EFFICIENT ORGANIC WASTE MANAGEMENT: COMPOSTING ANIMAL WASTE USING BLACK SOLDIER FLY LARVAE (*HERMETIA ILLUCENS* DIPTERA: STRATIOMYIDAE)

BY

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CERTIFICATION

This is to certify that this work was carried out by **Jane Itohan, OTABOR Mat. No. PG/SPE1512498,** of the Department of Environmental Standards, Faculty of SPESSE, University of Benin, Benin City, Edo State Nigeria.

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DEDICATION

To God who gave me the strength to complete this program and to myself for putting in the work.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Throughout history, human societies have always produced waste. However, modern urbanization, population growth, and industrialization have significantly increased global waste generation, creating challenges in waste management. Factors such as large-scale agriculture and shifting consumption patterns further contribute to this problem (Sharma *et al.*, 2018). Waste refers to any discarded or unusable material, including municipal solid waste, industrial byproducts, agricultural residues, construction debris, hazardous substances, medical waste, and electronic waste (Kumawat *et al.*, 2024).

Annually, approximately 2.01 billion tonnes of municipal solid waste are produced worldwide, with at least 33% being improperly managed, posing environmental risks (Valavanidis, 2023). Per capita waste generation averages 0.74 kg per day, but this varies significantly across regions, ranging from 0.11 kg to 4.54 kg (Kaza *et al.*, 2018). Despite comprising only 16% of the global population, high-income countries contribute 34% (683 million tonnes) of the world's waste. If current trends continue, global waste could reach 3.40 billion tonnes by 2050 (Kaza *et al.*, 2018). Regionally, East Asia and the Pacific account for the largest share (23%) of global waste, while the Middle East and North Africa produce the least (6%).

However, waste generation is increasing most rapidly in Sub-Saharan Africa, South Asia, and the Middle East and North Africa, driven by urbanization and population growth (Khan *et al.*, 2023). In Sub-Saharan Africa, 174 million tonnes of waste are generated each year, with organic waste making up over 50%. By 2050, the region's waste output is expected to triple. Nigeria, for example, produces 0.51 kg of waste per person daily. Waste disposal methods also vary by income level: in low-income countries, 93% of waste is either burned or dumped in open areas, roads, or waterways, compared to just 2% in high-income countries. Open dumping is particularly prevalent in South Asia and Sub-Saharan Africa, where more than two-thirds of waste is improperly discarded, exacerbating future waste management challenges (Kaza *et al.*, 2018).

Agriculture plays a vital role in the global economy, contributing substantially to the gross domestic product (GDP). According to the Food and Agriculture Organization (FAO, 2021), the sector's economic value grew at an average annual rate of 2.8%, rising from USD 2.9 trillion in 2012 to USD 3.7 trillion in 2021. This expansion has led to a surge in agricultural waste generation, which now exceeds municipal solid waste by more than fourfold (Kaza *et al.*, 2018). Countries with large-scale farming operations produce the most agricultural waste, which is often treated as a distinct waste stream due to its organic composition and potential reuse in farming. Agricultural waste primarily consists of animal manure, crop residues, and silage effluent. While these materials can be repurposed for energy production and industrial applications, improper handling poses significant environmental risks (Maji *et al.*, 2020).

The global rise in organic waste generation poses significant risks to human health, biodiversity, and ecosystems. Improper disposal leads to water, air, and soil pollution while facilitating pathogen transmission (Wynants *et al.*, 2019; Kawasaki *et al.*, 2020; Tanga *et al.*, 2021). Additionally, organic waste decomposition in landfills releases methane, a potent greenhouse gas. Current waste management practices such as landfilling, composting, and incineration, present limitations, including land-use inefficiency, pathogen proliferation, odor emissions, and slow decomposition rates (Chun *et al.*, 2019; Kinasih *et al.*, 2020; Kim *et al.*, 2021).

In many developing countries, traditional waste management methods like landfilling, composting, and incineration are still common. However, poor funding for waste collection, sorting, and processing limits effective handling of increasing organic waste (Kinasih *et al.*, 2020). To tackle this issue, more sustainable and efficient approaches are necessary. Certain natural microorganisms can break down organic waste into valuable nutrients like nitrogen, phosphorus, and potassium, which benefit plants. One example is vermicomposting, which uses worms to decompose waste (Sarpong *et al.* 2019). Despite its potential, vermicomposting is not widely adopted in low- and middle-income countries. This process relies on the combined action of earthworms and microorganisms under controlled conditions (Sarpong *et al.* 2019).

Another promising solution is the use of black soldier fly (*Hermetia illucens*) larvae (BSFL) for organic waste decomposition. BSF, a tropical and temperate species (Singh and Kumari, 2019), has gained attention for its cost-effectiveness and environmental benefits (Kim *et al.*, 2021). The black soldier fly is a wasp like fly distributed over the tropical and temperate regions of the world (Sarpong *et al.* 2018). The insect is native to America but through human-mediated dispersal, now they are found almost all over the world (Sarpong *et al.* 2018).

Black soldier fly larvae compost offers an eco-friendly method to transform organic waste into nutrient-rich fertilizer suitable for urban agriculture. This compost is packed with key plant nutrients such as nitrogen, phosphorus, and potassium, enhancing soil health and crop productivity (Mulyanti *et al.*, 2025). With rising costs and limited access to organic fertilizers in both rural and urban settings, BSF larvae-based compost serves as a cost-effective solution. By converting organic waste into fertilizer, BSF larvae reduce reliance on synthetic fertilizers, support sustainable farming practices, and boost food production in space-constrained urban environments (Liu *et al.*, 2021; Zheng, 2021).

Studies show BSFL can efficiently process various organic wastes, including food scraps, agricultural residues, and even human feces (Lalander *et al.*, 2019). Research confirms

BSFL's effectiveness in waste bioconversion (Kinasih *et al.*, 2018; Shumo *et al.*, 2019a, 2019b), though standardized application guidelines are still lacking. For instance, Ibadurrohman *et al.* (2020) found that BSFL can degrade up to 75% of organic waste, converting 4 kg of waste into 800 g of nutrient-rich biomass. While past reviews have examined BSF's role in waste treatment (da Silva and Hesselberg, 2020; Surendra *et al.*, 2020), further research is needed to optimize its use. The uniqueness of black soldier fly is their ability to successfully colonize a wide variety of resources such as swine manure and animal remains (Sarpong *et al.* 2019).

1.2 Statement of the Problem

The global increase in livestock production, driven by rising human population and food demand, has led to significant accumulation of organic animal waste. Poor management of these wastes contributes to severe environmental issues, including soil and water pollution, greenhouse gas emissions, and disease transmission. In Nigeria, common disposal methods such as open dumping, untreated land application, and direct discharge into water bodies, pose serious ecological and public health risks.

Several factors exacerbate waste mismanagement in Nigerian livestock farms, including inadequate infrastructure, lack of technical expertise, weak policy enforcement, and low awareness. Abattoirs also generate large quantities of organic waste, which is often improperly discarded, contaminating surrounding land and water sources (Akanni *et al.*, 2019). These wastes contain harmful pathogens, organic pollutants, and foul-smelling compounds, leading to water degradation and waterborne diseases. Waterborne diseases cause over 33.4 million deaths annually. Nutrient-rich waste runoff also contributes to eutrophication, threatening aquatic ecosystems.

Conventional composting, while useful, has limitations: it is space-intensive, labor-demanding, and emits greenhouse gases like methane. It also struggles to process high-moisture wastes (e.g., poultry and swine manure) and fails to fully eliminate pathogens. Thus, a more sustainable and efficient waste management approach is needed.

The BSFL offers a promising solution by rapidly converting organic waste into high-protein biomass (for animal feed) and nutrient-rich frass (for fertilizer). However, despite growing interest, key knowledge gaps remain regarding optimal waste substrates, scalability, and environmental conditions for efficient bioconversion.

1.3 Aim and Objectives

The aim of the study is to evaluate the efficiency of black soldier fly larvae in composting organic wastes.

The specific objectives are to:

i. Investigate the rate at which black soldier fly larvae breaks down animal waste and reduces its volume.
ii. Evaluate the impact of different waste types and their nutrient (proximate) and mineral composition on black soldier fly larvae growth rate.
iii. Evaluate the mineral (NPK) composition and suitability of the compost for agricultural application.

1.4 Scope of the Study

Experiments was carried out in a controlled laboratory setting, and replicated trials was set up for each type of waste to account for variability. This study focused on evaluating the efficiency of BSFL in composting animal waste as a strategy for sustainable organic waste management. The waste used were commonly generated animal wastes, particularly abattoir waste, poultry, pig, and cattle manure, which are known for their high organic load and environmental impact when improperly managed. These substrates were analyzed for their suitability as feedstock for BSF larvae. Also, the study assessed the growth rate, survival rate, biomass yield, and waste reduction efficiency of BSFL when reared on different types of animal wastes. Larval development stages will also be monitored under controlled conditions. Both the input (raw manure) and output (frass) was analyzed for key physicochemical parameters including moisture content, C:N ratio, total nitrogen, organic carbon, phosphorus, potassium, electrical conductivity and pH. This will help evaluate the compost quality and its potential use as a soil amendment. Furthermore, the study explore how BSFL-based composting contributes the promotion of circular economy, and food/feed security. However, the study is limited to organic waste streams derived from animal husbandry operation and does not address broader categories of organic waste such as food waste or crop residues, although findings may have implications for these areas. Also, socio-economic feasibility, policy integration, and full-scale implementation models are outside the direct scope but may be briefly discussed in the recommendations.

1.5 Justification of the study

Poor organic waste management in Nigeria has resulted in severe environmental issues, including pollution, greenhouse gas emissions, foul odors, and the spread of disease vectors. Conventional composting, though often promoted as a low-cost solution, has significant drawbacks in Nigeria: it is slow, land-intensive, difficult to scale, and yields only compost. Traditional methods also fail to produce other valuable byproducts that could help address Nigeria’s pressing needs for protein-rich animal feed, renewable energy, and sustainable agriculture.

In recent years, insect-based waste management has gained global attention as an innovative alternative. Among various species, the black soldier fly (BSF) larvae (BSFL) stand out for their efficiency in breaking down diverse organic wastes, including livestock manure, food waste, agricultural residues, and industrial byproducts (Beskin *et al.*, 2018; Lalander *et al.*, 2019; Gold *et al.*, 2020; Raksasat *et al.*, 2021). Unlike traditional composting, BSFL processing generates multiple high-value outputs, making it a more economically viable and sustainable approach.

Research confirms that BSFL play a crucial role in organic waste reduction (Czekała *et al.*, 2020; Purkayastha and Sarkar, 2021) while converting waste into commercially useful products (Adebayo *et al.*, 2021). The larvae produce nutrient-dense biomass rich in protein and fats (Kinasih *et al.*, 2020), which can replace conventional animal feed ingredients like soybean meal and fishmeal (Surendra *et al.*, 2020). This substitution helps conserve food crops for human consumption, enhancing food security. BSFL also contain bioactive compounds that may improve livestock health and reduce antibiotic dependency.

Beyond feed production, BSFL-derived fats can be processed into biodiesel, offering a sustainable energy source which is an urgent need in Nigeria. The residual frass (larval excrement) serves as an organic fertilizer, improving soil fertility. Thus, BSFL bioconversion provides a circular economy solution, addressing waste management, food security, renewable energy, and sustainable agriculture simultaneously. Given Nigeria's increasing waste generation, protein shortages, and energy challenges, BSFL technology presents a superior alternative to conventional composting. This study explores its potential in Nigeria, highlighting its capacity to deliver environmental, economic, and social benefits through integrated waste valorization.

CHAPTER TWO

LITERATURE REVIEW

2.1 Food Waste Bioconversion

Food waste constitutes a major portion of globally generated organic waste, with its production escalating rapidly due to rising living standards and population growth (Kim *et al.*, 2021). This surge in food demand has led to increased waste generation, creating socio-economic challenges (Kim *et al.*, 2021). Addressing the growing need for food, feed, and fuel while managing organic waste has become a critical global issue (Gold *et al.*, 2018; Kumar *et al.*, 2018). With the global population projected to reach 9.7 billion by 2050, this problem is expected to worsen (Duarte *et al.*, 2021).

The Food and Agriculture Organization (FAO) defines food waste as discarded food, primarily occurring during retail and consumption (Liu *et al.*, 2020). Annually, over 2.1 billion tonnes of municipal solid waste are generated worldwide, with food waste accounting for 45% of this total. However, only about 16% is recycled, while more than 46% is lost (Deus *et al.*, 2019). The increasing imbalance in global food systems due to food waste poses risks to human health, biodiversity, and ecosystems, particularly when hazardous waste is involved (Djekic *et al.*, 2019). The environmental and economic consequences are substantial, with roughly one-third of food production—equivalent to 1.3 billion tonnes—being wasted annually, contributing to greenhouse gas (GHG) emissions and economic losses (Kumar *et al.*, 2018). Without considering land use changes, food-related GHG emissions are estimated at 33 billion tonnes of CO_2 annually (Kumar *et al.*, 2018). The economic value of this wasted food reaches up to $7.5 billion (Li and Shimizu, 2021).

Organic waste management remains a pressing issue, particularly in developing and underdeveloped nations. Over the next 25 years, food waste is expected to increase significantly, driven by economic and population growth in Asian countries. For instance, between 2005 and 2025, food waste in Asia could rise from 278 to 416 million tonnes (Kim *et al.*, 2021).

Managing food waste is complicated by its high biodegradability (Singh and Kumari, 2019). The environmental impact of large-scale food waste generation has drawn significant attention (Somroo *et al.*, 2019). Additionally, food waste contains high levels of water-insoluble components like proteins, fats, and carbohydrates, increasing its potential as an environmental hazard (Kim *et al.*, 2021). These components also promote putrefaction, fostering microbial growth and foul odors (Chen *et al.*, 2020). Current disposal methods include landfilling, incineration, and anaerobic digestion, but more sustainable solutions are needed (Prateep Na Talang and Sirivithayapakorn, 2021).

2.2 Challenges of Current Organic Waste Management

Managing the increasing global demand for food, feed, and fuel while addressing substantial organic waste accumulation poses a critical challenge. Organic waste, characterized by its perishability, low energy content, and high organic composition, presents difficulties for conventional disposal methods like sanitary landfilling or incineration. Decomposition of organic waste in landfills generates landfill gases, primarily composed of 50% methane (CH_4), 50% carbon dioxide (CO_2), and trace non-methane organic compounds (Coskuner *et al.*, 2020; US EPA, 2021). Methane, a potent greenhouse gas (GHG), has a global warming potential 28–36 times greater than CO_2 (US EPA, 2021; Valta *et al.*, 2019). Additionally, landfill emissions contribute to air pollution, smog formation, and respiratory health issues such as asthma (Ali *et al.*, 2021). The high biodegradability of organic waste further complicates its management (Nanda and Berruti, 2021).

Current organic waste management approaches including landfilling, anaerobic digestion, and composting, meet regulatory standards but entail high costs and negative environmental impacts, such as GHG emissions, water contamination, and public health risks (de Titto and Savino, 2019; Singh *et al.*, 2020). Meanwhile, rising global population and consumption levels are intensifying demand for food, feed, and fuel, exacerbating waste generation. Without sustainable solutions, these trends may worsen environmental crises. Thus, developing circular economy strategies for organic waste valorization is essential to align with zero-waste principles in the future.

2.3 Black Soldier Fly

The black soldier fly, *Hermetia illucens* (Linnaeus), is a widespread Stratiomyidae species. They originated from the Neotropical region, and is now found globally (da Silva and Hesselberg, 2020). Adult flies lack stingers, mouthparts, and digestive organs, preventing them from biting or consuming waste. They measure about 7/8 inches long, with females having reddish abdomens and males displaying bronze coloration. Their legs are black with pale yellow forelegs, and their long, straight black antennae lack an arista. These flies mate mid-flight, and females lay around 500 eggs. The resulting larvae and prepupae, roughly ½-inch long, serve as fish feed or dietary supplements. Unlike other flies, *H. illucens* avoids human dwellings and does not feed on humans, lowering disease risks. Their presence in organic waste also deters other fly species (Liu *et al.*, 2019). Due to their rapid life cycle and efficient consumption, black soldier fly larvae (BSFL) are ideal for mass production. Effective management ensures cost-efficient, high-yield cultivation.

2.3.1 Morphological and Biological Characteristics of Black Soldier Fly

Hermetia illucens was first documented by Linnaeus in 1738 and is primarily found in the Americas between 45°N and 40°S. In China, it has been reported in multiple regions, including Beijing, Tianjin, Henan, Hebei, Shandong, Fujian, Sichuan, Yunnan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Taiwan, and Hong Kong. The species undergoes four life stages: egg, larva, pupa, and adult. In natural settings, females deposit eggs in dry locations adjacent to moist, decaying organic matter. Key environmental factors influencing adult mating and oviposition include temperature, humidity, and light intensity. Egg incubation typically lasts 4–14 days, varying by season, location, and temperature. The larval stage consists of six instars, with sizes ranging from 1.8 mm to 20 mm, the latter being considered mature. Larvae begin feeding immediately after hatching, with consumption rates rising significantly after the third instar. Upon reaching the sixth instar, they stop feeding and enter pupation before emerging as adults. Adult females start laying eggs 2–3 days post-mating, with a potential fecundity of up to 900 eggs per female. The nutritional composition and growth performance of *H. illucens* depend on the substrate, with protein- and lipid-rich diets enhancing protein and fat accumulation (Barragan-Fonseca *et al.*, 2018; Belghit *et al.*, 2018).

2.4 Life Cycle of Black Soldier Fly

The black soldier fly (BSF), *Hermetia illucens*, is a Diptera species belonging to the Stratiomyidae family and serves as an efficient biological waste recycler (da Silva and Hesselberg, 2020). Though native to tropical, subtropical, and northern regions of the Americas, BSF now inhabits tropical and temperate zones worldwide. Adults are weak fliers, primarily resting on vegetation, and survive solely on water for about two weeks. Unlike other flies, BSF adults lack stingers, mouthparts, and digestive organs, preventing them from biting or feeding. They measure 15–20 mm, with males exhibiting a bronze abdomen and females a reddish-brown coloration (Kumar *et al.*, 2018). Females mate and lay eggs only once in their lifetime. As a eurygamous species, BSF mates mid-flight, requiring ample space for nuptial flights (Surendra *et al.*, 2020).

Males emerge two days before females, with mating occurring two days post-emergence. Females deposit eggs in dry crevices near larval food sources, and the eggs hatch into neonate larvae within four days. The larvae thrive on organic waste such as manure, food scraps, municipal refuse, and decaying plant matter. At maturity, larvae can reach 27 mm in length, 6 mm in width, and weigh up to 220 mg (Amrul *et al.*, 2022). In the prepupal stage, larvae cease feeding, evacuate their digestive tracts, and migrate to dry areas for pupation—a "self-harvesting" trait that simplifies farming. Mature larvae contain 36–48% protein and 33% fat, developing into adults in approximately 14 days. Figure 2.1 illustrates the BSF life cycle, averaging 40–43 days in tropical climates (Amrul *et al.*, 2022). However, under suboptimal conditions, such as limited food, the cycle may extend to four months. BSFL consume organic waste voraciously until pupation, after which stored fats sustain adult mating and reproduction.

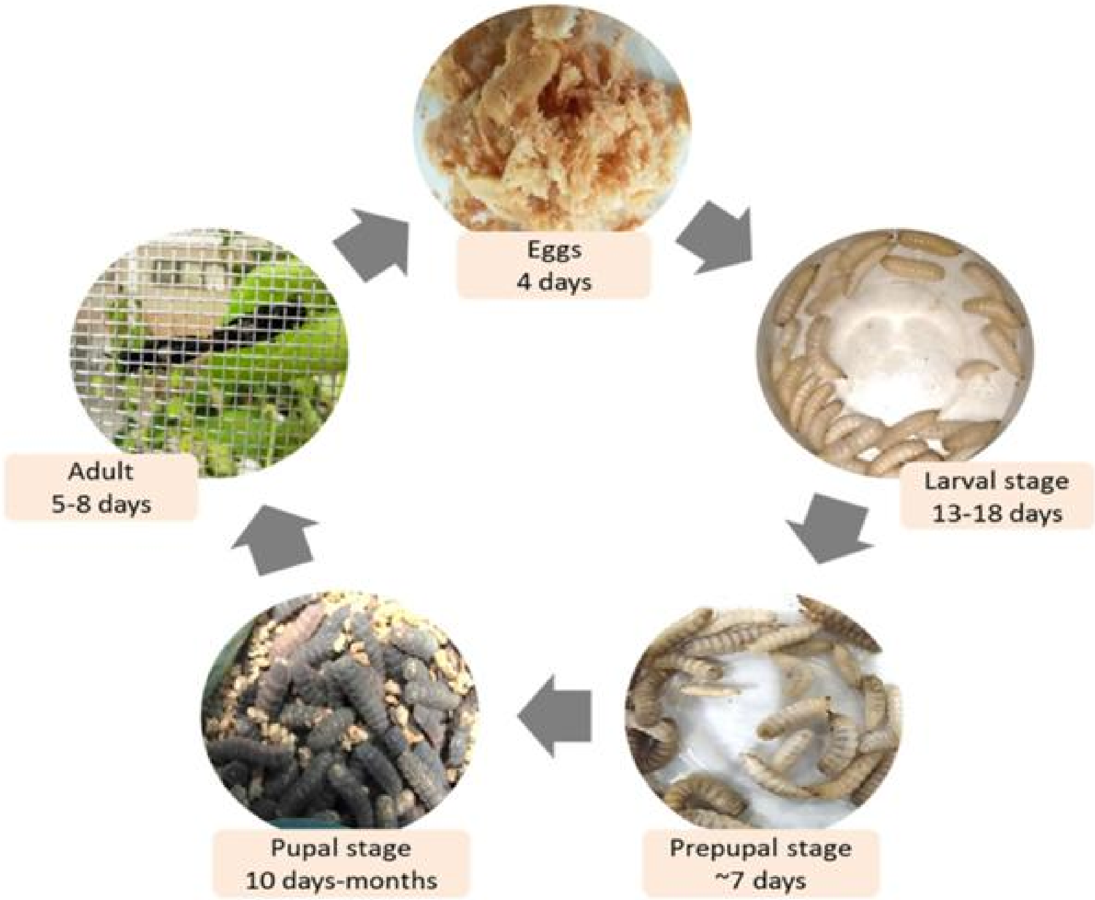

Figure 2.1. The life cycle of the black soldier fly**, *Hermetia illucens*** (Amrul *et al.*, 2022).

2.4 Environmental Factors Influencing Optimal Growth of BSF

2.4.1 Effect of Moisture Content

The conventional approach to organic waste (OW) conversion using black soldier fly (BSF) larvae involves direct feeding without moisture regulation (Amrul *et al.*, 2022). While this method is simple and efficient, it can complicate the separation of insect biomass from the residue due to excessive wetness and compaction, hindering sieving. Substrate moisture content significantly impacts BSF larval growth and survival, making moisture control essential (Laksanawimol *et al.*, 2024). Maximum prepupal growth was observed at 85% moisture in faecal sludge.

2.4.2 Effect of Temperature

Temperature critically influences BSF development, with controlled conditions enhancing growth and survival. Elevated temperatures can hinder larval development (Shumo *et al.*, 2019a). Some researchers reported optimal prepupal weight at 36°C, and adult emergence within 10–14 days at 27–30°C, and highest larval-to-adult survival rates within this range (Singh *et al.*, 2022).

2.4.3 Effect of pH

Waste substrates exhibit varying pH levels, with FW typically more acidic than animal manure (Naser El Deen *et al.*, 2023). System pH affects acid-producing bacterial activity, making it a key factor in arthropod growth (Ravi *et al.*, 2020). Many waste management studies regulate initial pH. Ma *et al.* (2018) investigated substrate pH effects on BSF, noting significant weight gain at pH 6.0, 7.0, and 10.0, while growth ceased below pH 1.8 and was minimal at pH 2.0 and 4.0.

2.5 The Benefits of Using BSFL for Biowaste Conversion

Insufficient management of organic waste leads to environmental pollution in both water and air while failing to generate useful by-products like protein, oil, or insect frass (larval excreta). As a result, insect-based organic waste management has emerged as a promising solution, attracting significant interest in recent years (Ayompe *et al.*, 2025). Among the most researched insects for waste conversion are mealworms, common houseflies, and black soldier flies (BSF), which also serve as alternative protein sources for animal feed (van Huis *et al.*, 2020). The larvae of these insects, especially black soldier fly larvae (BSFL), consume large quantities of decomposing organic material, making them effective in reducing various waste streams. These include livestock manure (from chickens, cows, pigs, etc.), human waste, poultry processing waste, food waste, fruit and vegetable scraps, and palm oil by-products (Palm Kernel Expeller) (Beskin *et al.*, 2018; Lalander *et al.*, 2019; Gold *et al.*, 2020; Raksasat *et al.*, 2021).

BSFL have garnered more attention than other fly species for organic waste processing due to their potential to address global challenges such as inadequate waste management, urban unemployment, and the rising need for sustainable animal feed (Dortmans *et al.*, 2021). From an environmental and operational standpoint, BSFL offer rapid waste reduction, a low carbon footprint, efficient feed-to-biomass conversion, and reduced pathogen and pest populations, all while avoiding disease transmission. They provide a cost-effective way to produce valuable materials with minimal water and land requirements compared to other protein sources. Beskin *et al.* (2018) also found that BSFL can decrease odorous compounds in poultry, swine, and dairy manure by over 87%, making them an eco-friendly alternative to conventional manure management.

These advantages position BSF as an effective technology for transforming organic waste into high-value products. As noted by Bortolini *et al.* (2020), the BSF system aligns well with circular economy principles by profitably converting waste into larval biomass and leaving no residual waste, as the frass can be recycled as a nutrient-rich soil amendment.

2.5.1 Efficient Conversion Capacity and Quality Output

Black soldier fly larvae (BSFL) demonstrate superior efficiency in organic waste bioconversion compared to traditional composting, achieving faster waste reduction and yielding high-quality agricultural byproducts under optimal conditions (27–30°C, 70–85% humidity, shade, and sufficient feed supply) (Dortmans *et al.*, 2021). Key performance indicators, such as waste reduction and bioconversion rate, assess BSFL treatment effectiveness (Lalander *et al.*, 2019; Gold *et al.*, 2020). Waste reduction is calculated on a dry mass basis as the difference between supplied feed and residue, divided by the initial feed quantity. The bioconversion rate, also in dry mass, is determined by dividing larval weight gain (final minus initial weight) by the total feed provided (Gold *et al.*, 2020).

Several factors influence bioconversion efficiency, including substrate composition (digestible nutrients, pH, moisture) and feeding rates. Larval density and feeding regimen (type, quantity, frequency, and nutritional content) also significantly impact waste conversion (Dortmans *et al.*, 2021). Optimal substrate moisture for BSFL ranges between 70–80%, with a lower threshold of 40–55% (Ermolaev *et al.*, 2019; Bortolini *et al.*, 2020; Dortmans *et al.*, 2021). High digestible carbon and protein content further enhance biomass yield (Lalander *et al.*, 2019; Dortmans *et al.*, 2021). Gold *et al.* (2020) note that substrate nutrient composition (protein, non-fiber carbohydrates, fiber, lipids, protein-to-carbohydrate ratio, and caloric content) affects both waste treatment efficiency and larval biomass production.

BSFL can reduce organic waste by up to 84.8%, with a waste-to-biomass conversion rate of 27.9%. Compared to poultry feed, BSFL performs similarly on municipal waste, food waste-1, and feed formulations F4 and F8, while excelling with human feces-1, F3, and F10 (73.0–84.8% reduction). Other substrates, such as human feces-2, vegetable waste, and formulations F5 and F7, yield comparable results to poultry feed, whereas food waste-2 and formulations F4 and F8 show higher efficiency. Notably, F4 and F8, with elevated lipid (19.0–22.3%) and reduced fiber (38.5–39.8%) content, enhance bioconversion rates and waste reduction (Gold *et al.*, 2020).

Blending different waste streams improves bioconversion performance by compensating for individual substrate limitations (Ermolaev *et al.*, 2019). Mixed waste increases larval survival (97–100%) compared to single substrates (Gold *et al.*, 2020). However, maintaining optimal macronutrient balance in mixed waste remains operationally challenging.

BSFL can reduce poultry manure accumulation by up to 60%, with a 52% substrate reduction and 28% bioconversion rate (dry basis) over 14 days (Ermolaev *et al.*, 2019). Despite its waste reduction potential, BSFL is primarily used for feed rather than human consumption due to food safety concerns. Beyond larval frass (a soil enhancer), BSFL processing yields chitin, a versatile biomaterial used in surgical sutures, edible films, and chitosan production (Nagdalian *et al.*, 2018; Surendra *et al.*, 2020). BSFL also exhibit antibacterial properties, suppressing pathogenic bacteria (Awasthi *et al.*, 2020).

2.5.2 Not Vectors of Disease

Black soldier flies (BSF) are less likely to pose significant health risks compared to other fly species, such as house flies, which are known to spread pathogens (Dortmans *et al.*, 2021). Unlike house flies, adult BSF have non-functional mouthparts, a short lifespan, and rely on energy reserves from their larval stage rather than feeding (van Huis *et al.*, 2020). They do not approach human food or living areas, and there is no evidence linking them to disease transmission. Their larval fat storage reduces the need for adult feeding, minimizing any potential disease spread. In contrast, house flies, which thrive near organic waste, are common disease vectors and are often targeted in pest control programs. Regulatory frameworks may therefore favor BSF over house flies, especially when using manure or feces as BSF larval feed (van Huis *et al.*, 2020).

2.5.3 Low-Carbon Footprint Production

Biowaste, including household kitchen waste, food waste, market and park waste, and food processing residues, constitutes up to 70% of waste in low- and middle-income regions, often ending up in landfills or wastewater. These disposal methods contribute roughly 90% of global waste sector emissions (Mertenat *et al.*, 2019). Decomposition in landfills releases greenhouse gases (GHGs) such as methane (CH_4), ammonia (NH_3), and nitrous oxide (N_2O), posing significant environmental and climate risks. Diverting this biowaste to feed black soldier fly larvae (BSFL) in mass production avoids landfill use while also reducing the environmental cost of producing equivalent raw materials like BSF protein meal and oils, thereby enhancing sustainability.

A study in Indonesia found that BSFL-based waste treatment emits fewer hazardous gases (CO_2, CH_4, N_2O) and consumes less energy (electricity and diesel) than open windrow composting (Mertenat *et al.*, 2019). Awasthi *et al.* (2020) also found that BSFL performance correlates positively with temperature, pH, C/N ratio, gas emissions, and microbial activity.

BSFL bioconversion has a lower Global Warming Potential (GWP) than soybean meal protein or rapeseed lipids. Replacing nitrogen fertilizer with larval frass compost and substituting soybean meal with BSF protein (dried larvae or meal) could further reduce carbon footprints. Similarly, Ermolaev *et al.* (2019) observed minimal direct GHG emissions (CH_4 and N_2O) over 11 days of BSFL treatment, with no detectable NH_3 emissions. Thus, BSFL treatment is an eco-friendly alternative, offering greater GWP reduction and lower GHG emissions than conventional organic waste management.

2.5.4 Lower Water and Land Usage Compared to Other Alternative Protein Sources

The primary protein sources in animal feed are soybean and fish meals. However, declining fish stocks due to overfishing, along with shrinking land and water resources, have increased reliance on imports to meet demand. Fish meal production also exacerbates overfishing, necessitating sustainable alternatives for animal feed (DiGiacomo and Leury, 2019; Dortmans *et al.*, 2021). Insects, particularly as organic waste decomposers, present a viable solution. Their cultivation requires minimal technology, and the resulting larval biomass can replace conventional protein sources like fish meal, especially in aquaculture (Ravi *et al.*, 2020).

Black soldier fly larvae (BSFL) meal is a promising substitute for traditional protein sources in animal feed. Its protein content is comparable to fish and soybean meals, while its amino acid and fatty acid profiles make it suitable for pet food, livestock, and aquaculture feeds (Ravi *et al.*, 2020). A life cycle assessment (LCA) by Smetana *et al.* (2019) evaluated water depletion in BSFL production across different diets, including chicken feed, distillers' grain, wheat middlings, and fruit/vegetable waste. Chicken feed and the Gainesville diet had the highest water depletion (0.39 L/g and 0.33 L/g, respectively), whereas fruit and vegetable waste resulted in a negative water depletion (-0.072 L/g), emphasizing the benefits of waste-based substrates. Thus, BSFL offers a sustainable alternative to conventional protein sources, with significantly lower water and land requirements.

2.5.5 Reduce pathogen and other vermin on decaying matter

Diarrheal diseases, often caused by pathogens like *Clostridium difficile* in manure, are widespread in low- and middle-income countries due to poor sanitation. Livestock and human waste contribute significantly to sanitation challenges, including groundwater pollution, greenhouse gas emissions, agricultural contamination, and disease transmission (e.g., diarrhea and cholera) (Awasthi *et al.*, 2020). Among harmful bacteria, *Proteobacteria*, along with *Firmicutes*, *Actinobacteria*, and *Bacteroidetes*, are frequently reported. Pathogenic genera such as *Escherichia*, *Salmonella*, *Vibrio*, and *Yersinia* (all under *Proteobacteria*) are linked to infectious diseases. However, black soldier fly larvae (BSFL) can effectively reduce these pathogens, producing mature compost suitable as fertilizer or soil conditioner (Awasthi *et al.*, 2020).

BSFL feeding has been shown to significantly decrease or inactivate pathogens like *E. coli* and *Salmonella* in alkaline chicken manure (27–32°C) and *Salmonella* in human feces within eight days. This antimicrobial effect occurs only under alkaline conditions. Nevertheless, disease transmission risk is reduced more through waste decomposition than direct pathogen inactivation (van Huis *et al.*, 2020; Dortmans *et al.*, 2021). BSFL treatment reduced pathogenic bacteria by 90–93% in chicken and cow manure within nine days, with *Salmonella* eliminated entirely. Reductions of 86–88% were observed in pig manure and sewage sludge (Awasthi *et al.*, 2020). Larval development and survival depend on feed age, moisture, nutritional content, and feeding frequency, with BSFL being more sensitive to these factors than houseflies (Miranda *et al.*, 2019; Dortmans *et al.*, 2021).

2.6 Production Systems for BSFL

The black soldier fly (BSF) is a highly effective decomposer for organic waste management (Kim *et al.*, 2021), favored for its simplicity in handling and cost-effectiveness in low-tech systems. To ensure global applicability, the technical design of BSF processing must be optimized for efficiency.

2.6.1 Breeding system considerations

The BSF breeding system must consider the availability and consistency of organic wastes that might be a problem in certain geographical areas. Moreover, the designs system should be adaptable to the specific conditions of local communities and their socio-cultural conditions.

i. Availability of Organic Materials

Research indicates that BSFL are polyphagous, capable of feeding on diverse animal- and plant-based organic materials (Bava *et al.*, 2019). Studies demonstrate their adaptability in bio-converting various wastes, such as vegetable scraps (Kinasih *et al.*, 2018), milkfish offal (Pamintuan *et al.*, 2019), and animal manure (Parodi *et al.*, 2020).

ii. Effects of Abiotic and Biotic Factors

While BSF can thrive under varied conditions, abiotic factors like temperature and humidity significantly influence their performance. Even small-scale systems must optimize these factors for optimal outcomes. Temperature critically impacts larval, prepupal, and pupal development, as well as adult lifespan. Chia *et al.* (2018a) found that a temperature of 30°C maximizes population growth and immature survival rates. Larval density also affects nutrient quality, particularly crude fat content, though protein levels remain stable (Barragan-Fonseca *et al.*, 2018). These findings suggest BSF can adapt to diverse environments, but commercial breeding requires controlled conditions.

iii. Starting with Local BSF

For small-scale breeding, trapping wild BSF adults is a practical method to establish a colony. Effective strategies include using preferred organic wastes to attract egg-laying. For instance, Ewusie *et al.* (2019) tested livestock manure and found pig manure most attractive for BSF oviposition. Dortmans *et al.* (2021) noted that females select substrates that protect eggs from predators and abiotic stressors like dehydration and sunlight.

2.6.2 Development of the breeding system

The breeding system was developed to address community needs, specifically waste management and economic benefits (Purkayastha and Sarkar, 2022). This study compares two approaches: the natural colonization system and the artificial mass breeding system. The first system is small-scale, suited for individual households or communities, and depends on local demand and resource availability. The second, more structured system is designed for commercial use, targeting large-scale organic waste processing while generating profit. Research by Gougbedji *et al.* (2021) demonstrated that small-scale breeding in movable plastic tanks can produce high-quality feed for Tilapia, offering economic benefits for lower-middle-income communities. Such systems can also integrate with sewage treatment (Joly and Nikiema, 2019), ensuring a steady supply of feedstock. This method aims to yield large quantities of high-quality, uniform prepupae biomass for commercial use.

2.7 BSF–Based Organic Waste Processing Products

Black soldier fly (BSF) larvae produce protein meal, oils, and other by-products that can be repurposed as animal feed, biodiesel, and fertilizer (Bakker, 2020). Due to their short lifecycle and rapid growth, BSFs offer a sustainable method for recycling organic waste (animal manure, food waste, and other biodegradable materials) (Boaru *et al.*, 2019). This helps to transform low-value waste into high-value products (Jalil *et al.*, 2021). BSFL-derived feed is safe for animals, as they do not harbor pests or accumulate harmful substances like mycotoxins and pesticides. However, societal reluctance toward insect consumption remains a challenge (Raksasat *et al.*, 2020). To address this, research has focused on analyzing BSFL biomass and residue to inform the public about its benefits.

The use of *Hermetia illucens* is advantageous, as the larvae provide high-quality protein while efficiently processing organic waste, reducing landfill burden (Amrul *et al.*, 2022). However, large-scale BSF farming generates secondary waste, including dead adult flies. According to Ushacova *et al.* (2019), this residual biomass can serve as a renewable source of pigments like melanin and ommochrome. All biomass from BSF-based waste processing can be converted into valuable products (Amrul *et al.*, 2022).

2.7.1 Larvae/Prepupae

Larvae are typically harvested from rearing containers (*larveros*) before reaching their maximum weight and nutritional value as prepupae (Amrul *et al.*, 2022). Post-harvest processing is necessary to sanitize the larvae before distribution. This refinement may involve killing, cleaning, sterilizing, and fractioning to separate protein and lipids. To ensure long-term storage, the final product should contain no more than 10% water and fat. Sun-drying effectively reduces moisture, while oil pressing decreases fat content (Ray Gyan *et al.*, 2019). The growing interest in black soldier fly larvae (BSFL) emerged alongside declining marine fish stocks, which increased reliance on soybean meal as an alternative protein source. Overexploitation of fishmeal has driven up prices, creating demand for sustainable substitutes like BSFL (Surendra *et al.*, 2020).

BSFL biomass must comply with quality standards for animal feed, as outlined by the Ministry of Agriculture, Livestock and Food Supply (MAPA) in normative instruction no. 04/2007. BSFL efficiently convert organic waste into protein and fat-rich biomass, making them a viable alternative to conventional animal feed proteins (Amrul *et al.*, 2022). Their nutritional composition, which is approximately 40% protein and 30% fat, depends on the substrate quality, particularly its protein and carbohydrate content. Animal manure provides higher protein, while municipal organic waste yields more lipids (Gold *et al.*, 2018). Research confirms that BSFL meal can replace a substantial portion of soybean meal in poultry diets without compromising performance (Yildirim-Aksoy *et al.*, 2020).

Although BSFL contain high-quality protein with all essential amino acids for humans, food safety remains a concern due to their waste-based diet. Studies suggest that substrate quality and blanching influence safety, highlighting the need for proper decontamination (Bessa *et al.*, 2021). While insect consumption is culturally accepted in regions like Thailand, Western consumers remain hesitant. However, educating consumers on sustainability and nutrition may increase acceptance (Lombardi *et al.*, 2018). Beyond animal feed, BSFL are also being explored for human consumption due to their high fat content (21–40% of dry mass).

BSFL utilize stored fats as energy during their non-feeding adult stage. These fats can be extracted and converted into biodiesel via transesterification (Wang *et al.*, 2020). Although biodiesel gained global attention decades ago, challenges such as competition with food crops and high costs have spurred interest in alternative production methods. BSFL offer a cost-effective solution by converting low-cost lignocellulosic biomass into biodiesel. BSF-derived biodiesel contains medium-chain saturated fatty acids, ensuring low viscosity and oxidative stability (Mai *et al.*, 2019). Research confirms that BSF biodiesel meets international standards, including ASTM D6751 and EN 14214, with favorable combustion efficiency and reduced emissions (Smets *et al.*, 2020).

2.8 Role of BSFL in Waste Management

The family Stratiomyidae (order Diptera) includes *Hermetia illucens* (BSFL), one of its most valuable species. Known as "phoenix worms," BSFL are used for bioconverting organic waste, controlling pests, and supplementing feed for livestock, poultry, and fish (Rehman *et al.*, 2021). They thrive on diverse substrates such as dairy manure, poultry manure, pig manure, and food waste (Rehman *et al.*, 2019; Ites *et al.*, 2020). Originally tropical, BSFL have spread to temperate regions in Europe, Asia, the Americas, and Australia through global trade. Their ease of breeding and broad adaptability have spurred global interest in mass production for alternative protein in animal feed, sustainable fat substitutes (e.g., margarine), and biodiesel (Rehman *et al.*, 2018; Smetana *et al.*, 2020).

BSFL play a significant role in waste management by efficiently converting organic waste into valuable resources (Czekała *et al.*, 2020; da Silva and Hesselberg, 2020; Fadhillah and

Bagastyo, 2020; Purkayastha and Sarkar, 2021). They also play a role in the valorization of biodegradable waste (Adebayo *et al.*, 2021; Chun *et al.*, 2019; Kawasaki *et al.*, 2020). The larval biomass produced from organic waste bioconversion serves as a valuable source of fats/oils (Kim *et al.*, 2021; Lu *et al.*, 2021; Tanga *et al.*, 2021) and proteins (Kinasih *et al.*, 2020; Shumo *et al.*, 2019b), with applications in animal feed, biodiesel production, biopolymer extraction (e.g., chitin), and soil composting (Purkayastha and Sarkar, 2021).

These larvae are voracious eaters and can consume a wide variety of organic materials, including food scraps, agricultural residues, and even manure, reducing waste volume by up to 50-70% within days (Shumo, 2020). Their ability to break down waste quickly not only minimizes landfill dependency but also mitigates greenhouse gas emissions, such as methane, which are typically released during organic waste decomposition in landfills. BSFL thrive in high-density environments, making them ideal for large-scale waste processing systems in urban and rural areas alike (Tariq *et al.*, 2025). BSFL also produce two valuable byproducts: nutrient-rich frass (insect manure) and protein-rich biomass (Basri *et al.*, 2022). The frass can be used as an organic fertilizer, enhancing soil health and reducing the need for chemical alternatives.

Sarpong *et al.* (2019) evaluated the potential of black soldier fly larvae (BSFL) for composting municipal organic waste and assessed the quality of the resulting fertilizer. The study tested varying feed quantities (2–4 kg) of mixed organic waste from markets, restaurants, and households, alongside a control (2 kg). Each treatment received 2,000 five- to six-day-old larvae. Nutrient content (NPK) and C:N ratio were analyzed in the substrate and compost, along with heavy metals (As, Cd, Fe, Pb, Ni). Results showed significant increases in nitrogen (41.2% ± 0.71%), phosphorus (32.4% ± 0.2%), and potassium (77.1% ± 0.19%), with over half the waste degraded within two weeks. Heavy metal concentrations decreased post-composting, meeting regulatory standards.

Lalander *et al.* (2019) investigated BSFL growth on eight urban organic waste streams and two control substrates. Using principal component analysis, they identified key substrate traits influencing waste-to-biomass conversion, larval development time, and prepupal weight. Total volatile solids and protein content most affected conversion efficiency and development time, while only volatile solids influenced prepupal weight. The study concluded that BSFL can process diverse organic wastes, provided they contain sufficient volatile solids and nitrogen. Highly suitable wastes included abattoir waste, food waste, human feces, and mixed fruit-vegetable waste.

Mulyanti *et al.* (2025) examined the role of Black Soldier Fly (BSF) larvae in organic waste decomposition and nutrient-rich compost generation, focusing on urban settings. The study assessed waste reduction efficiency and compost quality under controlled conditions, testing variables such as larval density, temperature, and moisture. Results showed that BSF larvae reduced organic waste by up to 86%, surpassing conventional composting, while producing compost rich in nitrogen, phosphorus, and potassium. However, challenges like space limitations, public acceptance, and scalability in urban areas were noted.

Attiogbe *et al.* (2019) investigated the impact of BSF larvae on composting mercury-contaminated organic waste. The study used food waste mixed with chicken manure and sawdust, spiked with mercury at concentrations of 1000 mg, 2000 mg, and 3000 mg. Larvae (100, 200, and 300) were introduced for 13 days, with triplicate samples analyzed. Mercury removal was proportional to larval numbers, and residual levels fell below EU safety thresholds (0.7–10 mg/kg). Nutrient analysis confirmed the compost's suitability for plant growth.

Addo *et al.* (2022) evaluated BSF larvae-produced compost for nutrient content, microbial activity, and heavy metal bioaccumulation. Using a pre-experimental design, five feeding groups were tested in triplicate. Post-decomposition, nitrogen, phosphorus, and potassium levels increased, but total coliform transfer from feed to prepupae was significant. Heavy metals like iron showed negligible increases, while high nutrient concentrations risked phytotoxicity.

Wong *et al.* (2020) studied the fermentation of waste coconut endosperm using *S. cerevisiae* before feeding it to black soldier fly larvae (BSFL). They found that adding 2.5 wt% yeast to the substrate maximized larval development (42.5 mg/larva) and waste-to-biomass conversion (11.5%). In contrast, the control group (without yeast) showed significantly lower growth (3.3 mg/larva). The improved performance was attributed to yeast breaking down monosaccharides in the coconut waste, enhancing nutrient absorption (Raksasat *et al.*, 2020). Rehman *et al.* (2019) introduced a cellulose-degrading microbial system to improve BSFL digestion of dairy manure (DM). Testing a DM-to-chicken feed mixture (2:3 ratio, DM40) with added cellulose-degrading bacteria yielded optimal results: 48.7% waste reduction, 10.1% bioconversion, 4.5% food conversion efficiency, and high nutrient utilization (71.2% protein, 67.8% fat). The study utilized BSFL alongside gut- and egg-associated bacteria, which significantly enhanced waste degradation and larval growth compared to the control (Mazza *et al.*, 2020).

2.9 Factors Influencing Bioconversion Efficiency

Factors such as larval density, temperature, and moisture levels, impact the ability of BSF larvae to break down organic waste.

2.9.1 Larval Density

The number of BSF larvae per unit area directly influences organic waste decomposition rates. Mulyanti *et al.* (2025) found that higher larval densities initially accelerate waste breakdown, but beyond an optimal threshold, overcrowding leads to reduced efficiency due to competition for resources (Mulyanti *et al.*, 2025). While increased larval density enhances bioconversion up to a point, excessive crowding negatively impacts performance. Thus, maintaining an ideal larval density is essential for efficient waste processing (Chaya *et al.*, 2025).

2.9.2 Temperature and Humidity

Temperature and humidity significantly affect BSF larvae's bioconversion efficiency. The larvae perform best in warm, moderately humid environments, with optimal decomposition occurring between 27°C and 30°C (Mulyanti *et al.*, 2025). Outside this range, larval activity slows, reducing waste processing rates. Larvae prefer slightly acidic to neutral pH levels (around pH 6), as extreme acidity or alkalinity can hinder their growth. Proper regulation of temperature and humidity is therefore critical for optimal waste reduction (Chaya *et al.*, 2025).

2.9.3 Moisture Content

Moisture levels in the substrate also impact decomposition efficiency. BSF larvae process high-moisture waste (e.g., food scraps) more effectively than drier materials (e.g., fibrous garden waste) (Mulyanti *et al.*, 2025). Adequate moisture facilitates easier consumption and breakdown of organic matter, highlighting the need for balanced moisture levels to maximize larval performance.

2.10 Research Gaps

Despite the demonstrated potential of black soldier fly larvae (BSFL) in organic waste management, critical gaps remain in optimizing their application for composting animal waste, especially within tropical and subtropical regions. Current research offers limited data on BSFL performance across diverse animal waste types. While their efficiency has been well established with homogeneous substrates like poultry manure, their waste reduction capacity, larval growth performance, and compost quality when fed with more complex and heterogeneous materials such as abattoir waste, cow, or pig manure remain underexplored. This study will address this gap by quantifying BSFL growth rate, biomass yield, and waste volume reduction across a range of these substrates.

There is also uncertainty surrounding the safety and nutrient suitability of compost produced from mixed animal waste using BSFL. Although previous studies suggest BSFL can reduce pathogens, the chemical and physical properties of the resulting frass—such as C:N ratio, nitrogen, phosphorus, potassium content, and pH—require systematic evaluation to determine their suitability as soil amendments. This study will therefore analyze these parameters to validate the compost's agricultural potential and safety. In addition, the role of BSFL composting in mitigating greenhouse gas emissions remains inadequately supported by empirical data. While it is generally assumed to emit fewer greenhouse gases than conventional methods like landfilling, direct measurements of methane and carbon dioxide emissions from BSFL-treated animal waste are lacking. This research will measure these emissions to assess the environmental advantages of BSFL-based composting.

Furthermore, existing literature often overlooks the specific challenges of applying BSFL technology in developing countries, particularly under tropical conditions where factors such as high humidity, waste variability, and limited infrastructure can influence outcomes. Most studies have been conducted in temperate regions or under highly controlled laboratory settings. This study will focus on the use of locally available animal wastes and simulate conditions typical of tropical developing contexts to ensure greater practical relevance. By filling these knowledge gaps, the research will provide actionable evidence for the deployment of BSFL in animal waste composting and will support the development of scalable, sustainable solutions tailored to the needs of tropical and low-resource settings.

CHAPTER THREE

METHODOLOGY

3.0 Materials and methods

The study comprised of both field work and laboratory analysis.

3.1 Field work

The field work constituted collecting the animal wastes (feedstock) from University of Benin Animal farm and abattoir. Five feedstocks were evaluated for their influence on the development and proximate composition of BSF larvae:

1. Poultry feed (Control): Dry poultry feed was purchased from poultry feed sellers in New Benin market, Nigeria. It was moistened at 60% with fresh water before use (Adebayo *et al*., 2021).

2. Cow blood meal (CBM) was obtained from University of Benin Animal farm stored at -4°C until needed for the experiment.

3. Cow rumen (CR): Fresh cow rumen was collected from the University of Benin animal farm, Nigeria.

4. Poultry manure (PM): Fresh poultry waste was collected from the Department of Agriculture poultry farm, University of Benin.

5. Pig manure (PiM): Pig manure was obtained from pig farm in the University of Benin animal farm, Nigeria.

6. Honey waste (HW): This comprised of honey combs obtained after extracting honey

7. Mixed (25% CBM + 25% CR + 25% PM + 25% PiM): Twenty-five percent of selected waste was be used as feedstock.

3.2 Laboratory setup

The laboratory setup comprised of rearing and harvesting the black soldier fly larvae which was done according to Adebayo *et. al.* (2021). BSF eggs were obtained from the Entomological Unit of the Nigeria Institute for Oil-palm Research (NIFOR), Edo State, Nigeria. The eggs were hatched in 250 ml plastic containers containing chicken feed (broiler's mash) mixed with distilled water (60% moisture content) to ensure a favourable moisture content for the growth of the larvae. After five days, the first instar larvae were sieved through a 1.2 mm diameter mesh screen and sorted into the various rearing substrates, replicated three times. The experiment was conducted in triplicate rectangular plastic containers measuring 30 cm x 18 cm x 9 cm and covered with mesh cloths to prevent other insects from infesting the feedstock. Two grams of 5- to 8-day-old larvae were placed in each treatment, replicated three times, with 300 g of fresh material of each substrate type in plastic containers (Adebayo *et al.,* 2021). The larvae were observed until the first few prepupae appeared in each container and harvested 6 days after the first prepupae appearance, which was about 2–4 weeks after the start of the experiment. All experiments were maintained at 25 ◦C with 75% humidity.

3.3 Experimental analysis

The experimental analysis involved determining the percentage waste reduction, percentage bioconversion efficiency rate, feed conversion ratio and the larval growth rate

3.3.1 Waste reduction analysis

Waste reduction analysis was determined according to Lalander *et al.* (2019). The formula is given below:

$$\% \text{ Waste Reduction} = \frac{\text{Initial waste (g) - Residue waste (g) x 100}}{\text{Initial waste (g)}} \quad (3.1)$$

Where Residue mass = weight of leftover (g); Substrate mass = initial weight of substrate (g).

3.3.2 The bioconversion efficiency residue (BER) analysis

The bioconversion efficiency residue (BER) was calculated using the equation stated by Bosch *et al.* (2020):

$$\% \text{ BER} = \frac{\text{Final Larvae Weight (DM, g)}}{\text{Initial substrate weight (DM, g) - Residue weight (DM, g) x 100}} \quad (3.2)$$

3.3.3 Feed conversion ratio (FCR) of black soldier fly larvae

The feed conversion ratio (FCR) was done at the end of the experiment. The feed was separated from the larvae, and the FCR was calculated based on the dry matter (DM) as stated by Broeckx *et al.* (2021) as follows:

$$\text{FCR} = \frac{\text{Initial substrate mass (g,DM) - Final substrate Mass (g,DM)}}{\text{Larvae output (g,WM)}} \quad (3.3)$$

3.3.4 Impact of different compost types and their nutrient (proximate) and mineral composition on the larval growth rate (LGR) of BSFL

To determine initial larval weight (Wi), a random sample of 20 larvae was collected from each replicate and weighed using a digital analytical balance. The mean value was recorded as the baseline weight at Day 0. Larvae was allowed to feed and grow until prepupae appears, with regular monitoring and replenishment of feed. At the end of the growth period, larvae were resampled, and the final average weight (Wf) was determined using the same procedure above. Larval Growth Rate was calculated using the formula:

$$\text{Larval growth rate} = \frac{\text{Final average weight (g) - Initial average weight (g)}}{\text{Number of days of the growth period}} \quad (3.4)$$

The proximate analyses consisted of analytical determinations of water (moisture), dry matter, crude protein, crude fat (ether extract), crude ash and crude fibre. Moisture content was determined by drying organic waste and compost samples in an oven at 105 oC for about 24 hours (Appiah–Effah *et al*. 2020). After determining the moisture content, the waste and compost samples was dried at 103°C for 16 h to determine the dry matter content and will also be put into a muffle furnace at a temperature set at 550°C to determine the ash content. The Kjeldhal method, adopted from Mádlíková *et al*. (2018), was used to determine the crude protein. Digestion, distillation, and titration processes was used to determine the total nitrogen content of the samples. To estimate the protein content, a conversion factor of 4.76 was used for a more accurate estimation of the protein content in waste samples.

3.3.5 Nutrient composition and suitability of the compost for agricultural application

The nutrient composition and suitability of the compost for agricultural application was estimated according to methods by Sarpong *et al.* (2019). Samples of feedstock and residue was collected for further analysis of total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), and total potassium (TK) using standard methods. The temperature, pH, Electrical conductivity (EC) and moisture contents of the substrate and residue were investigated (Awasthi *et al.*, 2020).

3.4 Statistical Analysis

Means ± Standard errors for all treatments were recorded while differences in treatments were analyzed using one-way analysis of variance (ANOVA) in the IBM Statistical Package for the Social Sciences (SPSS) version 23, with a 95% confidence interval performed to identify statistically significant differences between developmental parameters and proximate composition. Where a significant difference was found, a Tukey post-hoc test with 95% confidence interval was performed. P-values below 0.05 was considered statistically significant.

Figure 3.1: BSFL eggs

Figure 3.2: 150g of chicken feed

Figure 3.3: 5-day old BSFL

Figure 3.4: Weighing waste into containers

Figure 3.5: Experimental setup

Figure 3.6: Weighing the BSF 5- day old larvae

Figure 3.7: 15-day old larvae from chicken feed (control)

Figure 3.8: 15-day larvae from mixed

Figure 3.9: 15-day larvae from Chicken manure

Figure 3.10: 15-day larvae from cow rumen

Figure 3.11: 15-day larvae from cow blood meal

Figure 3.12: 15-day larvae from honey waste

Figure 3.13: 15-day larvae from pig manure

Figure 3.14: Newly emerged Black Soldier fly

Figure 3.15: Poultry feed frass

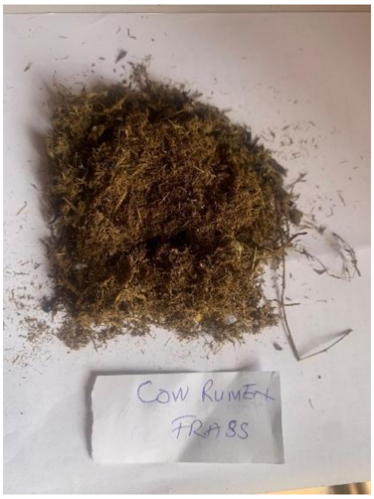

Figure 3.16: Cow rumen frass

Figure 3.17: Chicken manure frass

Figure 3.18: Cow blood meal frass

Figure 3.19: Mixed waste frass

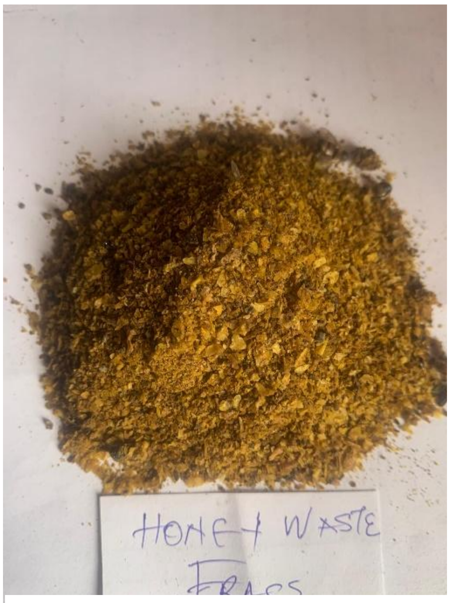

Figure 3.20: Honey waste frass

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Rate at which black soldier fly larvae breaks down animal waste and reduces its volume.

The rate at which black soldier fly larvae breaks down animal waste and reduces its volume was determined using three indices; percentage waste reduction, percentage bioconversion efficiency rate (%BER), feed conversion ratio (FCR) in Figure 4.1 to Figure 4.4.

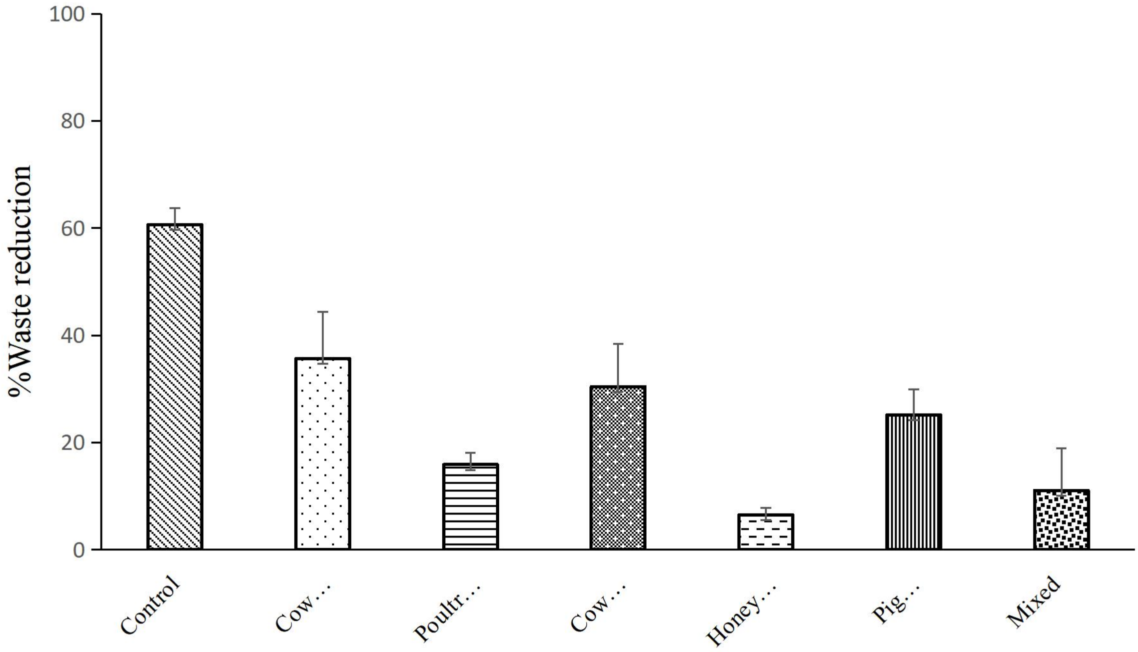

Figure 4.1: Percentage waste reduction of the different waste substrates by bsfl. (*Note that same alphabets mean that there is no statistical difference p>0.05).

Figure 4.1 shows the percentage waste reduction of each substrate by BSF larvae. The control had the highest value (60.64 ± 1.79), indicating that a larger fraction of the initial substrate was consumed, while the least percentage waste reduction was recorded in the honey waste (6.51 ± 0.72). The percentage waste reduction in the control differed significantly from all other treatments ($p < 0.05$). There was no significant difference in waste reduction among cow rumen, cow blood meal, and pig manure ($p > 0.05$). However, cow rumen differed significantly from poultry manure, honey waste, and the mixed substrate ($p < 0.05$). Our experiments revealed that the control substrate (poultry feed) achieved the highest percentage waste reduction, significantly exceeding all other tested waste treatments, whereas honey waste exhibited the lowest reduction. This pattern closely aligns with findings reported in earlier works. For example, Lalander *et al.* (2019) demonstrated that poultry feed produced the greatest waste reduction compared to ten other organic substrates, a difference that was statistically significant. Similarly, Broeckx *et al.* (2021) observed that poultry feed significantly outperformed chicken manure in waste-reduction efficiency. These results are consistent with broader research showing that waste conversion by BSFL differs depending on the type of substrate (Diener *et al.*, 2011; Banks *et al.*, 2014; Tanga *et al.*, 2021; Gobi *et al.*, 2022; El Deen *et al.*, 2023; Hao *et al.*, 2023; Hosseindoust *et al.*, 2023; Opoku *et al.*, 2023).

The superior performance of poultry feed can be attributed to its enhanced nutritional balance. As a formulated feed, it provides a readily digestible combination of protein, carbohydrates, fats, vitamins, and minerals designed to maximize animal growth (Guillaume *et al*., 2022). BSFL likely benefit from this balance, requiring less metabolic adjustment to compensate for nutritional deficiencies. In contrast, substrates such as honey waste - composed primarily of simple sugars, are nutritionally incomplete and lack structural components necessary for microbial pre-processing and larval ingestion. The poor conversion efficiency observed in honey waste thus reflects not only its unbalanced nutrient profile but also its unfavorable physical properties (Klammsteiner *et al*., 2021). Honey waste have high viscosity and may reduce aeration, encouraging anaerobic microzones that hinder microbial co-metabolism and larval feeding.

These observations emphasize that energy density alone does not guarantee efficient waste reduction. Substrate digestibility, physical structure, nutrient completeness, and moisture regulation are interdependent determinants of conversion efficiency. In particular, physical factors such as substrate compactness or porosity can affect larval mobility and access to nutrients, as well as oxygen diffusion and microbial activity—all of which directly influence decomposition rates (Diener *et al.*, 2011; Lalander *et al.*, 2019; Banks *et al.*, 2014).

Yet, there are key caveats worth acknowledging. Waste reduction rates may vary with larval density, feeding rate, and substrate depth. Lalander *et al.* (2019) demonstrated that altering substrate depth can significantly change the oxygen and temperature profiles, thereby influencing decomposition efficiency. In our experiment, variations in substrate packing density may have created microenvironmental differences that partially explain the magnitude of waste reduction observed among treatments. Additionally, the reduced performance of mixed waste suggests potential antagonistic interactions between substrates. Moisture dilution, uneven nutrient distribution, or the presence of inhibitory compounds could suppress larval feeding efficiency. Studies by Banks *et al.* (2014) and Pliantiangtam *et al.* (2021) also reported similar non-additive effects when multiple wastes were combined, indicating that substrate blending does not always produce synergistic benefits.

Another dimension worth considering is BSFL waste reduction is not driven solely by larval digestion but also by complex larva - microbe interactions. Distinct waste substrates foster specific microbial communities that can either facilitate or compete with larval metabolism. Recent work by Eriksen *et al.* (2024) modeled these interactions, showing that microbial composition significantly alters substrate breakdown kinetics and intermediate metabolite profiles, ultimately affecting larval assimilation rates. This insight highlights the need to integrate microbial ecology into BSFL waste management models.

Furthermore, methodological differences across studies—such as whether waste reduction is reported on a wet or dry-matter basis, or whether the endpoint corresponds to a specific larval stage – complicate direct comparison (Siddiqqui *et al*., 2024). The lack of standardization in measurement and normalization methods (e.g., moisture correction, frass separation) introduces potential bias. Therefore, while our findings are broadly consistent with the literature, they must be interpreted within the experimental context, acknowledging potential deviations arising from differences in system scale, substrate preparation, and measurement protocols (Lalander *et al.*, 2019).

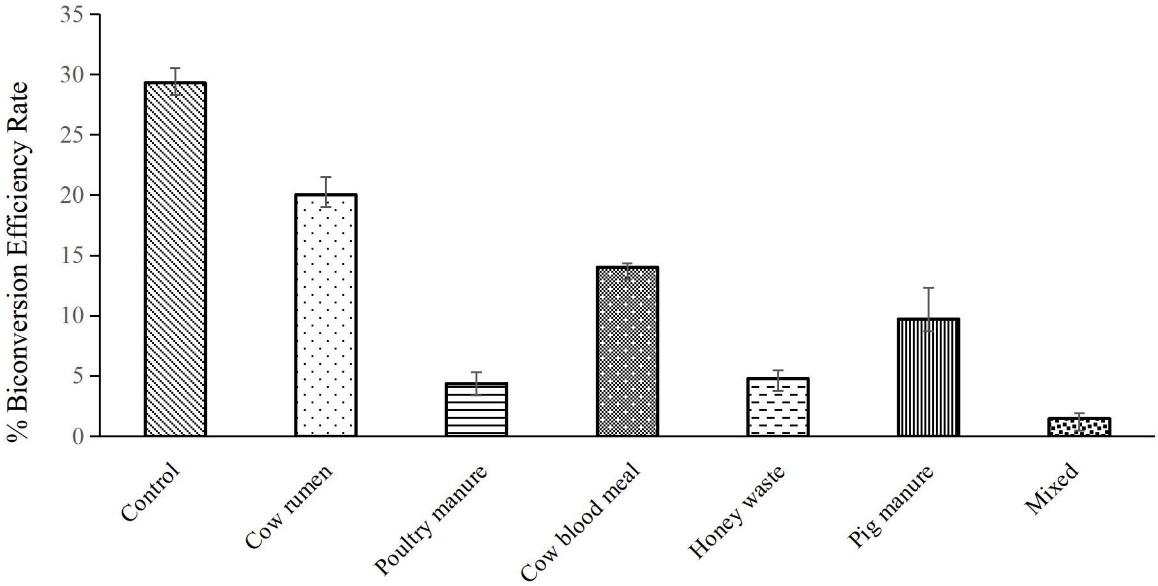

Figure 4.2: Percentage Bioconversion efficiency rate (%BER) of the different waste substrates. Same alphabets mean there is no statistical difference between substrates (p>0.05).

Figure 4.2 presents the percentage bioconversion efficiency rate (%BER) of BSF larvae reared on different substrates. The control recorded the highest %BER (29.31 ± 0.70), indicating superior conversion of waste into larval biomass, while mixed waste had the lowest value (1.48 ± 0.24). The %BER of the control differed significantly from all other treatments ($p < 0.05$). Also, there was a significant difference observed among cow rumen, cow blood meal, and pig manure ($p < 0.05$), whereas these treatments differed significantly from poultry manure, honey waste, and the mixed substrate ($p < 0.05$). However, there was no significant difference between poultry manure, honey waste, and the mixed substrate ($p > 0.05$). These findings mirror those of Broeckx *et al.* (2021), who observed elevated %BER in chicken feed, although their study found no statistically significant difference between feed and manure, likely a result of higher nutrient quality in their manure samples. Similarly, Gold *et al.* (2022) reported comparable BER values between poultry feed and human faeces, emphasizing that protein and lipid content are primary predictors of conversion efficiency. Also, Eriksen *et al.* (2024) demonstrated through carbon balance modeling that larvae can convert approximately 53–58% of assimilated carbon into biomass, but total substrate-to-biomass conversion efficiency can vary widely from 14 to 48 % depending on substrate composition and system conditions. These findings corroborate our observation that % BER is highly substrate dependent.

Bioconversion efficiency is governed by multiple interacting variables, including substrate digestibility, nutrient availability, moisture content, larval density, and pH stability. Highly digestible substrates rich in protein and lipids typically support higher BER, whereas those deficient in nitrogen or containing indigestible fibers lead to reduced efficiency (Siddiqqui *et al*., 2024). Moisture levels also play a dual role, hence, excessively dry substrates hinder microbial pre-digestion, while overly wet substrates promote microbial competition for nutrients or anaerobic conditions may reduce substrate availability to larvae or generate inhibitory by-products, such as ammonia and volatile fatty acids.

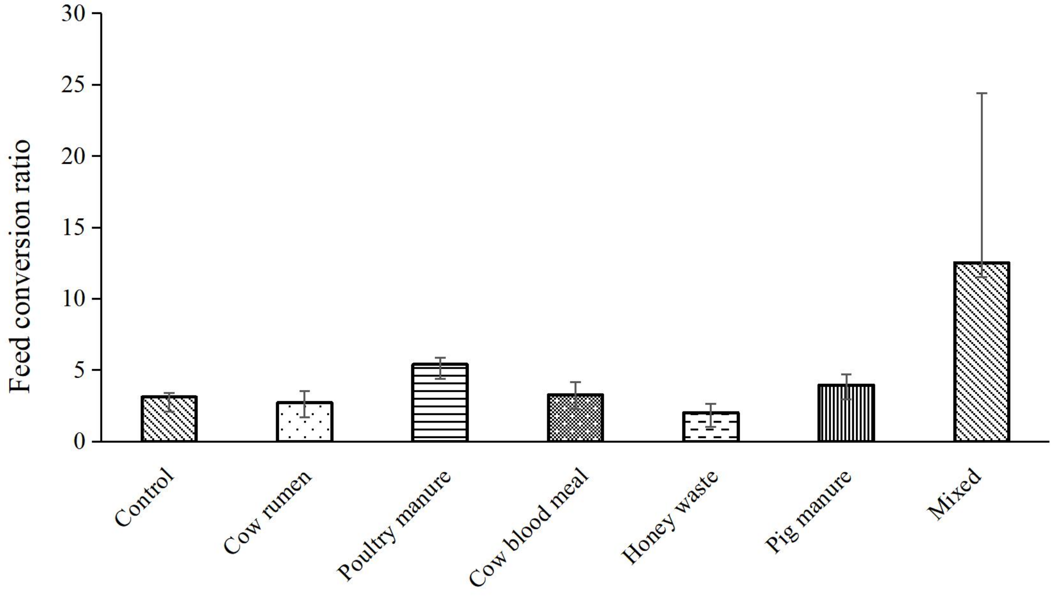

Figure 4.3: The feed conversion ratio of the different waste substrates. Same alphabets indicate that there is no statistical difference between substrates (p>0.05).

Figure 4.3 illustrates the feed conversion ratio (FCR) of BSF larvae fed on different substrates. The honey waste had the lowest FCR (2.12 ± 0.80), while the highest FCR value was observed in the mixed waste (13.47 ± 0.27). Statistical analysis showed no significant difference in FCR among the treatments ($p > 0.05$). Other studies have reported similar patterns. For example, Broeckx *et al.* (2021) reported FCR values between 1.58 and 8.90 across various waste substrates, while Gligorescu *et al.* (2020) found FCRs between 1.7 and 3.6 for food waste under optimized conditions. Nayak *et al.* (2024) and Tirtawijaya *et al.* (2024) further demonstrated that FCR responds sensitively to substrate composition, reporting improved feed efficiency (FCR 2.09–3.5) when nutrient supplementation or substrate substitution was applied.

The absence of significant differences in our study may stem from several intertwining hypotheses. First, FCR estimates are often subject to high variance due to measurement errors, moisture fluctuations, and heterogeneous substrate distribution (Siddiqqui *et al*., 2024. Small sample sizes may therefore limit statistical power. Second, some larvae in some treatments may consume more substrate but convert it less efficiently, leading to similar FCR values despite divergent BER. Third, stable feed conversion ratios (FCR) are possible, where minor variations in substrate quality produce little change until critical nutritional thresholds are crossed (Oonincx *et al*., 2015; Barragán-Fonseca *et al*., 2017; Lalander *et al*., 2019). Additionally, methodological inconsistencies such as how moisture correction, larval mortality, and harvest timing are managed, can introduce bias. For instance, harvesting all treatments simultaneously may capture larvae at differing developmental stages, inadvertently inflating FCR in slower-growing substrates (Eriksen *et al.,* 2024; Eugster *et al.,* 2024).

4.2 The impact of different waste types and their nutrient (proximate) composition on black soldier fly larvae growth rate

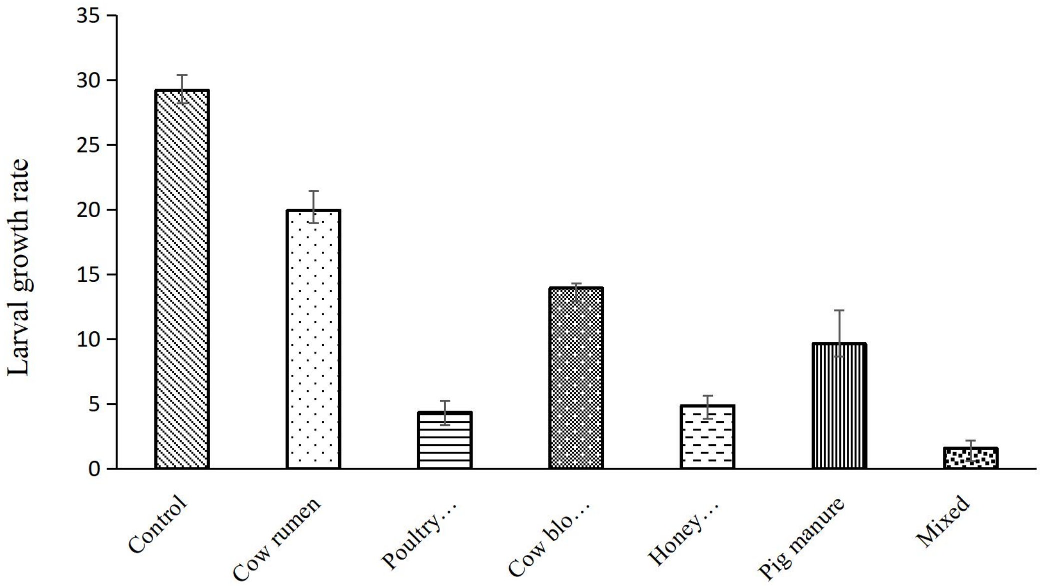

Figure 4.4: The larval growth rate of the different waste substrates. Same alphabets mean there is no statistical difference between substrates (p>0.05).

Figure 4.4 shows the larval growth rate of BSF larvae across different substrates. The control recorded the highest growth rate (29.19 ± 0.70), while the mixed waste produced the lowest growth rate (1.56 ± 0.34). The growth rate of larvae in the control treatment differed significantly from all other treatments ($p < 0.05$). No significant difference was observed among poultry manure, honey waste and mixed ($p > 0.05$); however, these differed significantly from control, cow rumen, cow blood meal and pig manure ($p < 0.05$). The larval growth rate of BSFL was strongly influenced by the nutrient composition of the rearing substrates (Figure 4.4). The control substrate (poultry feed) produced the highest larval growth rate (29.19 ± 0.70), significantly surpassing all organic waste treatments ($p < 0.05$). This superior performance aligns with its nutrient-rich composition, notably high in protein (7.20%), fat (2.40%), and nitrogen-free extract (51.89%) - key macronutrients that support rapid biomass accumulation and energy metabolism in larvae. Similar findings were reported by Diener *et al.* (2009) and Lalander *et al.* (2019), who observed that BSFL perform best on balanced, energy- and protein-dense substrates such as poultry feed or food waste blends.

In contrast, the mixed waste (1.56 ± 0.34) and cow rumen treatments exhibited the lowest growth rates, corresponding to their minimal nutrient profiles—particularly low protein (0.58–1.23%) and fat (0.15–0.32%) contents, coupled with high moisture (94–96%). Excessive moisture has been shown to reduce oxygen availability and substrate aeration, leading to suboptimal larval feeding and metabolic efficiency (Gold *et al.*, 2020; Nyakeri *et al.*, 2017). Moreover, substrates low in digestible carbohydrates and lipids fail to meet larval energy demands, explaining the markedly slow growth observed in these treatments.

Moderate larval growth was recorded on pig manure, poultry manure, and cow blood meal, which contained intermediate protein (3.76–4.50%) and fat (0.68–1.01%) levels. Although these values were substantially lower than the control, they were sufficient to sustain modest larval development. These results agree with Meneguz *et al.* (2018) and Liu *et al.* (2021), who reported that animal manures support slower but consistent BSF growth due to moderate protein availability and the presence of indigestible or inhibitory compounds (e.g., ammonia and fibrous residues).

Interestingly, honey waste—despite its high carbohydrate content (NFE = 41.95%)—did not enhance larval growth. This may be attributed to its very low nitrogen and mineral content, particularly calcium and zinc, which are essential for larval tissue formation and enzyme function (Cheng *et al.*, 2017; Oonincx *et al.*, 2015). Furthermore, its high crude fibre (18.84%) may have limited digestibility, reducing nutrient assimilation efficiency.

Overall, these results reaffirm that BSF larval growth depends not merely on substrate energy but on a balanced combination of protein, fat, and minerals. The control diet provided this optimal balance, explaining its superior performance. In contrast, substrates deficient in protein or excessively moist, like cow rumen and mixed waste, were nutritionally and physically unsuitable for rapid larval development.

Table 4.1: The proximate and mineral composition of different organic substrates used for black soldier fly larval rearing

Treatment	Moisture (%)	Fat (%)	Ash (%)	Crude Fibre (%)	Protein (%)	N.F.E Car (%)	Ca (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	K (mg/kg)
Poultry feed (control)	60.82 ± 1.50[b]	2.40 ± 0.07[e]	2.76 ± 0.05[f]	15.66 ± 0.32[e]	7.20 ± 0.19[d]	51.89 ± 0.37[e]	2.14 ± 0.08[a]	26.15 ± 0.65[b]	18.57 ± 0.54[e]	497.08 ± 7.78[c]
Cow Rumen	96.13 ± 0.82[e]	0.15 ± 0.00[a]	0.18 ± 0.00[a]	0.28 ± 0.00[a]	0.58 ± 0.01[a]	2.68 ± 0.81[a]	2.45 ± 0.12[a]	17.09 ± 0.43[a]	6.83 ± 0.06[a]	112.79 ± 0.61[a]
Poultry manure	71.51 ± 1.38[c]	1.01 ± 0.04[d]	1.58 ± 0.02[e]	2.34 ± 0.01[bc]	4.38 ± 0.17[b]	19.17 ± 1.46[c]	3.17 ± 0.07[c]	17.14 ± 0.35[a]	8.12 ± 0.30[ab]	234.62 ± 3.36[b]
Cow blood meal	83.76 ± 1.02[d]	0.68 ± 0.01[bc]	0.85 ± 0.01[c]	1.43 ± 0.04[b]	3.76 ± 0.16[b]	9.52 ± 1.02[b]	3.41 ± 0.09[cd]	17.52 ± 0.43[a]	10.44 ± 0.19[cd]	201.11 ± 1.93[b]
Pig manure	80.00 ± 0.50[d]	0.50 ± 0.05[ab]	1.20 ± 0.05[d]	3.00 ± 0.10[cd]	4.50 ± 0.10[b]	10.80 ± 0.30[b]	3.00 ± 0.10[c]	17.00 ± 0.50[a]	8.00 ± 0.50[ab]	200.00 ± 5.00[a]
Honey waste	27.76 ± 0.35[a]	2.26 ± 0.08[e]	3.03 ± 0.07[g]	18.84 ± 0.45[f]	6.16 ± 0.30[c]	41.95 ± 0.40[d]	2.86 ± 0.01[bc]	19.61 ± 0.66[a]	8.99 ± 0.17[bc]	511.11 ± 25.80[c]
Mixed	94.20 ± 0.61[e]	0.32 ± 0.01[a]	0.50 ± 0.02[b]	0.77 ± 0.02[ab]	1.23 ± 0.01[a]	2.98 ± 0.63[a]	2.83 ± 0.08[ab]	19.79 ± 1.00[a]	9.93 ± 0.24[c]	102.03 ± 2.60[a]
***p*-value**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**

Note that the same alphabets in a column mean there is no significant difference (p>0.05)

4.2.1 Proximate and Mineral Composition of Different Organic Substrates used for Black Soldier Fly Larval Rearing

The proximate and mineral composition of the organic substrates used in this study revealed significant variation in their nutritional and physicochemical properties. Such variability is consistent with previous reports emphasizing that substrate composition strongly influences the growth, development, and bioconversion efficiency of BSFL (Spranghers *et al.*, 2017; Meneguz *et al.*, 2018; Lalander *et al.*, 2019).

The moisture content of the substrates differed significantly ($p < 0.05$), ranging from 27.76 ± 0.28 to 96.13 ± 0.82%. Cow rumen (96.13 ± 0.82%) and the mixed substrate (94.20 ± 0.61%) had the highest moisture contents and were statistically similar. Pig manure (80.00 ± 0.50%) and cow blood meal (83.76 ± 1.02%) also exhibited high moisture levels, while poultry manure and poultry feed had moderate moisture contents of 71.51 ± 1.38 and 60.82 ± 1.5% respectively. In contrast, honey waste (27.76 ± 0.35%) had the lowest mean values (Table 4.1). The very high moisture contents of cow rumen and the mixed substrate are comparable to those reported for animal slurries and ruminal wastes, which are typically semi-liquid and dilute in nature (Diener *et al.*, 2009; Lalander *et al.*, 2019). Similarly, Meneguz *et al.* (2018) observed that drier feed-based substrates supported higher larval feeding efficiency than excessively wet manures. The low moisture content of honey waste aligns with the findings of Spranghers *et al.* (2017), who noted that some substrates often contain limited water due to processing and storage requirements. Moisture differences across substrates not only affect nutrient concentration but also influence aeration, microbial activity, and larval feeding behavior.

Fat content varied significantly among substrates ($p < 0.05$). The highest fat percentages were observed in poultry feed (2.40 ± 0.07%) and honey waste (2.26 ± 0.08%), which were statistically similar and reflected the lipid-rich nature of these substrates. Cow rumen (0.15 ±

0.00%), mixed substrate (0.32 ± 0.01%), and pig manure (0.50 ± 0.05%) had the lowest fat contents, indicating that they were poor sources of lipids. Poultry manure (1.01 ± 0.04%) and cow blood meal (0.68 ± 0.01%) contained moderate levels of fat (Table 4.1). These trends are consistent with prior studies indicating that formulated feeds and certain food-processing wastes possess higher lipid levels than animal manures or ruminal residues (Spranghers *et al.*, 2017). The low fat observed in cow rumen and manure-based substrates corresponds to the aqueous, microbially fermented nature of these materials (Wang *et al.*, 2017). Conversely, poultry feed typically includes oil-rich grains or additives, while honey waste may contain wax and pollen residues, both of which can elevate total lipid content.

Ash content, an indicator of total mineral matter, also showed significant variation ($p < 0.05$). Honey waste recorded the highest ash value (3.03 ± 0.07%), followed by poultry feed (2.76 ± 0.05%), suggesting higher mineral concentrations in these substrates. Conversely, cow rumen had the lowest ash content (0.18 ± 0.00%), statistically similar to the mixed substrate (0.50 ± 0.02%). Intermediate ash contents were observed in pig manure (1.20 ± 0.05%), cow blood meal (0.85 ± 0.01%), and poultry manure (1.58 ± 0.02%) (Table 4.1). Similar observations have been made by Barragán-Fonseca *et al.* (2017) and Gold *et al.* (2020), who attributed elevated ash content in processed or plant-derived materials to mineral fortification or natural soil contamination. In contrast, cow rumen and the mixed substrate had notably low ash values, consistent with their diluted, semi-digested nature (Diener *et al.*, 2011). Variations in ash among wastes may therefore arise from both compositional differences and processing effects, as also highlighted by Ewald *et al.* (2020).

Crude fibre content differed significantly ($p < 0.05$) among treatments. The highest fibre content was found in honey waste (18.84 ± 0.45%) and poultry feed (15.66 ± 0.32%), indicating their high structural carbohydrate content. In contrast, cow rumen (0.28 ± 0.00%) and the mixed substrate (0.77 ± 0.02%) recorded the lowest fibre values, likely due to their semi-digested or liquid nature. Pig manure (3.00 ± 0.10%) and poultry manure (2.34 ± 0.01%) had moderate fibre contents, while cow blood meal was relatively low (1.43 ± 0.04%) (Table 4.1). This observation aligns with earlier findings that plant materials substrates tend to be richer in fibrous materials compared to animal manures (Spranghers *et al.*, 2017; Meneguz *et al.*, 2018). Conversely, the low fibre content of cow rumen (0.28%) and the mixed substrate (0.77%) can be attributed to microbial degradation and the partial digestion of plant matter within the rumen (Lalander *et al.*, 2019). Substrate fibre level is a key determinant of larval assimilation efficiency, with highly fibrous materials generally reducing digestibility and slowing larval growth (Diener *et al.*, 2009).

Protein content varied significantly ($p < 0.05$), with poultry feed (7.20 ± 0.19%) and honey waste (6.16 ± 0.30%) having the highest values among the treatments. Moderate protein levels were observed in pig manure (4.50 ± 0.10%), poultry manure (4.38 ± 0.17%), and cow blood meal (3.76 ± 0.16%). The lowest protein contents were found in the mixed substrate (1.23 ± 0.01%) and cow rumen (0.58 ± 0.01%), suggesting limited nitrogen availability in these materials compared to more nutrient-dense substrates like poultry feed (Table 4.1). These findings are consistent with reports by Spranghers *et al.* (2017) and Barragán-Fonseca *et al.* (2017), who found that substrates rich in nitrogen and protein may promote higher larval biomass yield and protein content. Conversely, low protein levels in the mixed substrate and cow rumen indicate poor nitrogen availability, which may limit larval performance. Similar trends were observed by Lalander *et al.* (2019), who noted that protein-deficient wastes, particularly those of animal origin with high moisture content, often result in reduced larval growth rates.**)**

The nitrogen-free extract, representing the soluble carbohydrate fraction, also showed significant differences ($p < 0.05$). Poultry feed had the highest N.F.E (51.89 ± 0.37%), followed by honey waste (41.95 ± 0.40%), indicating that these substrates contained readily

digestible carbohydrates. Poultry manure (19.17 ± 1.46%) and pig manure (10.80 ± 0.30%) showed moderate levels, while cow rumen (2.68 ± 0.81%) and the mixed substrate (2.98 ± 0.63%) recorded the lowest values, consistent with their fibrous or aqueous nature (Table 4.1). This aligns with findings by Diener *et al.* (2009) and Gold *et al.* (2020), who demonstrated that poultry feed is a rich source carbohydrate which accelerate larval development and increase conversion efficiency. In contrast, cow rumen (2.68%) and the mixed substrate (2.98%) had very low NFE values, suggesting that most fermentable carbohydrates had already been metabolized by rumen microbes prior to collection (Lalander *et al.*, 2019).
Significant differences were also observed in the mineral content of the substrates (Table 4.1). Calcium concentration was highest in cow blood meal (3.41 mg/kg) and poultry manure (3.17 mg/kg), a pattern that diverges slightly from typical blood meal composition but could be attributed to bone contamination during processing (Newton *et al.*, 2005). Poultry feed exhibited the highest zinc (26.15 mg/kg) and copper (18.57 mg/kg) concentrations, consistent with earlier findings that commercial feeds are fortified with mineral premixes to enhance animal nutrition (Spranghers *et al.*, 2017; Yildirim-Aksoy *et al.*, 2020). In contrast, lower trace metal concentrations in manures and rumen materials are expected due to dilution effects and the variable composition of livestock diets (Diener *et al.*, 2011). Potassium content was highest in honey waste (511.11 mg/kg) and poultry feed (497.08 mg/kg), both of which are derived from plant-based materials rich in soluble minerals. Similar high potassium values were reported by Meneguz *et al.* (2018) and Gold *et al.* (2020) for food and fruit wastes used in BSFL rearing. Meanwhile, cow rumen and the mixed substrate showed minimal potassium levels, reflecting their high moisture and microbial-degraded nature (Lalander *et al.*, 2019).

Differences between this study and some previous reports may also reflect variations in waste source, collection method, or analytical approach. For instance, differences in moisture basis (wet vs. dry weight), mineral extraction methods, or feed composition can produce minor discrepancies in reported values (Ewald *et al.*, 2020; Lu *et al.*, 2022). Nonetheless, the general pattern observed here highlights the critical role of substrate composition in determining BSFL performance, nutrient recovery, and the quality of the resulting frass fertilizer.

Table 4.2 Physicochemical Properties of Different Compost Treatments and Their Suitability as Organic Fertilizer

	Treatment (Mean ± SE)									
Parameter	**Mixed**	**Poultry Feed (Control)**	**Cow Rumen**	**Poultry Manure**	**Cow Blood Meal**	**Honey Waste**	**Pig Manure**	**p-value**	**Range for Organic Fertilizer**	**Suitability as Compost**
pH	7.68 ± 0.15b	7.47 ± 0.09b	7.31 ± 0.02b	7.51 ± 0.04b	7.600.03 b	6.85 ± 0.10a	7.59 ± 0.12b	<0.05	6.5–8.0	All suitable (optimum pH range)
EC (mS cm⁻¹)	3.71 ± 0.39a	3.97 ± 0.33a	3.23 ± 0.19a	4.49 ± 0.32a	4.15 ± 0.43a	3.10 ± 0.28a	3.98 ± 0.51a	>0.05	< 4.0	Slightly high in Poultry manure & Cow blood meal; others suitable
Dry Matter (%)	54.48 ± 0.87ab	56.11 ± 0.56ab	59.73 ± 0.80b	52.93 ± 1.10ab	57.50 ± 2.45b	46.83 ± 4.16a	55.44 ± 2.14ab	<0.05	40–70	All suitable
Total C (g/kg DM)	367.56 ± 9.29c	263.01 ± 9.86b	176.00 ± 0.00a	337.19 ± 2.11b	432.67 ± 20.27d	162.53 ± 4.16a	288.81 ± 7.91b	<0.05	200–400	Suitable except Cow rumen & Honey waste (too low) and Cow blood meal (too high)
C:N Ratio	8.68 ± 0.22a	10.38 ± 0.39bc	11.00 ± 0.00c	9.11 ± 0.06ab	8.65 ± 0.41a	16.25 ± 0.42d	10.70 ± 0.29c	<0.05	10–20	Suitable for most; slightly low for Mixed, Poultry manure, Cow blood meal
Volatile Solids (g/kg DM)	538.63 ± 13.62c	385.42 ± 14.44b	258.13 ± 0.00a	494.12 ± 3.09c	634.03 ± 29.70d	238.18 ± 6.09a	423.22 ± 11.58b	<0.05	>300	Suitable except Cow rumen & Honey waste (too low)
Nitrogen (g/kg)	42.86 ± 2.32e	25.83 ± 1.40c	16.34 ± 1.06b	37.37 ± 1.16d	50.56 ± 2.38f	10.46 ± 1.22a	27.38 ± 1.23c	<0.05	10–30	High in Mixed, Poultry manure, Cow blood meal; optimal in others
Phosphorus (g/kg)	11.42 ± 1.21d	8.33 ± 0.86bc	5.35 ± 1.12ab	19.36 ± 0.77e	25.51 ± 1.57f	3.29 ± 0.88a	9.77 ± 0.97cd	<0.05	5–15	Suitable except Poultry manure & Cow blood meal (too high)
Potassium (g/kg)	12.68 ± 0.87c	10.42 ± 0.89c	2.67 ± 0.98a	30.26 ± 1.20e	5.58 ± 0.83b	10.62 ± 0.62c	19.62 ± 0.88d	<0.05	5–20	Suitable except Cow rumen (too low) and Poultry manure (too high)

*Superscripts of Means ± SE with the same alphabet within the same row are not statistically significant

Table 4.3: Overall summary of compost suitability as organic fertilizer

Treatment	**Key Strengths**	**Limitations**	**Overall Compost Suitability**
Mixed	Balanced nutrients (N, P, K); pH and C:N within optimal range; good VS content	Slightly high N content but acceptable	Highly Suitable
Poultry feed (Control)	Moderate N, P, and K; good stability; EC within limit	Slightly low C but still within acceptable range	Highly Suitable
Cow rumen	Acceptable pH; moderate C:N ratio	Low C and VS; poor organic matter quality	Less Suitable
Poultry manure	Very high nutrient content; good pH; adequate VS	EC slightly high; may cause salinity if applied in excess	Moderately Suitable
Cow blood meal	Extremely rich in N and P; high C and VS	N and P above optimal range; may cause nutrient imbalance	Moderately Suitable
Honey waste	Acceptable K and pH	Very low C, VS, and nutrient balance; high C:N ratio	Less Suitable
Pig manure	Balanced nutrients; pH, EC, and C:N within range; good VS	Slight variation in EC but within acceptable limit	Highly Suitable

4.3 Suitability of frass from different waste streams as organic fertilizer

The nutrient composition and physicochemical properties of black soldier fly larvae (BSFL) frass varied significantly across substrates, confirming that the type and quality of feedstock strongly determine the fertilizer potential of the resulting frass. Similar trends have been reported in several recent studies (Beesigamukama *et al.*, 2020; Abd Manan *et al.*, 2024; Lomonaco *et al.*, 2024), emphasizing that substrate nutrient richness, digestibility, and mineral balance directly influence frass quality and its agronomic performance (Table 4.2).

Nitrogen content differed significantly among the treatments, ranging from 10.46 ± 1.22 g/kg in honey waste to 50.56 ± 2.38 g/kg in cow blood meal. Cow blood meal produced the highest nitrogen level, followed by the mixed substrate (42.86 ± 2.32 g/kg) and poultry manure (37.37 ± 1.16 g/kg). In contrast, cow rumen (16.34 ± 1.06 g/kg) and honey waste (10.46 ± 1.22 g/kg) had significantly lower nitrogen contents. This study revealed that frass derived from protein-rich substrates such as cow blood meal, poultry manure, and the mixed substrate exhibited the highest nitrogen concentrations, exceeding the standard threshold (10–30 g/kg) for effective organic fertilizer (Romano *et al.*, 2022; Gärttling, 2022). This observation aligns with the findings of Beesigamukama *et al.* (2021) and Lopes *et al.* (2022), who reported nitrogen values ranging from 25–45 g/kg in frass from nutrient-dense wastes such as abattoir residues and poultry manure. The enrichment of nitrogen in these treatments can be attributed to the higher protein and amino acid content of the input wastes, which are only partially assimilated by larvae, leaving a residue rich in organic nitrogen compounds and microbial biomass. As Lomonaco *et al.* (2024) noted, frass nitrogen partly originates from larval excreta and uneaten feed residues enriched with microbial metabolites, resulting in higher residual fertility. Conversely, substrates such as cow rumen and honey waste produced low nitrogen frass, consistent with their low protein content and poor degradability. These substrates contain high moisture and fibrous material, leading to nutrient dilution and slower decomposition, as similarly observed by Jasso *et al.* (2024) and Nyakeri *et al.* (2017).

Phosphorus concentration also varied significantly across the substrates. Cow blood meal had the highest phosphorus content (25.51 ± 1.57 g/kg), followed by poultry manure (19.36 ± 0.77 g/kg) and the mixed substrate (11.42 ± 1.21 g/kg). These treatments were significantly different from the control (8.33 ± 0.86 g/kg) and pig manure (9.77 ± 0.97 g/kg), which showed moderate phosphorus levels. The lowest phosphorus contents were observed in cow rumen (5.35 ± 1.12 g/kg) and honey waste (3.29 ± 0.88 g/kg). The high phosphorus values in cow blood meal and poultry manure indicate their potential as phosphorus-rich organic fertilizers derived from nutrient-dense animal waste. The phosphorus-enriched frass from cow blood meal and poultry manure supports the assertion of Boudabbous *et al.* (2023) and

Beesigamukama *et al.* (2020) that frass derived from animal-based substrates tends to have higher mineral content due to the original phosphorus bound in muscle and bone residues. Similarly, Romano *et al.* (2022) and Woo *et al.* (2024) reported that BSFL frass produced from manure and kitchen waste could contain between 10–25 g/kg phosphorus, comparable to organic fertilizers like composted poultry litter. The lower phosphorus content observed in honey waste and cow rumen frass may result from both substrate deficiency and differential microbial immobilization. Honey waste, being carbohydrate-dense but protein-poor, lacks sufficient phosphorus precursors, while rumen residues often undergo prior digestion in the animal gut, depleting soluble phosphorus. Abd Manan *et al.* (2024) further observed that the phosphorus fraction in frass is highly substrate-dependent, and enrichment often occurs when larvae are fed on substrates containing animal proteins or bone meal.

Potassium levels in BSFL frass also showed significant variation among treatments. Poultry manure recorded the highest potassium concentration (30.26 ± 1.20 g/kg), followed by pig manure (19.62 ± 0.88 g/kg), while cow rumen had the lowest value (2.67 ± 0.98 g/kg). The control (10.42 ± 0.89 g/kg), honey waste (10.62 ± 0.62 g/kg), and mixed substrate (12.68 ± 0.87 g/kg) had moderate potassium contents. The results suggest that substrates of animal origin, particularly poultry manure and pig manure, enhance potassium accumulation in frass, thereby improving its suitability as a nutrient source for soil amendment. Both values exceed or approach the optimal range (5–20 g/kg) for organic fertilizer materials (Gärttling, 2022). These results corroborate the findings of Beesigamukama *et al.* (2020), who observed that BSFL frass from poultry manure enhanced soil potassium content and maize yield, suggesting high plant-available K. Similarly, Lopes *et al.* (2022) and Awad *et al.* (2024) found that frass from manure and food waste had elevated K due to the high solubility and mobility of this element during larval digestion.

Conversely, cow rumen frass exhibited the lowest potassium concentration (2.67 ± 0.98 g/kg), similar to values reported by Meneguz *et al.* (2018) and Gold *et al.* (2020) for digested or fibrous feedstocks. This reduced K level may be linked to leaching losses during decomposition and the fibrous, waterlogged nature of the rumen substrate, which limits mineral retention. The moderate potassium concentrations in the mixed, control, and honey waste treatments (10–13 g/kg) suggest balanced nutrient recycling potential without posing salinity risks to soil.

The physicochemical parameters of the frass (Table 4.2) were largely within the acceptable ranges for mature organic fertilizer materials. All treatments exhibited near-neutral pH (6.85–7.68), aligning with the findings of Salomon (2025) and Beesigamukama *et al.* (2021), who reported that BSFL frass typically stabilizes between pH 6.5–8.0 due to ammonia volatilization and buffering from organic acids. Electrical conductivity (EC) values were below or slightly above the 4 mS cm^{-1} threshold in some treatments (notably poultry manure and cow blood meal), reflecting moderate salinity levels that may enhance nutrient solubility but should be managed to avoid osmotic stress on crops (Romano *et al.*, 2022; Woo *et al.*, 2024).

The carbon content of frass ranged from 162.53 g/kg (honey waste) to 432.67 g/kg (cow blood meal), with corresponding C:N ratios of 8.65–16.25. These values suggest that most frass materials were well-stabilized and suitable for soil application, as optimal compost maturity generally requires C:N ratios between 10 and 20 (Abd Manan *et al.*, 2024; Beesigamukama *et al.*, 2020). The lower ratios in cow blood meal and poultry manure frass indicate a high degree of nitrogen mineralization and potential for rapid nutrient release, while the higher ratio in honey waste reflects incomplete degradation and potential nitrogen immobilization upon soil application.

Volatile solids (VS), indicative of organic matter content, were highest in cow blood meal (634 g/kg) and poultry manure (494 g/kg), consistent with high nutrient and energy densities in their parent substrates. In contrast, cow rumen and honey waste had very low VS (<300 g/kg), corroborating their limited organic stability and low fertilization potential (Gärttling, 2022; Lomonaco *et al.*, 2024).

Based on integrated evaluation (Table 4.4), the frass from the mixed substrate, poultry feed (control), and pig manure were classified as highly suitable organic fertilizers. They combined optimal pH, balanced C:N ratios, and nutrient levels within the agronomic range. Poultry manure and cow blood meal frass were moderately suitable, primarily due to excessive nutrient concentrations (especially N and P) and slightly elevated EC, which could cause nutrient burn or salinity if applied excessively. In contrast, honey waste and cow rumen frass were less suitable due to poor organic matter quality and low nutrient density.

This pattern aligns with the broader consensus in recent literature that frass derived from nutrient-rich, proteinaceous substrates yields superior fertilizer quality but may require dilution or co-composting to prevent over-fertilization (Boudabbous *et al.*, 2023; Woo *et al.*, 2024; Anedo *et al.*, 2025). Conversely, frass from fibrous or carbohydrate-dominant substrates has lower nutrient and organic matter content but may improve soil texture and microbial activity when applied alongside other amendments.

In summary, the current results confirm that substrate type plays a decisive role in determining the nutrient composition, maturity, and overall quality of BSFL frass. The nutrient-rich frass from cow blood meal, poultry manure, and mixed wastes demonstrates high agronomic potential, aligning with prior reports that BSFL-derived fertilizers can effectively substitute or complement conventional organic fertilizers. However, appropriate management—such as rate adjustment or blending with low-nutrient materials, is essential to optimize nutrient release and avoid soil imbalances.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

This study demonstrated that black soldier fly larvae (BSFL) offer a viable and environmentally friendly solution for managing animal waste while producing nutrient-rich organic fertilizer. The results clearly showed that the efficiency of waste bioconversion and larval growth performance depended largely on the type and quality of the substrate. Poultry feed produced the highest waste reduction and bioconversion efficiency, indicating that substrates with balanced nutrients support optimal larval activity and biomass production. In contrast, honey waste and the mixed waste substrate showed limited degradability, emphasizing that substrate composition—particularly its protein, carbohydrate, and moisture balance—is a key factor influencing BSFL performance. Larval growth rates closely mirrored the waste reduction pattern. Rapid development was observed in nutrient-rich substrates, while low-protein, fibrous, or overly moist wastes restricted larval performance. Although feed conversion ratios varied among treatments, the differences were not statistically significant, suggesting that more standardized measurements or larger experimental replicates may be required for consistent interpretation. The quality of the frass produced also varied with substrate composition. Animal- and protein-based wastes such as cow blood meal and poultry manure yielded frass with high nitrogen and phosphorus concentrations, which could be beneficial for crops if properly managed. However, these may exceed safe agronomic limits if applied directly. On the other hand, frass derived from cow rumen and honey waste contained lower levels of essential nutrients and would be more appropriate as soil conditioners rather than stand-alone fertilizers. Overall, frass from mixed waste, pig manure, and poultry feed proved highly suitable for use as organic fertilizers, while those from poultry manure and cow blood meal were moderately suitable. In summary, the study confirms that BSFL composting can significantly reduce waste volume, enhance nutrient recovery, and contribute to sustainable waste management in developing contexts. However, careful substrate selection, optimization of rearing conditions, and post-treatment management of frass are essential to ensure environmental safety and maximize agricultural benefits.

5.2 RECOMMENDATION

The following recommendations have been made from this study

1. The use of mixed waste, and pig manure as primary substrates should be encouraged, since they yielded the highest waste reduction, nutrient recovery, and frass quality. Low-performing wastes such as honey waste and cow rumen should be improved through pre-treatment methods like drying, co-substrate blending, or mild fermentation to enhance nutrient accessibility and conversion efficiency.
2. Maintain suitable rearing environments—temperatures between 27–30°C, proper humidity, and appropriate larval density—to enhance larval growth and waste conversion. Substrates deficient in nutrients should be supplemented with small quantities of protein or minerals to improve larval performance and productivity.
3. Growth and conversion metrics should be recorded on a dry-matter basis, and standard protocols for rearing, substrate preparation, and frass collection should be established. This will ensure consistency, data reliability, and easier replication across production systems.
4. Frass should be categorized and applied according to its nutrient composition. Highly suitable frass (from mixed waste, poultry feed, and pig manure) can be applied directly, while moderately suitable types (from poultry manure and cow blood meal) should be diluted or co-composted. Frass from cow rumen and honey waste should be

used as soil conditioners rather than direct fertilizers. Regular pathogen and heavy-metal screening must precede large-scale agricultural use.

5. Establish BSFL-based composting units at farms and abattoirs to assess economic feasibility, greenhouse gas reduction, and long-term soil health impacts. Successful models can guide broader adoption through extension programs and local government support.
6. Develop practical training programs and policy incentives that promote BSFL technology adoption. Encourage the utilization of larval biomass for animal feed and lipid extraction for bioenergy to close resource loops, enhance waste valorization, and advance sustainable agricultural practices.

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APPENDIX

Appendix 1: Data on waste reduction and larval weight gain

Treatment	Day 0	Day 3	Day 6	Day 9	Day 12	Day 15	Initial waste (Day 0) – final waste (Day 15)	Initial larval weight (g)	Final Larval weight (g)
Control 1	150	142.5	124	84.8	69.3	56.6	93.4	2.1	28.2
Control 2	150	144.4	128	88.2	72.8	56.1	93.9	2.1	29.2
Control 3	150	139.6	121.1	79.4	65.6	64.4	85.6	2.1	30.6
Cow rumen 1	150	166.8	142.5	130.2	109.8	87.1	62.9	2.1	19.1
Cow rumen 2	150	160.2	139.2	143.6	129.3	111.2	38.8	2.1	21.8
Cow rumen 3	150	168.2	145.1	131.2	110.1	91	59	2.1	19.3
Poultry manure 1	150	173.3	158.6	145.5	135.9	129.8	20.2	2.1	3.4
Poultry manure 2	150	172.2	155.8	139.3	128.2	125.4	24.6	2.1	4.9
Poultry manure 3	150	167.1	142.8	128.3	127.1	123.3	26.7	2.1	5.1
Cow blood meal 1	150	157.4	127.7	129.2	110.5	94	56	2.1	14.1
Cow blood meal 2	150	158	128.7	126.7	123.2	101.6	48.4	2.1	13.7
Cow blood meal 3	150	156.8	125.1	124.5	121.6	117.4	32.6	2.1	14.4
Mixed 1	150	152.2	140.2	139.2	129.2	122.1	27.9	2.1	1.1
Mixed 2	150	153.9	147.7	145	152.5	132.5	17.5	2.1	1.7
Mixed 3	150	152	117.6	167.5	145.6	145.6	4.4	2.1	2.3
Honey waste 1	150	175.9	175.4	159.9	150.5	139.2	10.8	2.1	5.1
Honey waste 2	150	172.5	169.1	158.3	150.6	142.4	7.6	2.1	5.7
Honey waste 3	150	179.9	176.9	152.7	145.8	139.1	10.9	2.1	4.2
Pig manure 1	150	178.8	154.5	142.2	121.8	109.8	40.2	2.1	12.6
Pig manure 2	150	173.8	149.5	138.2	132.8	120.2	29.8	2.1	7.5
Pig manure 3	150	168.2	145.1	131.2	110.1	106.7	43.3	2.1	9.2

Source: Author's Fieldwork, 2025

Appendix 2: Results of %waste reduction, %BER, FCR and Larval growth rate

Treatment	**% Waste Reduction (DM)**	**% BER**	**FCR**	**Larval growth rate**
Control 1	62.27	28.18	3.31	28.06
Control 2	62.60	29.18	3.22	29.06
Control 3	57.07	30.58	2.80	30.46
Cow rumen 1	41.93	19.07	3.29	18.96
Cow rumen 2	25.87	21.75	1.78	21.66
Cow rumen 3	39.33	19.26	3.06	19.16
Poultry manure 1	13.47	3.30	5.94	3.26
Poultry manure 2	16.40	4.81	5.02	4.76
Poultry manure 3	17.80	5.02	5.24	4.96
Cow blood meal 1	37.33	14.06	3.97	13.96
Cow blood meal 2	32.27	13.66	3.53	13.56
Cow blood meal 3	21.73	14.34	2.26	14.26
Mixed 1	18.60	1.02	25.36	0.96
Mixed 2	11.67	1.58	10.29	1.56
Mixed 3	2.93	1.82	1.91	2.16
Honey waste 1	7.20	4.91	2.12	4.96
Honey waste 2	5.07	5.42	1.33	5.56
Honey waste 3	7.27	4.01	2.60	4.06

Pig manure 1	26.80	12.55	3.19	12.46
Pig manure 2	19.87	7.43	3.97	7.36
Pig manure 3	28.87	9.15	4.71	9.06

Appendix 3: Results of the nutrient components of the waste substrates

Treatment	Treatment ID	Moisture (%)	Fat (%)	Ash (%)	Crude Fibre (%)	Protein (%)	N.F.E Car (%)	Ca (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	K (mg/kg)
Mixed	3	94.55	0.32	0.51	0.74	1.21	2.67	2.96	19.81	9.45	97
Mixed	3	93.01	0.29	0.47	0.79	1.24	4.2	2.68	21.51	10.17	103.43
Mixed	3	95.04	0.34	0.52	0.79	1.23	2.08	2.85	18.06	10.16	105.67
Poultry feed	4	60.13	2.54	2.86	15.74	7.48	51.25	2.16	26.84	19.15	487
Poultry feed	4	63.54	2.31	2.7	15.08	6.85	52.52	1.98	26.76	17.5	512.38
Poultry feed	4	61.59	2.34	2.73	16.17	7.28	51.89	2.27	24.85	19.06	491.85
Cow Rumen	6	97.41	0.14	0.18	0.29	0.58	1.4	2.43	17.23	6.93	112
Cow Rumen	6	94.59	0.15	0.19	0.28	0.6	4.19	2.67	17.75	6.84	112.39
Cow Rumen	6	96.39	0.15	0.18	0.28	0.55	2.45	2.25	16.28	6.71	113.98
Poultry manure	9	72.35	1.02	1.57	2.34	4.32	18.4	3.12	17.54	8.21	233
Poultry manure	9	68.82	1.07	1.63	2.36	4.12	22	3.31	16.45	7.55	229.79
Poultry manure	9	73.37	0.94	1.55	2.32	4.71	17.11	3.07	17.42	8.59	241.08
Cow blood meal	10	81.73	0.7	0.84	1.45	3.74	11.54	3.23	18.32	10.73	204
Cow blood meal	10	84.8	0.67	0.84	1.36	4.05	8.28	3.54	16.85	10.52	197.44
Cow blood meal	10	84.76	0.67	0.86	1.48	3.48	8.75	3.46	17.4	10.07	201.9
Honey waste	11	27.68	2.33	2.89	18.34	6.23	42.53	2.88	19.43	9.11	512
Honey waste	11	28.41	2.35	3.05	18.45	5.61	42.13	2.84	18.57	8.65	555.34
Honey waste	11	27.19	2.11	3.14	19.73	6.64	41.19	2.85	20.83	9.2	465.98
Pig manure	12	79.5	0.45	1.15	2.9	4.4	10.5	2.9	16.5	7.5	195
Pig manure	12	80	0.5	1.2	3	4.5	10.8	3	17	8	200
Pig manure	12	80.5	0.55	1.25	3.1	4.6	11.1	3.1	17.5	8.5	205

Source: Author's Fieldwork, 2025

Appendix 4: Physico-chemical parameters of Frass

Treatment	Treatment ID	pH	EC (mS cm⁻¹)	Dry matter (%)	Total C (g/kg DM)	C:N ratio	Volatile Solids (VS, g/kg DM)
Mixed	1	7.48	3.37	56.13	367	8.67	537.8
Mixed	1	7.97	4.49	53.2	383.93	9.07	562.62
Mixed	1	7.6	3.27	54.12	351.76	8.31	515.47
Poultry feed	2	7.58	3.57	55.59	281.92	11.13	413.13
Poultry feed	2	7.54	3.72	57.22	248.74	9.82	364.51
Poultry feed	2	7.3	4.63	55.51	258.37	10.2	378.62
Cow Rumen	3	7.33	3.22	58.35	176	11	258.13
Cow Rumen	3	7.27	3.57	61.12	176	11	258.13
Cow Rumen	3	7.32	2.9	59.73	176	11	258.13
Poultry manure	4	7.53	4.24	54.3	339.66	9.18	497.73
Poultry manure	4	7.44	5.13	50.75	338.92	9.16	496.66
Poultry manure	4	7.57	4.1	53.74	333	9	487.98
Cow blood meal	5	7.56	3.3	54.92	457.5	9.15	670.42
Cow blood meal	5	7.66	4.69	55.18	448	8.96	656.5
Cow blood meal	5	7.59	4.45	62.39	392.5	7.85	575.17
Honey waste	6	6.7	3.2	39.39	164.7	16.47	241.35
Honey waste	6	6.83	2.57	47.35	154.5	15.45	226.41
Honey waste	6	7.03	3.54	53.76	168.4	16.84	246.77
Pig manure	7	7.76	4.78	59.65	279.72	10.36	409.9
Pig manure	7	7.35	3.04	52.65	304.56	11.28	446.3
Pig manure	7	7.65	4.11	54.03	282.15	10.45	413.47

Source: Author's Fieldwork, 2025

Appendix 5: Mineral component of frass

Treatment	Treatment ID	Nitrogen (g/kg)	Phosphorus (g/Kg)	Potassium (g/Kg)
Poultry feed (control)	1	25.47	8.12	10.63
Poultry feed (control)	1	27.38	7.59	9.44
Poultry feed (control)	1	24.65	9.27	11.18
Mixed	2	42.84	11.05	12.91
Mixed	2	45.19	12.77	13.42
Mixed	2	40.56	10.43	11.72
Cow rumen	3	15.21	5.66	2.34
Cow rumen	3	17.32	4.11	1.89
Cow rumen	3	16.48	6.29	3.77
Poultry manure	4	36.13	19.24	30.58
Poultry manure	4	38.42	18.65	31.27
Poultry manure	4	37.55	20.18	28.93
Cow blood meal	5	48.09	25.44	4.72
Cow blood meal	5	52.83	27.11	6.38
Cow blood meal	5	50.76	23.97	5.64
Honey waste	6	10.24	3.18	10.85
Honey waste	6	11.77	4.22	11.09
Honey waste	6	9.36	2.48	9.91
Pig manure	7	26.15	9.57	18.72
Pig manure	7	28.61	10.83	20.48
Pig manure	7	27.39	8.92	19.66