Evaluation of Organic Substrates for Optimised Black Soldier Fly (Hermetia illucens) Rearing

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ABSTRACT

The Black Soldier Fly (Hermetia illucens) has emerged as a sustainable solution for organic waste valorisation and as an alternative protein source for livestock feed within biocircular economies. A key challenge is the optimisation of rearing substrates, as nutrient balance, protein–energy ratio, and digestibility directly influence larval growth, biomass yield, and nutrient composition. This study evaluated BSF larval performance on seven locally available substrates identified through a mapping exercise based on availability, consistency, and volume. Larvae were reared under controlled laboratory conditions, and growth performance, biomass yield, and developmental progression were monitored for 41 days. Results demonstrated marked differences across substrates. Poultry bedding supported the fastest development, with hatching at day 9, sixth instar reached by day 22, and prepupation at day 32, though pupae were small, indicating nutrient limitations. Cooked maize meal and rice substrates showed moderate performance, with hatching at day 7, sixth instar at day 24, and prepupation at day 33. Meat facilitated rapid hatching (day 5) but failed to support progression to prepupation. Cow dung, sheep manure, fruit, and vegetable substrates performed poorly, with delayed development, high mortality, and failure to reach prepupation within the trial period. These findings highlight nutrient composition and carbon-to-nitrogen balance as primary drivers of BSF productivity. The study contributes new technical insights into substrate optimisation for BSF rearing in Zimbabwe, reinforcing its potential for sustainable waste management and insect-based protein production.

Keywords: Hermetia illucens, insect-based feed, substrate optimisation, larval development, organic waste valorisation

INTRODUCTION

Hermetia illucens (Linnaeus, 1758) is a species of fly in the family Stratiomyidae. Commonly known as the black soldier fly (BSF), it belongs to the genus Hermetia. BSF has gained global attention as a sustainable solution for organic waste management and alternative protein production. BSF undergoes complete metamorphosis through egg, larval, pupal, and adult stages, with the larval stage being the most critical for waste conversion and biomass accumulation (Li et al., 2011; Popa & Green, 2012). The BSF larvae undergo six instars, each marked by a moult, with feeding intensity and biomass accumulation peaking in the middle instars before declining as they prepare for pupation. The BSF substrate is the feeding medium in which BSF larvae are reared and provides the foundation for their growth and development. It provides essential energy and nutrients, including proteins, carbohydrates, fats, and minerals that directly influence larval survival, growth rate, and overall biomass yield (Barragan-Fonseca et al., 2017). The larvae are highly efficient at valorising diverse substrates, producing nutrient-rich frass that can be used as an organic fertiliser, while the harvested larval biomass serves as a protein and fat-rich ingredient for livestock and aquaculture feeds (Banks et al., 2014; Erickson et al., 2004). BSF larvae reduce waste volume by up to 50-70%, thereby lowering greenhouse gas emissions and odour problems associated with organic waste (Diener & Studt, 2011a).

The substrate also acts as the growth medium for the larvae. This dual functionality makes the BSF feed substrate critical for both sustainable waste valorisation and alternative insect-based protein generation. The choice of substrate is a key determinant for the success of BSF production, influencing larval growth rate, biomass yield, and nutrient composition (Barragan-Fonseca et al., 2017). BSF larval survival is closely influenced by substrate quality. Nutrient-rich substrate with highly digestible and balanced protein, carbohydrates, and moisture promotes higher survival, while poor-quality substrates that are nutrient-deficient, too dry, or too wet result in slow growth and high mortalities (Barragan-Fonseca et al., 2017). Survival outcomes also vary across organic waste, with poultry manure and food waste generally supporting better performance than fibrous, low-nutrient, and low-digestibility residues (Dortmans et al., 2017; Wang & Shelomi, 2017). In addition, environmental conditions linked to the substrate, such as moisture, temperature, and microbial activity, play a critical role.

Excess moisture can create anaerobic, pathogen -prone environments, whereas overly dry substrates hinder feeding efficiency (Diener & Studt, 2011b). Previous studies have demonstrated that BSF larvae can thrive on a wide range of organic waste, including poultry, pig, cattle, and goat manure, kitchen waste, and agricultural residues (Cichlidae et al., 2022; Popa & Green, 2012; Wang & Shelomi, 2017). However, substrate variability in nutrient composition, moisture content, and contamination risk means that no universal substrate has been established.

BSF larvae have gained considerable attention as a sustainable protein source, containing approximately 40-45% crude protein and 30-35% fat on a dry matter basis (Van Huis, 2013; Makkar et al., 2014). Given the rising demand for sustainable protein sources and the need to reduce reliance on conventional feedstocks such as fish meal and soybean meal (Van Huis, 2013; Makkar et al., 2014). Evaluating locally available substrates for BSF rearing is essential for optimising BSF production. Despite numerous studies, comparative evaluations of substrate suitability under standardised conditions are limited, and substrate performance can vary with geographic location due to differences in waste composition and climate (Barragan-Fonseca et al., 2017).

Furthermore, the impact of substrate choice on the nutritional quality and safety of harvested larvae remains underexplored. The localised studies are therefore essential to identify optimal substrates tailored to regional waste availability and production goals. This study investigates the performance of BSF larvae growth on different organic waste substrates, assessing their effects on larval growth, biomass yield, and nutrient content. The findings aim to identify suitable substrates that maximise BSF productivity while supporting the sustainable waste valorisation and circular economy principles (Diener et al., 2011b).

MATERIALS AND METHODS

Study Design

A controlled laboratory experiment was conducted to assess the growth performance, biomass yield, and nutrient composition of BSF larvae reared on different organic waste substrates. A total of seven locally available substrate types were selected based on preliminary waste characterisation and ease of access. To ensure reliability, substrate mapping was conducted to assess the availability, quantities, and consistency of supply for each organic waste stream.

Conceptual framework

The conceptual framework for this study (Figure 1) illustrates the relationship between substrate quality and BSF larvae's overall performance. It is grounded in the understanding that substrate characteristics such as protein content, energy value, and digestibility directly influence larval growth rates and bioconversion efficiency. These intermediate factors, in turn, affect the length of the development cycle and the mortality rates, which collectively determine the overall productivity and viability of BSF production. This framework guides the evaluation of substrate effects on larval performance, supporting the study's aim to identify optimal organic waste inputs for sustainable BSF rearing.

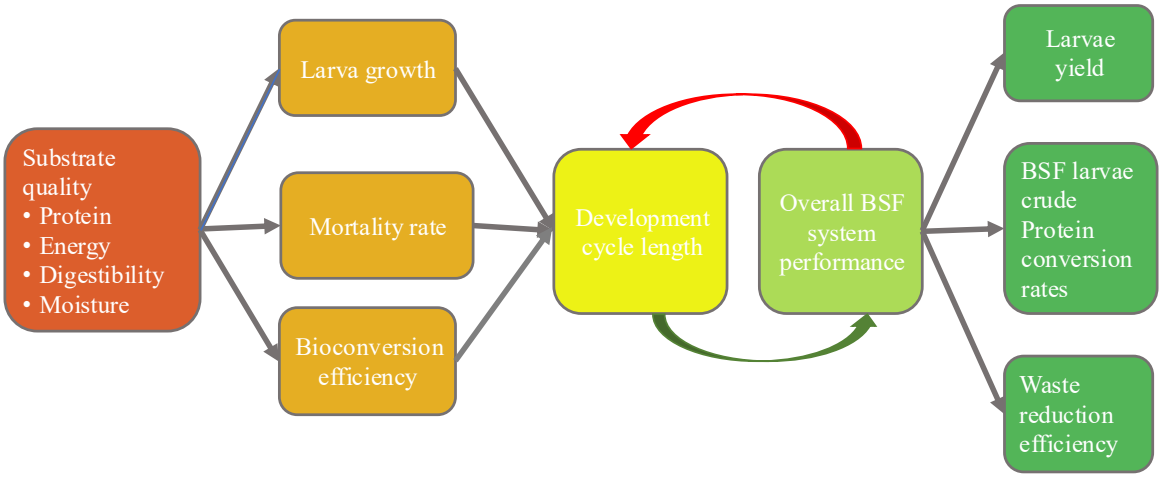


Figure 1: Conceptual framework illustrating the key areas of substrate quality on Black Soldier Fly production performance.

Substrate Selection and Preparation

The substrates tested in the study comprised a diverse range of organic materials, including kitchen swill such as fruit, vegetables, cooked maize meal locally known as cooked maize meal, rice, livestock manure from sheep and cattle, and chicken droppings mixed with hay, which are some of the locally available substrates. In addition, protein-rich materials such as meat and eggs were evaluated. The selection of substrates provided a broad spectrum of feedstock types, enabling assessment of their potential for the intended experimental or processing outcomes. All substrates were subjected to various pretreatments, summarised in Table 1. Each substrate was collected fresh, homogenised, and characterised for moisture content, pH and temperature. These substrates were also used as both the hatching and growing medium. Before the introduction of eggs for incubation, the substrates were adjusted to an optimal moisture content of approximately 60-70%. More water was added as and when necessary for substrates that dry out fast.

Table 1: Substrate description and pretreatment

Substrate	Description	Preparation and pretreatment
Maize meal	Cooked maize meal	Mixed with water and ground into porridge/paste
Rice	Cooked rice	Mixed with water and ground into porridge/paste
Eggs	Raw eggs, including both yolk and egg white	Beaten to a uniform paste-like consistency
Meat	Mostly beef and chicken from kitchen waste	Cooked, chopped, and minced
Poultry bedding	Hay and poultry bedding	Ground to powder, mixed with water to porridge/paste

Cow dung	Fresh, within 24 hours of excretion	Mixed with water and ground into porridge/paste
Sheep manure	Fresh, within 24 hours of excretion	Mixed with water and ground into porridge/paste
Fruit & vegetables	Farmers market rejects, damaged but not rotten	Ground to porridge/paste

Larvae Rearing Conditions

BSF eggs were obtained from a colony at the Scientific and Industrial Research and Development Centre (SIRDC) insectary. Eggs weighing one gram were placed in a tray containing 2 kg of wet substrate. The same substrate was used both as a hatching medium and feed during the first and fifth instar larval rearing stages. Larvae were reared at an ambient temperature of 27±4°C, a relative humidity of 60-80% under natural photoperiod conditions. The experiment lasted forty-two days, which is a typical duration from hatching to the pupal stage.

Research design

The study employed a Randomised Complete Block Design (RCBD) with three replicates per substrate to minimise environmental variation and ensure reliable comparisons. Seven substrate treatments were evaluated under uniform moisture conditions and temeperatue conditions. Any variation in temperature observed during the trials was attributable to inherent substrate effects rather than external environmental factors. Each experimental unit consisting of 200 larvae reared in trays containing equal initial substrate mass. Substrate quantities were subsequently adjusted based on larval valorisation rates to maintain optimal feeding conditions. Data collection focused on key performance indicators, including hatch rate, larval weight gain, biomass yield, survival percentage, and frass composition. Statistical analysis was conducted using ANOVA to determine treatment effects, while regression analysis was applied to explore relationships between substrate nutrient composition and larval performance.

Data Collection

Data collection was organised by key stages in the BSF life cycle. During the egg stage, measurements included hatch rate, days to hatch, substrate temperature and pH. During the larval stage, data collected included substrate temperature and pH, total feed consumed, and qualitative observations of larval movement, responses to temperature variation, and signs of developmental stagnancy. The data were used to assess larval growth performance, substrate temperature and pH, time required to reach the prepupal or pupal stage and larval survival rate, providing an integrated assessment of growth efficiency and developmental progression across substrates.

Statistical Analysis

Data were analysed using Microsoft Excel. Descriptive statistics, means, and standard deviations were calculated to compare and summarise larval growth performance, biomass yield, and nutrient composition across substrate types. Comparative analyses were conducted to evaluate differences among substrates. Where applicable, percentage differences and relative performance indices were computed to facilitate cross-substrate comparison. Results were presented using tables and graphical visualisation to illustrate trends and performance patterns among substrate categories. All analyses focused on identifying performance differences associated with substrate type rather than on formal hypothesis testing, given the heterogeneity of experimental conditions across the included treatments.

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RESULTS AND DISCUSSION

Days from hatching to the pupal stage

Days to hatch were determined by looking for signs of hatching through visible eggshell and larval movement in the substrate. Protein-rich foods, such as meat, resulted in eggs hatching within 5 days; poultry eggs took 6 days; whilst high-fibre substrates, such as fruit and vegetables, took 8 days. BSF eggs incubated in poultry bedding took the longest, up to 9 days (Table 2). Manure-based substrates took up to 8 days for BSF eggs to hatch.

Table 2: Substrate Influence on BSF Developmental Stages

Substrate	January													February																
	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Stage	Hatching				First to sixth instar larvae																		Prepupae							Pupae										
Adamtey et al., 2024; Morgan & Zimmerman, 2016	4days				18days																		7days							11days										
Poultry bedding	9days													19days															4 days						8days					
Cooked maize meal & rice	7days													22days																				8days					3 days	
Fruit and vegetables	6days													34days																										
Cow dung	8days													32days																										
Meat	5days													35days																										
Chicken eggs	6days													34days																										
Sheep manure	8days													32days																										

The period from the first to the sixth instar varied across substrates, with a minimum of 19 days for poultry bedding to more than 35 days for fruit and vegetables, cow dung, meat, chicken eggs and sheep manure. In this trial, only poultry bedding, rice, and cooked maize meal reached the prepupal to pupal stage, indicating a shortened developmental cycle. The larval developmental periods observed, except for poultry bedding and cooked maize meal and rice, were comparable to previous studies reporting an average development period of 24 ± 6.2 days. Fruit and vegetables, cow dung, meat, chicken eggs and sheep manure resulted in larvae development periods being longer than those reported in the literature, which is not ideal for optimised BSF larvae rearing. Across all the substrates, none of the larvae or pupae from the different substrates reached the adult fly stage within the 40-day trial period.

Starch-based substrates, cooked maize meal and rice, and the protein-rich substrate, eggs, produced the highest larval and pupal weights despite notable differences in pH among the substrates. The observed pH ranged from 3.65 to 7.97 (Figure 3), with varying larval performance indicating the broad pH tolerance of BSF larvae. Rice and cooked maize meal were relatively acidic with a pH of 4, whereas eggs were closer to neutral with a pH of 6 (Figure 3). In contrast, fruit and vegetable substrates with a pH of 6 yielded the lowest larval weights. This pattern indicates that pH alone does not determine larval growth performance.

Larval development requires two to four weeks, depending on temperature and food availability (Barragan-Fonseca, 2017; Diener et al., 2009). In similar studies by Lalander et al. (2019), the pH of the substrate after five days ranged between 4.3 for dog food, fruit & vegetables, and 8.9 for poultry manure. The findings point to substrate nutritional composition as a strong driver of larval development. Starch-rich and protein-rich substrates provide readily digestible energy and amino acids that support rapid biomass accumulation and efficient nutrient conversion (Barragan-Fonseca et al., 2017; Meneguz et al., 2017). Fruits and vegetables, which are lower in protein levels and higher in fibre and moisture, consequently have limited larval growth performance.

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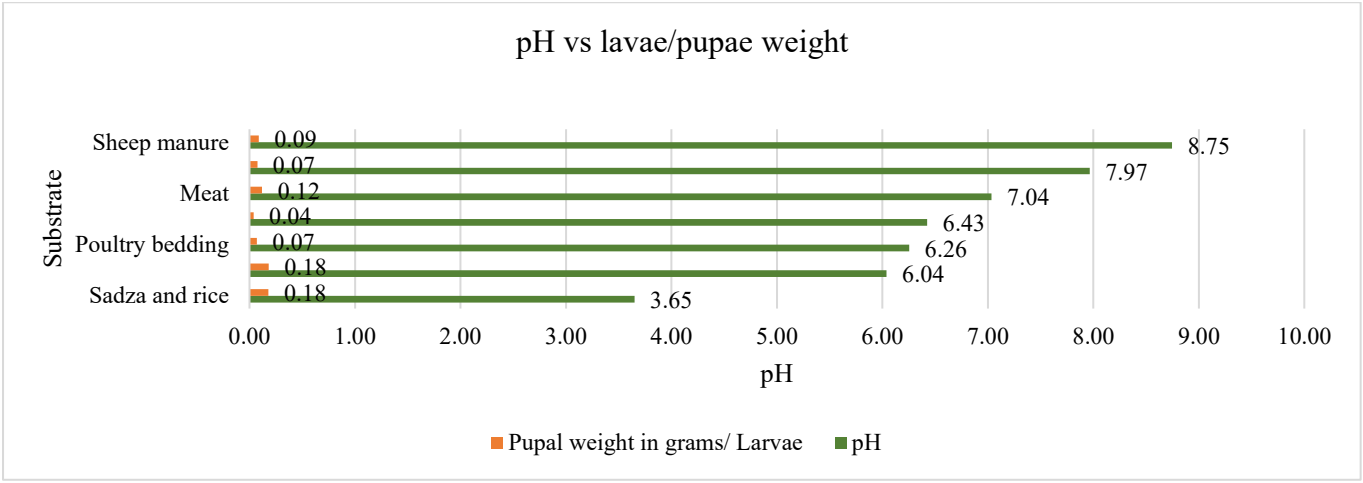


Figure 2: Substrate pH and corresponding Black Soldier Fly larval performance.

The results indicate no direct linear relationship between pH and larval growth, highlighting the importance of nutrient quality and digestibility. Previous studies similarly report that BSF larvae can develop under a wide range of substrate conditions, provided nutritional requirements are met (Diener et al., 2009; Lalander et al., 2019). Therefore, while pH levels may influence microbial activity and substrate palatability, optimal larval growth appears to depend more strongly on nutrient balance, digestibility, and moisture content than on pH in isolation.

Temperature variation among substrates was observed (Figure 4), with starch-based substrates such as cooked maize meal and rice recording lower temperatures, averaging 23.1 °C, while sheep manure exhibited the highest temperature, averaging 25.4°C. Despite these differences, no clear trend in substrate-associated temperature and larval growth performance was detected across treatments. This likely reflects the fact that all recorded temperatures fell within the generally accepted optimal rearing range for BSF. Previous studies indicate that BSF larvae perform well between approximately 20 °C and 30 °C, with optimal growth commonly reported around 25–30 °C (Barragan-Fonseca, 2017; Dicke & Loon, 2017; Diener & Studt, 2011b; Tomberlin et al., 2002).

Within this favourable thermal window, moderate temperature variation may have a limited influence on growth compared to factors such as nutrient composition, moisture content, and substrate digestibility (Barragan-Fonseca et al., 2017; Meneguz et al., 2017). Therefore, the absence of a temperature growth relationship in this study is consistent with the species' known thermal tolerance and suggests that under near-optimal conditions, substrate quality exerts a stronger influence on larval growth performance than small temperature differences. Temperatures across the substrates remained within the biologically favourable range for BSF larvae, and no consistent relationship with growth performance was observed.

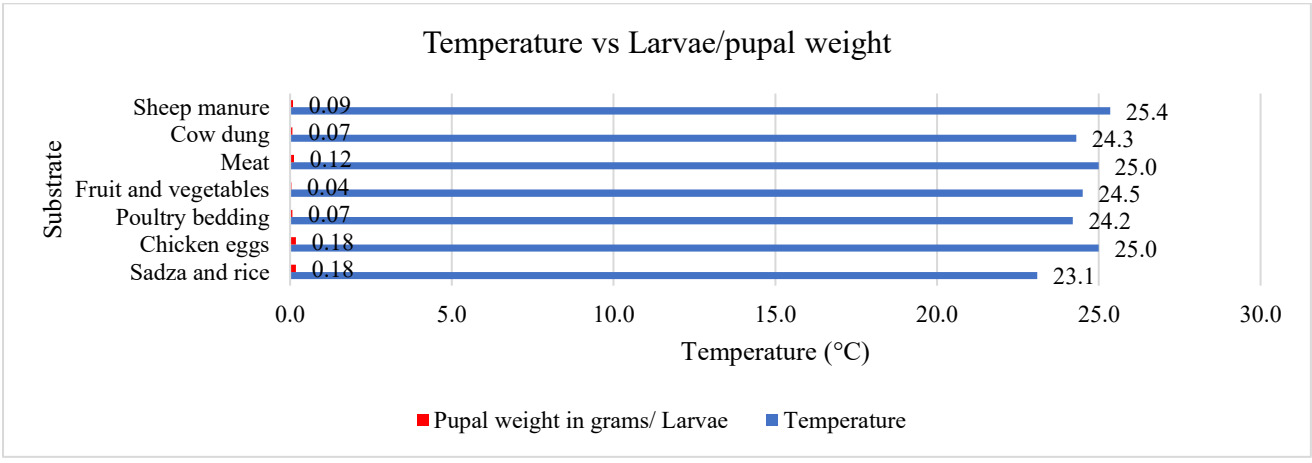


Figure 3: Substrate-associated temperature and BSF larval growth.

Growth performance varied markedly among the seven substrate treatments, largely due to differences in nutritive value, particularly the carbon-to-nitrogen ratio and substrate digestibility. Substrates with an imbalanced carbon-to-nitrogen ratio can limit protein availability and energy supply, thereby constraining larval growth and biomass accumulation (Barragan-Fonseca et al., 2017; Cichlidae et al., 2022; Dicke & Loon, 2017; Meneguz et al., 2017). In contrast, larvae reared on poultry bedding exhibited more uniform growth and successfully reached the pupal stage, although the pupae produced were relatively small in size. This indicates that poultry bedding can provide adequate conditions for development and completion, but its nutrient profile may limit the maximum accumulation of biomass. Previous studies similarly note that substrates with moderate nutrient value support development but do not yield optimal larval size (Barragan-Fonseca et al., 2017; Diener & Studt, 2011b). Overall, these findings highlight the importance of substrate nutrient balance, particularly protein availability and digestible energy, in determining larval growth performance and uniformity in larval size by day 40. Larvae reared on cow dung, fruit and vegetable waste, meat, and sheep manure exhibited substantial variation in growth rates within treatments, with visible signs of runting and stunting (Figure 5). Such heterogeneity in larval size is commonly associated with nutrient limitations, high fibre content, or uneven substrate quality, which can reduce feed conversion efficiency and prolong development (Lalander et al., 2019; Lalander et al., 2014; Meneguz et al., 2017).



Figure 4: Images showing variation in larval growth performance across substrate treatments at day 40.

The number sampled varied as a result of high mortality levels in some substrates, such as fruit and vegetables and sheep manure. These differences highlight the importance of substrate nutrient quality and the carbon-to-nitrogen balance in determining growth outcomes. Visual evidence confirms that starch-based and protein-rich substrates supported rapid larval development and biomass accumulation (Barragan-Fonseca et al., 2017; Cichlidae et al., 2022; Meneguz et al., 2017), whereas fibre-rich or imbalanced wastes reduce feed conversion efficiency and prolong development (Diener et al., 2009). Poultry bedding sustained development but yielded smaller larvae, consistent with previous findings that manure-based substrates often require supplementation for optimal growth (Lalander et al., 2014).

Overall, substrate nutrient composition, rather than substrate type alone, emerged as the primary driver of BSF larval performance. High mortality rates in fruit and vegetable substrate, cow dung, and sheep manure further indicate that these substrates are unsuitable when used individually, underscoring the need for balanced substrate nutrient composition, rather than substrate type alone, as the primary driver of BSF larval performance.

Nutritional Composition of Dried Non-defatted BSF Larvae

Larvae that were fed starch-based substrates, cooked maize meal and rice, and protein-based eggs and meat were selected based on their higher larval performance and were analysed for their nutritive value. Table 2 presents results from the proximate and mineral compositions of BSF larvae reared on starch-based substrates, poultry eggs, and meat in comparison with other findings from the literature. The table highlights how substrate type influences key nutritional parameters, including crude protein and lipid content, mineral composition, fibre, and metabolisable energy. Literature values are included to contextualise the observed results and to assess the suitability of the tested substrates for producing nutritionally balanced BSF larvae for livestock feeds and waste valorisation applications.

Table 3: Nutritional composition of BSF larvae compared with literature values

	Starch based	**Protein-based**		
Parameter	**Cooked maize meal and rice**	**Eggs and meat**	**Literature Range**	**References**
Dry Matter (DM, %)	92.1	90.1	90 – 95	Makkar et al., 2014
Crude Protein (CP, %)	32.8	37.1	40 – 45	Barragan-Fonseca et al., 2017; Huis, 2013; Lalander et al., 2019
Crude Fibre (CF, %)	8.56	10.35	6 – 10	Lalander et al., 2013
Acid Detergent Fibre (ADF, %)	9.85	12.28	8 – 12	Lalander et al., 2013
Neutral Detergent Fibre (NDF, %)	33.7	37.82	30 – 40	Lalander et al., 2013
Fat (%)	30.41	23.97	25 – 35	Meneguz et al., 2017; 2018
Ash (%)	13.4	16.1	10 – 15	Henry et al., 2015
Calcium (Ca, %)	3.49	4.04	3 – 5	Henry et al., 2015
Phosphorus (Phos, %)	0.67	0.97	0.6 – 1.0	Henry et al., 2015
Metabolizable Energy (ME, MJ/kg)	11.48	11.03	11 – 13	Makkar et al., 2014

The proximate analysis carried out on BSF larvae reared on starch-based cooked maize meal and rice substrates, and on protein-based egg and meat substrates, was broadly consistent with values reported in the literature (Figure 6). The dry matter content of larvae was high in both substrates, with larvae fed starch-based substrate having 92.1 and 90.1 for protein-based substrates, aligning with the typical range of 90-95% for BSF larvae (Makkar et al., 2014). Crude protein was higher in larvae reared on protein-based substrates, with 37.1% crude protein compared to 32.8% for larvae fed starch-based substrates. However, both treatments showed crude protein levels below the commonly reported 40-45% range (Huis, 2013; Barragan-Fonseca et al., 2017). This confirms that protein-rich substrates enhance protein deposition while starch-based substrates primarily support energy accumulation.

Fat content was markedly higher in starch-based larvae, with a fat content of 30.41%, compared to protein-based larvae, with 23.97% fat content, consistent with findings by Meneguz et al. (2017, 2018). The fibre fractions, crude fibre, acid detergent fibre, and neutral detergent fibre, were higher in protein-based larvae, which may reduce digestibility and prolong development, as per previous findings by Lalander et al. (2013, 2019). Mineral content, ash, calcium, and phosphorus were higher in larvae fed protein-based substrate, indicating enhanced mineral assimilation in agreement with findings by Henry et al. (2015).

Metabolisable energy values were slightly higher in larvae fed starch-based diets at 11.48 MJ/kg than in larvae fed protein-based diets at 11.03 MJ/kg. The findings from both fall within the expected range of 11–13 MJ/kg (Makkar et al., 2014). This highlights a clear nutritional trade-off: starch-based substrates promote fat deposition and increase energy density. Protein-based substrates promoted protein accumulation and mineral content. Overall, the results demonstrate that substrate composition strongly shapes BSF larval nutrient profiles and that balanced substrate formulations combining energy-dense and protein substrates are likely to optimise larval productivity, nutritive value, feed quality, and waste bioconversion efficiency.

DISCUSSION

The results provide important insights into how substrate quality influences BSF larvae development from hatching to pupation. Larval weight gain, growth rates, and bioconversion efficiency vary markedly among substrates. This confirms that substrate characteristics are primary drivers of BSF performance. This aligns with the broader consensus that BSF larvae are highly responsive to substrate nutrient composition and digestibility (Barragan-Fonseca, 2017; Diener et al., 2009). Carbohydrates, proteins, lipids and minerals are essential for larval metabolism and tissue synthesis. BSF larvae have been shown to efficiently convert protein and carbohydrate-rich substrates into biomass due to their high digestive capacity and voracious appetite (Barragan-Fonseca, 2017).

Poultry bedding promoted rapid development, probably due to its relatively high nitrogen content. However, the production of small pupae suggests that high nitrogen alone may accelerate development without supporting optimal biomass accumulation. Similar trade-offs between development rate and final size have been reported when larvae are reared on nutritionally imbalanced diets (Meneguz et al., 2018). Despite this limitation, poultry bedding remains a practical and low-cost substrate, particularly in rural areas and peri-urban areas where it is readily available. Conversely, fruit and vegetable waste, cattle dung, and sheep manure produced lower biomass and slower growth rates. These substrates typically contain higher lignocellulosic fractions and lower nitrogen availability, which can reduce digestibility and nutrient uptake (Lalander et al., 2013; Lalander et al., 2014). The observed runting and stunting likely reflect poor nutrient accessibility and reduced feed conversion efficiency. High fibre content has previously been associated with prolonged larval development and lower biomass yields (Gold et al., 2021). The findings underscore the importance of substrate formulation strategies. Co-feeding or blending nutrient-poor and nutrient-rich substrates can improve the carbon-to-nitrogen ratio and enhance larval performance. Optimising the carbon-to-nitrogen ratios has been shown to significantly improve bioconversion efficiency and larval protein yield (Lalander et al., 2019). Beyond nutrient composition, physical substrate properties influence outcomes. Sticky substrates such as eggs and cooked maize meal limited mobility and aeration, potentially reducing feeding efficiency. Adequate substrate structure is known to facilitate larval aggregation and oxygen flow, both of which are important for optimal larval development. Fruit and vegetable substrates also attracted fruit fly infestations, introducing competition and contamination risks that may reduce the efficiency of BSF larvae rearing.

Importantly, substrate optimisation affects not only larval growth but also mortality, waste-reduction efficiency, and frass quality. BSF frass has increasing value as an organic fertiliser; its nutrient profile depends strongly on the original substrate (Klammsteiner et al., 2020). Thus, substrate choice has implications for both upstream insect protein production and downstream agricultural applications. Overall, the variation observed among substrates reinforces that BSF production systems benefit from deliberate substrate selection and formulation. Strategies that balance nutrients, improve texture, and reduce contamination risks can significantly enhance BSF larvae productivity and sustainability.

CONCLUSION

This study confirms that substrate quality is the dominant factor influencing BSF larval growth, development, and bioconversion efficiency. Nutrient-rich substrates such as poultry bedding, starch-based feeds, eggs, and meat supported larval performance, whereas high-fibre nutrient-poor substrates did not. The findings suggest that balanced nutrition, particularly adequate protein, highly digestible carbohydrates, and an optimal carbon-to-nitrogen ratio, is more critical than substrate type alone. Poultry waste, while readily available, appears nutritionally incomplete when used as the sole feedstock. This highlights the value of co-substrate and substrate formulation strategies to enhance low-quality substrates for both the hatching medium and larval feeding. In addition, the physical characteristics of the substrate influence larval mobility, feeding efficiency, and substrate selection, ultimately shaping frass quality and the potential for waste valorisation. Therefore, future BSF rearing should prioritise substrate formulation approaches that optimise nutrient balance and texture to maximise larval productivity, waste conversion efficiency, and overall sustainability.

Limitations of the Study

This study provides valuable insights into the influence of substrate quality on BSF larval development; however, several limitations must be acknowledged. Quantitative information on key performance indicators such as larval weight gain, biomass conversion ratio, feed conversion efficiency, survival percentage, and nutrient composition of harvested larvae was limited. Importantly, the nutritional composition of substrates was not directly analysed in the laboratory but inferred from literature values, which restricts the ability to establish precise correlations between substrate chemistry and larval growth outcomes. These omissions limit the generalisability of the findings and constrain the development of precise substrate optimisation strategies. Future studies should incorporate direct substrate nutrient analyses, replicated trials under controlled conditions, and comprehensive performance metrics to strengthen the reliability and applicability of results.

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