manufacturing practices (GMP), expected shelf life is 7 months at 25 °C with 5% moisture and 80 µm polyethylene film. At 35 °C, cricket meal shelf life drops 3–4 times, and BSFL powder becomes unsuitable [19]. No shelf-life tests were conducted in the BioInsectonomy project.

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Preservation	In the BioInsectonomy project, BSFL meal was frozen at –21 °C in triple-layer plastic bags with oxygen barrier and hermetic seal.
Regulations	EU Regulation 2015/2283 on novel foods [20]. IPIFF Hygiene Guide (Feb 2024) [13]. Colombia Resolution 061252 (2020) on feed manufacturing/import requirements [15].
Intended Use	Ingredients for balanced animal diets (e.g., feed, pellets); in BioInsectonomy project, used for fish feed.

* *Not detected* indicates levels below the detection limit of the respective analytical method.

3.2. Flow Diagram to Produce BSFL Meal

Figure 1 illustrates the processing stages to produce BSFLM and the variables to be controlled at each step. The flow diagram was reviewed and validated by the HACCP team in accordance with the established processing steps at CINAT.

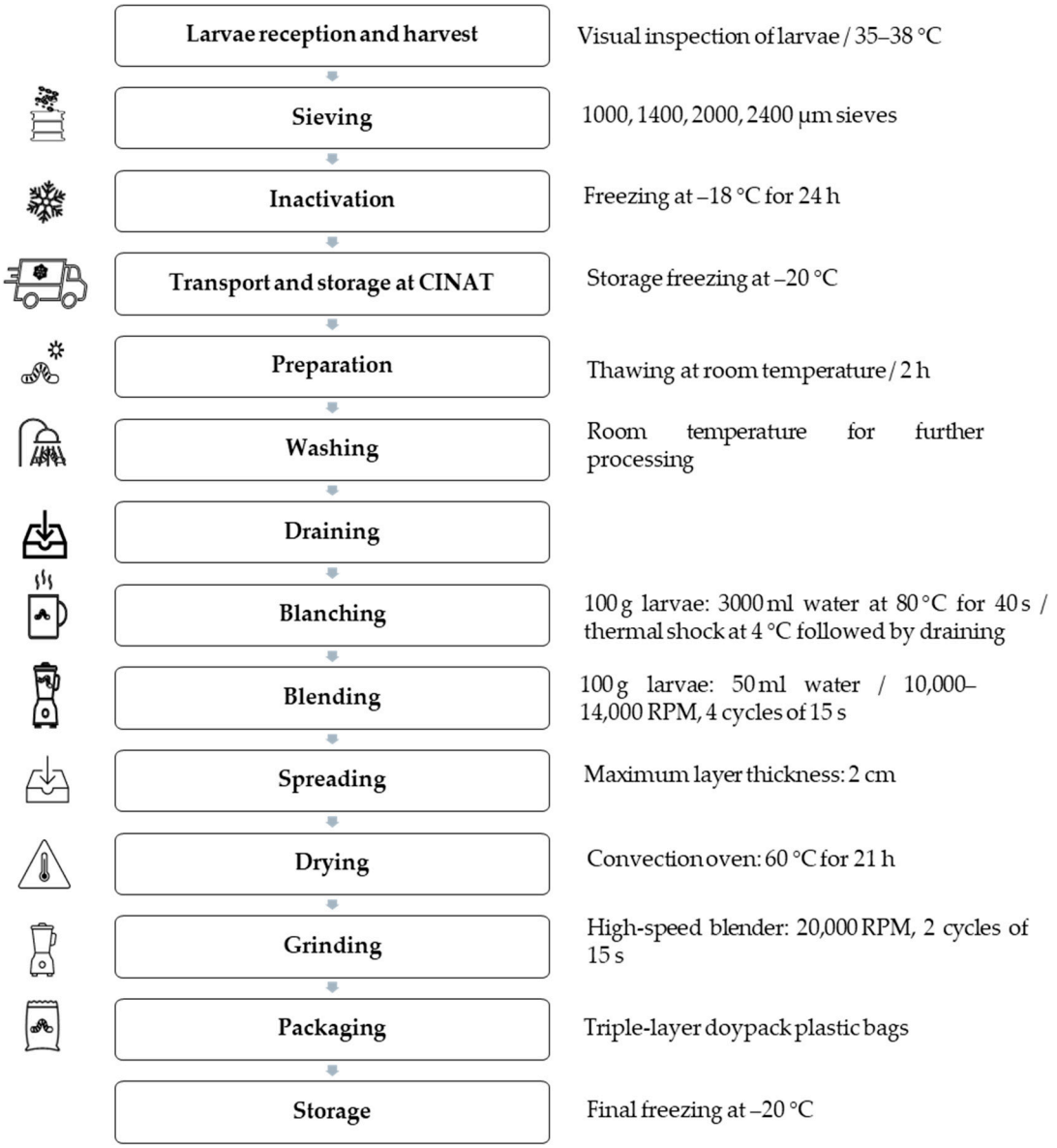

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Figure 1. Flow diagram of the BSFLM production process. Adapted from the CINAT production system and informed by selected literature sources [21–26].

3.3. Hazard Analysis and Preventive Measures

The hazard analysis (Table 2) identified the highest risks in the early processing stages, particularly during larval reception and substrate handling. Microbial contaminants such as *Aspergillus* spp., *Escherichia coli*, and *Bacillus cereus*, along with chemical residues including pesticides, heavy metals, and allergenic proteins, were classified as moderate to high risk. In subsequent steps such as sieving, blending, and drying, the nature of the hazards shifted toward cross-contamination, pathogen survival, and physical risks introduced by processing equipment, notably metal fragments from worn blades or damaged trays. These risks were mitigated through the implementation of good manufacturing practices, strict sanitation protocols, equipment inspection before and after use, and time and temperature controls. Additional actions such as larval surface cleaning, improved ventilation in drying areas, and the use of natural antimicrobial compounds like organic acids contributed to enhanced microbial safety.

Table 2. Hazard analysis and control measures in BSFLM production.

Stage	Hazards	Description	Probability	Severity	Risk	Preventive Control Measures Implemented at CINAT
Stage 1. Larvae Reception	Biological	*Aspergillus* spp.	5	4	High (20)	Use high-quality substrates and potable water throughout. Train personnel in hygiene and handling. Apply strict cleaning and disinfection routines. Remove substrate residues and organic waste to prevent mould growth. Apply thermal treatment at any stage to control fungal contamination. Ensure substrates are mycotoxin-free before processing.
		Bacillus cereus	3	4	High (12)	Implement good production (GAP) and manufacturing practices (GMP) from rearing to packaging. Control temperature and humidity. Use high-quality ingredients. Apply thermal treatment during processing.
		Faecal coliforms	1	2	Low (2)	Maintain strict hygiene and quality control. Ensure potable water, robust cleaning, pest control, and well-maintained facilities. Use quality ingredients. Train personnel in GMP. Conduct regular lab testing. Apply thermal treatment to reduce contamination.

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Total coliforms	5	2	Moderate (10)	Strict quality and hygiene controls from larval rearing to final packaging. Maintain robust cleaning/disinfection routines, pest control, potable water, and facility integrity. Use high-quality ingredients, reinforce GMP training for staff, and conduct routine lab testing. Apply heat treatment at some processing stage.
Enterococcus	3	2	Moderate (6)	Use clean, controlled-origin substrates to reduce initial microbial load. Avoid high-risk substrates like untreated manure. Enforce strict cleaning protocols in the reception area. Apply heat treatment at some stage to control the microorganism.
Escherichia coli – Shiga toxin	1	5	Moderate (5)	Ensure optimal hygiene from larval handling to final processing. This includes equipment and surface cleaning, and continuous staff training. Substrates (e.g., manure-based) must be pre-treated or controlled. Perform routine microbiological testing.
Escherichia coli	3	4	High (12)	Clean all equipment and surfaces in contact with larvae to prevent recontamination. Use clean, controlled substrates to reduce microbial load. Enforce strict cleaning in the reception area. Implement sorting to discard visibly contaminated larvae. Apply heat treatment to control microorganisms.
Listeria monocytogenes	1	5	Moderate (5)	Use substrates from controlled sources, free from known Listeria contamination. Apply pretreatments such as fermentation or thermal methods. Enforce rigorous cleaning protocols for facilities, equipment, and tools. Train staff in safe handling. Conduct frequent microbiological tests on incoming material and finished product.

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	Sthapylococcus aureus	2	4	Moderate (8)	Strengthen operator hygiene and biosecurity. Improve cleaning protocols during larval packaging and transport. Train staff in good handling practices. Implement strict sanitation routines for equipment and facilities. Use physical pest control methods and avoid chemical contamination. Ensure potable water use. Apply thermal treatment. Perform routine microbiological analyses.
Chemical	Mineral oil hydrocarbons, dioxins, PCBs, and PAHs	3	3	Moderate (9)	Use only feed-grade substrates free from chemical contaminants and additives. Locate rearing and processing facilities away from industrial or high-traffic areas. Ensure trays, containers, and tools in contact with larvae are made of food-grade materials that do not release chemical residues.
	Heavy metals	2	3	Moderate (6)	Use regulated, low-risk plant-based substrates. Locate facilities away from industrial/agricultural pollution. Conduct regular heavy metal analyses. Implement strict supplier control and traceability systems. Rotate substrates periodically to avoid accumulation.
	Mycotoxins	2	4	Moderate (8)	Use fungus-free agro-industrial by-products (e.g., free of Aspergillus, Fusarium). Inspect substrates for mould or abnormal odour. Keep processing areas dry and dust-free.
	Pesticides and insecticides	3	4	High (12)	Enforce strict supplier control. Ensure careful substrate selection to avoid chemical residues.
	Allergens (tropomyosin, arginine kinase, chymosin)	5	2	Moderate (10)	Train staff on allergen handling and prevention of cross-contamination. Apply thermal blanching to reduce allergenicity. Enforce strict cleaning protocols between batches. Including allergen risk in labelling.

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	Physical	Small metal particles	2	3	Moderate (6)	Establish daily cleaning and inspection of sieves and screens. Train staff to detect wear or corrosion. Replace worn parts. Use high-grade stainless-steel materials
		Gravel, stones	2	3	Medio (6)	Perform visual and tactile checks and fine mesh sieving to remove coarse particles before larval feeding. Establish SOPs for substrate inspection upon entry. Train reception staff in identifying/removing physical contaminants. Maintain equipment (e.g., grinders, conveyors, sieves) regularly.
		Insect parts, pest insects	2	2	Low (4)	Conduct visual/tactile checks and fine mesh sieving to remove insect parts. Establish SOPs for substrate inspection. Train reception staff to identify and remove physical contaminants. Inspect larvae at reception for pest contamination.
		Plastic fragments and microplastics	2	3	Moderate (6)	Separate plastic waste from larval feed inputs. Train staff to spot foreign particles. Sieve and inspect substrates. Use approved gloves/aprons that don't degrade. Regularly inspect tools and facilities for plastic debris. Use filtered water. Avoid single-use plastics.
Stage 2. Sieving	Biological	Aerobic mesophilic bacteria	3	2	Moderate (6)	Use substrates from trusted sources. Apply strict cleaning and disinfection protocols in processing areas.
		Moulds and yeasts	3	2	Moderate (6)	Maintain clean production areas. Use airtight packaging to avoid moisture. Prefer modified atmosphere or desiccants. Store in cool, cross-contamination-free areas.
		Aspergillus spp.	3	4	High (12)	Train staff on hygiene and handling to prevent contamination. Use clean work clothing and hand sanitisation (e.g., antibacterial gel). Clean equipment, surfaces, and facilities regularly. Remove organic

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						waste and feed residues to prevent mould growth.
		Total coliforms	2	2	Low (4)	Use substrates with low microbial load. Apply GMPs and strict hygiene. Ensure robust cleaning/disinfection, access control, and staff training. Dry the meal at high temperatures (>60 °C). Keep humidity low in processing/storage areas. Ensure proper ventilation and apply disinfectant sprays.
		Staphylococcus aureus	3	4	High (12)	Strengthen worker hygiene and biosecurity. Reinforce cleaning and disinfection protocols in larval packaging and transport. Strict pest control: seal cracks, install air curtains, use mesh barriers, insect traps, and monitoring devices.
	Chemical	Pesticides (insecticides, herbicides)	3	4	High (12)	Install physical barriers (closed walls and ceilings) around the sieving area to minimise contamination from neighbouring crop pesticide use.
	Physical	Metal fragments and particles	2	3	Medium (6)	Establish daily cleaning and inspection protocols for sieves. Train staff to visually detect mesh damage. Regularly inspect sieves for wear, corrosion, or breakage. Use stainless steel mesh. Inspect product for metal contamination.
Stage 3. Inactivation	Biological Chemical Physical	Non identified Non identified Non identified				
Stage 4. Transport and Storage at CINAT	Biological Chemical Physical	Non identified Non identified Non identified				
Stage 5. Thawing	Biological	Aerobic mesophilic bacteria	3	3	Medium (9)	Use substrates from reliable sources. Implement strict cleaning and disinfection protocols for all areas. Maintain constant control of temperature, humidity, and

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						ventilation to avoid bacterial proliferation.
		Moulds and yeasts	1	2	Low (2)	Keep production areas clean and with low humidity. Regularly disinfect equipment to avoid contamination. Use pretreated substrates to reduce microbial load. Ensure final moisture content of meal is below 10% to inhibit microbial growth during storage. Apply heat treatment and hermetic packaging in later stages.
	Chemical	Non identified				
	Physical	Non identified				
Stage 6. Washing	Biological	*Sthapylococcus aureus*	1	4	Low (4)	Apply good handling practices, ensuring potable water at all processing sites. Provide robust food safety training to all staff. Reinforce operator biosecurity and hygiene protocols.
	Chemical	Heavy metals	2	3	Medium (6)	Install specialised filters (e.g. activated carbon with resin or reverse osmosis). If water quality is uncertain, use distilled, demineralised or purified water for washing. Regularly inspect strainers and utensils for wear or corrosion; replace with stainless steel equipment.
	Physical	None identified				
Stage 7. Draining	Biological	Non identified				
	Chemical	Non identified				
	Physical	Non identified				
Stage 8. Blanching	Biological	Survival of microorganisms from previous stages	2	3	Medium (6)	Keep scalding water at 85 °C; calibrate thermometers regularly. Continuously monitor scalding temperature. Ensure cold shock water stays at 4 °C and is clean. Filter or treat water to reduce microbial load. Train staff on time-temperature controls during scalding and chilling.
	Chemical	None identified				
	Physical	None identified				

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Stage 9. Blending	Biological	*Staphylococcus aureus*	2	4	Medium (8)	Train personnel in proper handling of larvae and equipment sanitation during blending. Clean and disinfect blender and tools before each use with effective disinfectants (e.g., hydrogen peroxide or quaternary ammonium). Apply heat treatment afterwards.
		Salmonella spp.	3	5	High (15)	Avoid using larvae from animal faeces or faecal-contaminated waste. Train personnel in safe handling and disinfection procedures. Thoroughly clean and disinfect the blender, tools, surrounding surfaces, and nearby equipment before use to prevent cross-contamination.
	Chemical Physical	None identified Metal fragments and splinters	1	3	Low (3)	Establish a cleaning and inspection protocol for the blender before and after each production day. Train staff to visually detect blade damage. Regularly inspect blender blades for wear, corrosion, or cracks. Replace blades before reaching critical wear. Use high-quality stainless-steel blades. Conduct regular product inspections to detect metal contamination.
Stage 10. Spreading	Biological	Moulds and yeasts	1	2	Low (3)	Keep production areas clean and dry. Disinfect equipment regularly. Use hygienic or pretreated substrates to lower initial microbial load. Ensure meal moisture content remains below 10% to inhibit growth. Apply heat treatment afterwards.
	Chemical Physical	None identified Aluminium foil particles	1	2	Low (2)	Avoid using aluminium foil to cover trays. Use food-safe materials like stainless steel trays that are easy to clean and do not shed particles. Prefer non-stick coated trays. Visually inspect foil before each cycle; if damaged, replace with suitable materials.

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Stage 11. Drying	Biological	Survivors of previously mentioned microorganisms	2	4	Medium (8)	Ensure previous steps reduce microbial load: use substrates free of spores, thoroughly clean larvae, maintain strict hygiene in processing areas to prevent cross-contamination, improve air quality in drying area with ventilation, and use additional treatments such as powdered natural antimicrobials, lactic or citric acid.
	Chemical	Traces of sodium aluminate and aluminium phosphate	3	2	Medium (6)	Perform strict visual inspection of tray-lining materials before each use to ensure no contamination or damage (e.g., flaking aluminium foil).
	Physical	Aluminium foil particles	2	2	Low (4)	Use non-stick coated trays instead of foil. Inspect trays to ensure no damage or loose materials that may shed during drying. Confirm trays and foil are in good condition (no tears or breaks). Perform a visual inspection before drying to remove any visible contaminants.
Stage 12. Grinding	Biological	Moulds and yeasts	1	2	Low (2)	Keep production areas clean and dry. Regularly disinfect equipment. Use hygienic or pretreated substrates to lower microbial load. Ensure final meal moisture is below 10% to inhibit growth. Apply heat treatment to eliminate microorganisms without affecting product quality. Use hermetic, moisture- and air-resistant packaging (e.g., modified atmosphere). Store in dry, cool, contamination-free areas.
	Chemical	None identified				
	Physical	Metal fragments and splinters	2	3	Medium (6)	Check the blender's container, blades, screw fittings, and base before each batch. Conduct maintenance of every fixed number of usage hours (e.g., every 20 hours or 30 batches). Replace blades according to the manufacturer's lifespan recommendations. Control grinding time and batch load to avoid motor strain and

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						excessive vibrations. Use fine sieves or filters after grinding to capture any metal particles.
Stage Packaging	13.Biological	Moulds and yeasts	1	2	Low (2)	Keep production areas clean and dry. Regularly disinfect equipment. Ensure the meal is dried to below 10% moisture. Use hermetic packaging that prevents moisture and air entry. Store product in dry, cool areas, free from cross-contamination.
	Chemical	Bisphenols	1	4	Low (4)	Ensure packaging materials are BPA-free and food-grade. Avoid contact with old, reused, or deteriorated plastics. Store BSF meal in cool, dry conditions.
	Physical	Foreign particles or metal fragments	1	3	Low (3)	Conduct regular product inspections for metallic contamination. Install a metal detector at the end of the packaging line if possible.
Stage 14. Storage	Biological	Microorganisms viable at freezing temperatures	1	3	Low (3)	Use high-precision sensors for continuous freezing temperature monitoring. Establish SOPs to prevent fluctuations. Conduct preventive maintenance on freezing equipment and ensure proper function.
	Chemical	None identified				
	Physical	None identified				

* Source: Authors. Hazards were identified through literature review and HACCP team expertise; some were confirmed via BSFLM sample analysis. References: [27–60].

Later stages of the process, including grinding, packaging, and storage, presented lower but still relevant risks. Potential hazards such as bisphenol migration from packaging materials and microbial viability during storage under freezing conditions were managed by using food-grade, BPA-free containers, hermetic sealing, reduction of moisture content below 10 percent, and continuous environmental monitoring. Across all processing steps, the integration of prerequisite programs, comprehensive staff training, and systematic hygiene and environmental controls supported a robust and reliable food safety system.

3.4. Identification of CCPs

The CCPs results revealed that while many hazards were effectively managed through existing preventive measures and PRPs, a limited number required formal CCP designation (Table 3). In the early stages of the process, particularly during larval reception and substrate sourcing, met the criteria to be CCPs. These findings underscore the importance of stringent supplier selection, substrate quality assurance, and routine laboratory testing at the point of raw material intake.

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Table 3. Decision tree analysis for Critical Control Point (CCP) identification in BSFLM production*.

Stage	Hazard Type	Hazard Description	Significance	Q1	Q2	Q3	Q4	Decision
1. Larvae reception	Biological	*Aspergillus spp.*	High	No	Yes	Yes	No	PRP
		Bacillus cereus	High	No	Yes	Yes	No	PRP
		Total coliforms	Medium	No	Yes	Yes	No	PRP
		Enterococcus	Medium	No	Yes	Yes	No	PRP
		E. coli – Shiga toxin	Medium	No	Yes	Yes	No	PRP
		E. coli	High	No	Yes	Yes	No	PRP
		Listeria monocytogenes	Medium	No	Yes	Yes	No	PRP
		Staphylococcus aureus	Medium	No	Yes	Yes	No	PRP
	Chemical	Mineral oil hydrocarbons, dioxins, PCBs, PAHs	Medium	Yes	—	—	—	PRP
		Heavy metals	Medium	No	Yes	No	Yes	CCP
		Mycotoxins	Medium	No	Yes	No	Yes	CCP
		Pesticides and insecticides	High	No	Yes	No	Yes	CCP
		Allergens (tropomyosin, arginine kinase, chymosin)	Medium	No	Yes	No	Yes	CCP
	Physical	Metal fragments/splinters	Medium	Yes	—	—	—	PRP
		Gravel, stones	Medium	Yes	—	—	—	PRP
		Plastic/microplastics	Medium	No	Yes	Yes	No	PRP
2. Sieving	Biological	Aerobic mesophiles	Medium	No	No	Yes	No	PRP
		Moulds and yeasts	Medium	No	Yes	Yes	No	PRP
		Aspergillus spp.	High	No	Yes	Yes	No	PRP
		Staphylococcus aureus	High	No	Yes	Yes	No	PRP
	Chemical	Pesticides	High	No	Yes	No	No	PRP
	Physical	Metal particles	Medium	Yes	—	—	—	PRP
5. Thawing	Biological	Aerobic mesophiles	Medium	Yes	—	—	—	PRP
6. Washing	Chemical	Heavy metals	Medium	Yes	—	—	—	PRP
8. Blanching	Biological	Microorganism survival	Medium	No	Yes	Yes	—	PRP
9. Blending	Biological	*Staphylococcus aureus*	Medium	No	Yes	Yes	No	PRP
		Salmonella spp.	High	No	Yes	Yes	No	PRP
11. Drying	Biological	Surviving microorganisms	Medium	No	Yes	No	Yes	CCP
	Chemical	Sodium aluminate/phosphate traces	Medium	Yes				PRP
14. Grinding	Physical	Metal fragments and splinters	Medium	Yes	—	—	—	PRP

*PRP = The hazard is controlled by a Prerequisite Program. Q1–Q4 refer to the decision tree questions applied to determine CCPs during HACCP.

Further along the process, drying stage was established as a CCP. Despite upstream measures to reduce microbial loads, the drying step represents the final and most critical barrier for microbial inactivation. To be effective, the process must consistently maintain validated time and temperature combinations (at least 60 °C for 21 hours) across all batches. This step is essential to control residual pathogens such as *Salmonella* spp., *Escherichia coli*, and *Staphylococcus aureus*, which may remain viable after rearing or blending.

Other hazards such as the presence of *Aspergillus* spp., aerobic mesophilic bacteria, metal splinters, or bisphenol residues were deemed sufficiently controlled through robust PRPs, equipment inspections, facility hygiene, and handling protocols.

3.5. Establishment of Critical Limits, Monitoring System, and Corrective Actions

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Table 4 presents the proposed critical limits for each identified CCP, as well as the monitoring system and corrective actions tailored to the capacities of small- and medium-scale BSFLM producers, based on CINAT's experience and HACCP team input.

Table 4. Critical limits, monitoring system, and corrective actions for BSFLM production.

Stage	Hazard Type	Critical limits		Monitoring			Corrective actions
		Min	Max	What	How	When	
Stage 1. Larvae reception	Heavy metals	Absence	0.50 (for crustaceans) Cd: 2 ppm Pb: 10 ppm Hg: 0.1 ppm	Concentrations of Pb, Cd, Hg, As in mg/kg	Send samples to a laboratory for detection tests	Random batches according to the sampling plan	Reject the affected batch and prevent its use or distribution. Notify the supplier immediately, conduct an audit, and re-evaluate the supplier to ensure compliance with quality and safety standards. Increase the stringency of quality sampling protocols for future batches.
	Mycotoxins	Absence	Aflatoxin: 0.02 ppm Ochratoxin A: 5 ppm	Mycotoxin analysis in substrates (HPLC or ELISA)			Reject the batch and confirm contamination with a secondary analysis. Determine whether the product can be reprocessed or must be destroyed. Investigate the root cause and update preventive measures in the HACCP plan.
	Pesticides and insecticides	Absence	0.01 mg/kg DDT: 0.2 mg/kg Glyphosate: 300 mg/kg Endosulfan: 0.1 mg/kg Chlorpyrifos: 0.05 mg/kg	Pesticide residue analysis (GC or HPLC)			Reject the batch, perform confirmatory testing, and decide on reprocessing or destruction. Identify contamination sources and strengthen control strategies in the HACCP plan.
	Allergens (Tropomyosin, Arginine kinase, and Chymosin)	Absence	Gluten: 20 ppm)	Allergen detection tests (ELISA)			If distributed, notify authorities and consider a product recall. Revalidate the allergen control program, evaluate labelling effectiveness, and apply fasting to larvae to reduce allergen levels. Improve the product recall system.

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Stage 11. Drying	Microorganisms identified in hazard analysis and surviving this process	60°C / 21 hours	63°C / 21 hours	Process temperature verification	Using a thermocouple installed in the drying oven, connected to monitoring software. Alarm system in place	Each batch	Segregate the batch, test for microbial load, and adjust drying parameters as needed. If the maximum temperature was exceeded, assess product quality. Calibrate thermal equipment to ensure process reliability.

Source: Authors and references [23,24,61–64].

3.6. Validation and Verification of HACCP System

Table 5 proposes potential validation strategies for small-scale insect processors to demonstrate that one or more control measures, when properly implemented, effectively control a specific hazard. Although validation was not conducted in the BioInsectonomy study, these recommendations aim to help artisanal or low-tech processors approach validated safety conditions and improve market access.

Table 5. Suggested validation strategies for CCPs and control measures in BSFLM production.

CCP	Hazard	Control measure	Critical parameters	Validation factors	Logistical considerations
Larvae reception	Heavy metals (Pb, Cd, Hg, As)	Use of regulated substrates and supplier control	Concentrations of Pb, Cd, Hg, As (mg/kg)	Substrate type; analysis frequency	Accredited laboratories; cost considerations
	Mycotoxins (Aflatoxins, Ochratoxin A)	Use of fungus-free substrates; visual inspection and frequent testing	Mycotoxin levels (µg/kg)	Substrate type; storage conditions	Environmental control; visual inspection
	Pesticides and insecticides	Supplier control; proper substrate selection	Residue levels (mg/kg)	Substrate type; agricultural history	Substrate history; supporting documentation
	Allergens	Staff training; proper cleaning between batches; labelling	Presence/absence or ppm level	Allergen types; cleaning effectiveness	Kit availability; staff training
Drying	Microbiological control through thermal processing (60°C for 21 h)	Pre-processing reduction of microbial load; larval cleaning; hygienic processing conditions; ventilation; use of natural antimicrobials and organic acids before drying	Log reduction of pathogens (e.g., Salmonella, E. coli)	Drying temperature/time; use of additional treatments	Temperature and humidity control; equipment availability; staff training

* This proposal assumes low-volume and/or intermittent production. It is recommended to use a completely randomized design for testing to ensure sample representativeness and statistical validity of the results.

Table 6 outlines the proposed verification system for the HACCP plan. Verification should be conducted by individuals not responsible for daily monitoring to ensure that all HACCP procedures

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are being followed. Strategies, frequency, and methods may vary by facility, and in some cases, a validation strategy may also serve as a verification method [11].

Table 6. Verification strategies for the implementation of the HACCP plan in BSFLM production.

Stage	Hazard	Type	What is verified	How	When	Responsible
Larvae reception	Chemical	Heavy metals	Presence/absence of heavy metals	Randomly select samples from different batches and send them to an accredited lab for testing. Conduct an internal audit programme to review the full HACCP system, including prerequisite programmes, staff training, food safety policies, and food safety culture.	Quarterly	Quality assistant
	Mycotoxins (Aflatoxins, Ochratoxin A)	Mycotoxins	Presence/absence of aflatoxins and ochratoxins	Substrate type; storage conditions	Monthly	Quality assistant
	Pesticides and insecticides	Pesticides and insecticides	Presence/absence of pesticide and insecticide residues	Substrate type; agricultural history	Quarterly	Quality assistant
	Allergens	Allergens (tropomyosin, arginine kinase, chymosin)	Presence/absence of specific allergens	Allergen types; cleaning effectiveness	Monthly	Quality assistant
Drying	Biological	Microorganisms (as identified in hazard analysis)	Proper functioning of the drying oven to eliminate microbial hazards	Drying temperature/time; use of additional treatments	Weekly	Quality assistant and laboratory

3.8. Required Documentation for HACCP Implementation

Proposed documents must demonstrate proper implementation of the HACCP plan, enable process traceability, facilitates regulatory audits and allow timely consultation of CCPs and critical parameters. It should also support verification and validation activities. The recommended records include: (1) operational records generated during the HACCP system's operation; (2) a summary of the hazard analysis, including justifications for hazard identification and control measures; (3) the complete HACCP plan covering the 12 implementation steps; (4) all documents related to the validation of the HACCP plan; and (5) records of internal audits, corrective actions taken, and continuous improvement processes applied to each step.

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4. Discussion

4.1. Product Technical Specification

The proximate composition of BSFLM (Table 1) revealed a slightly lower protein content than previously reported [64], while the lipid content exceeded the values documented by other authors [4,65]. Microbiological analyses confirmed an acceptable profile for animal feed use, except for aerobic mesophiles, which reached 15,000 CFU/g, above the threshold suggested by IPIFF <10,000 CFU/g [12,66]. This may be due to specific handling or processing conditions in the laboratory and can be effectively managed by strengthening hygiene practices, staff training, and prerequisite programs. Similar microbial results have been reported by other authors [67] which indicates that it is possible to achieve acceptable microbiological results with the thermal process applied to BSFLM.

4.2. Interpretation of the Results of the Hazard Analysis

The main hazards were concentrated in the first two processing stages, larvae reception and sieving (Table 2), due to the use of agro-industrial residues as substrates, which often contain various contaminants and are difficult to trace. These initial stages have been identified as critical control points for biological risks, as larvae typically retain microbial loads from the substrate environment in which they develop [33,41,46,47]. Certain studies have reported the presence of pathogenic bacteria and fungi during these phases, highlighting the importance of substrate monitoring and early intervention [48,57]. However, other research has shown that the larvae's natural bioconversion activity may contribute to reducing microbial contamination during rearing. Some studies observed a decrease in microbial load associated with larval digestion, although this is not sufficient for complete decontamination [28,33]. The effect is more consistent when pretreated or heat-processed substrates are used, improving microbial safety outcomes [58,68].

Preventive measures should include strengthening supplier control programs and ensuring infrastructure that protects the product from cross contamination while allowing hygienic handling from larval manipulation to final processing. On the other hand, allergens classified as chemical hazards from larvae or some from substrates can be controlled by treating the substrate, fasting the larvae and reporting their presence on the product label. During the BioInsectonomy project, the CINAT laboratory implemented more than 50% of the prerequisite programs and was undergoing structural improvements. This context led to a long list of potential hazards that could likely be avoided in better equipped facilities with developed GMP systems.

It is therefore recommended that insect producers implement robust supplier control programs and formulate diets using pretreated substrates, such as fermented or heat-treated materials, to ensure safety prior to larval consumption. Fermentation may help reduce microbial loads and improve digestibility [69]. In addition, the sieving stage, often performed outdoors and without controls in small scale systems, should ideally be conducted in enclosed, controlled environments to prevent contamination during handling and exposure.

In this study, a final sieving step was not applied after grinding, as the fine powder texture obtained using the high-speed blender made it unnecessary. The HACCP team determined that under these specific conditions, using a high-performance new device, the risk of metal fragments was minimal. Nonetheless, it is advisable to include this step in other settings to reduce physical hazards such as metal particles from grinders or residual substrate contaminants, as noted in previous studies [70].

In all cases, it is essential that insect meal producers apply HACCP methodology to assess whether a hazard is likely to occur depending on the specific conditions of their production system. As previously mentioned, the HACCP team identified the main CCPs (Table 3) under these conditions in the larval reception and production stages (mainly for chemical hazards such as heavy metals, mycotoxins, pesticides, and allergens), and in the drying stage (for the control of biological hazards). Applying adequate controls at these points ensures that BSFLM complies with safety

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standards for animal feed. Other hazards can be controlled or reduced to acceptable levels through the implementation of the preventive measures proposed at each step (Table 2).

The minimum and maximum limits for control variables (Table 4) were defined based on routine sample analysis for chemical hazards and temperature monitoring for biological hazards. Although this type of control may be difficult to implement for small-scale or subsistence producers due to cost limitations, robust GMPs remain essential to reduce risk and manage most hazards effectively. During the validation phase, HACCP guidelines recommend evaluating the adequacy of CCPs, critical limits, and monitoring procedures to ensure pathogen reduction [71]. This validation may rely on scientific evidence, expert judgment, pilot-scale trials, or lab simulations, followed by internal data collection [17,18]. In this study, the HACCP team proposed strategies such as the use of regulated, fungus-free, or pretreated substrates, supplier control, and staff training to reduce biological risks in the early stages of production. These measures require a proper sampling plan and experimental design, ideally a completely randomized setup, to confirm hazard control effectiveness with statistical confidence exceeding 95%.

4.3. Effectiveness of the HACCP System and Challenges in Implementation

The implementation of control measures at CCPs, such as time and temperature monitoring during drying, proved effective in reducing biological hazards, as confirmed by microbiological results. However, the process also revealed operational challenges and the need to strengthen other control measures that remained insufficient. For instance, substrate variability and environmental conditions affected the reliability of control during the reception stage, where hazard probability remained high.

Studies on BSFL production and derivatives have shown that consistency in substrate composition and controlled environmental conditions significantly improve product quality. Nutrient balance, particle size, and substrate texture also play a key role in larval nutrition and contribute to a differentiated nutritional profile in the final product [72].

The establishment of control measures and CCPs through HACCP offers a solid technical basis to support regulation and the safe trade of insect derived products [13]. Implementing HACCP in small and medium scale BSFL production can help define quality and safety standards that facilitate exports, open access to international markets, and improve producer competitiveness. These findings may also inform national regulatory frameworks and help simplify HACCP adoption and food safety oversight for insect-based products.

It is essential to implement training and monitoring programs to ensure HACCP effectiveness and compliance with international regulations [10]. A continuous review of the literature will help identify the best practices and tailor risk management strategies to local production systems. Further research should address emerging risks such as antimicrobial resistance and toxin accumulation and explore methods to improve the accuracy and specificity of HACCP systems. Enhancing hazard classification and control can support the production of high-quality insect meals that meet strict safety requirements [28].

5. Conclusions

The implementation of the HACCP system for BSFL meal production enabled a systematic hazard assessment, the definition of CCPs, and the establishment of monitoring systems and critical limits suitable for the CINAT context. However, it also revealed the challenges of applying this system rigorously in small scale settings, where limited resources may hinder adequate control at each stage. This experience showed that most local producers will need to redesign their prerequisite programs to achieve effective hazard prevention.

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Abbreviations

The following abbreviations are used in this manuscript:

BSFLM	Black soldier fly larvae meal
HACCP	Hazard Analysis and Critical Control Points
CCP	critical control points
FSIS	Food Safety and Inspection Service
PPR	Prerequisite Program
EFSA	European Food Safety Authority
CINAT	Centre for Terrestrial Arthropod Research (Spanish acronym)
IPIFF	International Platform of Insects for Food and Feed
GMPAF	Good Manufacturing Practices for Animal Feed
BPM	Good Manufacturing Practices

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