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Circular bioeconomy poultry feed pellets from food waste using black soldier fly larvae

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ABSTRACT

This study aimed to develop and evaluate a waste-derived poultry feed pellet that simultaneously addresses protein, mineral, and waste-management gaps by optimizing the combined use of BSF larvae meal and chicken feet bone flour. We hypothesized that moderate inclusion levels would yield nutritionally adequate pellets capable of supporting acceptable growth performance while reducing production costs. Using a design-based research (DBR) approach, five feed variants with differing proportions of BSF meal and bone flour were formulated, pelletized, and subjected to proximate analysis and a 14-day feeding trial on semi-free-range chickens. Key findings showed that all formulations met minimum protein (21–27%) and moisture standards, although ash and fiber levels exceeded national standard limits at higher bone flour proportions. Growth trials revealed that low–moderate inclusion variants supported satisfactory weight gain and feed conversion, while performance declined in high-substitution treatments due to reduced metabolizable energy. Cost analysis demonstrated up to 25% feed cost reduction, driven by the use of post-consumption food waste and poultry by-products. The study provides new evidence that integrating BSF larvae meal with chicken bone flour in pelletized form offers a technically feasible and economically advantageous pathway for circular bioeconomy feed production. The findings fill a research gap on combined protein–mineral waste valorization in poultry feed and demonstrate the potential of multi-waste bioconversion systems for sustainable livestock nutrition.

Keywords: black soldier fly, food waste valorization, poultry feed, circular economy, sustainable agriculture, bioeconomy.

INTRODUCTION

Livestock production is a major contributor to global food security but also a significant consumer of natural resources (Akash et al., 2022; Michalk et al., 2019). In particular, poultry farming has grown rapidly in developing regions due to its relatively low environmental footprint and high feed conversion efficiency (Birhanu et al., 2021). However, feed ingredients such as fishmeal and soybean meal remain costly and environmentally burdensome due to their intensive resource requirements and competition with human food systems (Alhotan, 2021). According to Feed accounts for up to 75% of total poultry production costs, making feed efficiency a critical determinant of both profitability and sustainability (Nkukwana, 2019). This challenge has spurred a global search for alternative protein sources derived from local, renewable, and waste-based materials.

In this context, the black soldier fly (BSF; *Hermetia illucens*) has emerged as a promising bioconversion agent capable of transforming organic waste into high-value protein and lipid biomass (Raman et al., 2022; Siddiqui et al., 2024; Sumardiono et al., 2024). Through larval feeding, post-consumption food waste can be rapidly converted into Maggot meal rich in amino acids and micronutrients suitable for poultry diets. Numerous studies have reported that BSF larvae meal can partially or completely replace fishmeal in poultry and aquaculture feeds without compromising animal performance or product quality (Iqbal et al., 2025; Liu et al., 2022; Parodi et al., 2021). Furthermore, the use of insect larvae supports the principles of a circular bioeconomy, where organic waste streams are recaptured into productive loops instead of being disposed of in landfills or open dumps (Liu et al., 2022).

Beyond the protein component, bone-derived calcium and phosphorus are also essential for optimal poultry growth, bone strength, and eggshell quality. Chicken feet bones represent an underutilized mineral source that can be processed into bone flour with high bioavailable calcium and phosphorus content (Malakiano et al., 2025). Combining Maggot meal with chicken feet bone flour thus provides a dual approach to valorizing waste from both household food and animal processing sectors. Integrating these ingredients into pelletized feed formulations further enhances storage stability, uniformity, and feed conversion efficiency during poultry rearing.

While extensive research has demonstrated the nutritional potential of BSF larvae meal as a sustainable protein substitute in poultry feed, most studies have focused primarily on its protein composition and effects on growth performance in isolation (Ahmed et al., 2023; Fuso et al., 2021; Huang et al., 2022). Comparatively little attention has been given to integrated feed formulations that combine BSF larvae meal with locally sourced mineral supplements such as bone-derived calcium and phosphorus. In particular, the valorization of chicken feet bone flour, a readily available byproduct of poultry processing, remains underexplored as a complementary mineral source in insect-based feeds. Furthermore, there is limited empirical data on how the combined inclusion of BSF larvae meal and chicken bone flour in pelletized form affects poultry growth performance, feed efficiency, and bone quality parameters. This lack of holistic evaluation constrains the optimization of circular feed systems that could simultaneously address protein, mineral, and waste management challenges in poultry production.

Addressing this gap is increasingly urgent given the escalating costs and environmental impacts associated with conventional feed ingredients such as fishmeal and soybean meal. The global poultry industry faces mounting pressure to transition toward resource-efficient, waste-based feed systems that align with circular bioeconomy principles. Simultaneously, food waste and animal byproduct accumulation continue to pose serious environmental and public health risks in many developing regions. Developing and validating feed formulations that integrate BSF larvae meal and chicken feet bone flour offer a timely, locally adaptable solution to these intersecting challenges. Such innovation can enhance feed self-sufficiency, reduce dependence on imported inputs, and promote sustainable waste valorization practices – thereby supporting both food security and environmental sustainability goals.

Therefore, this study aims to develop and evaluate a waste-derived poultry feed pellet that integrates BSF larvae meal with chicken feet bone flour to simultaneously address the gaps in protein supply, mineral supplementation, and multi-waste valorization. Specifically, the research seeks to determine how varying proportions of BSF larvae meal and bone flour influence the nutritional composition of pellets, growth performance, and feed conversion in semi-free-range chickens, an aspect that remains insufficiently explored in existing literature.

The study is designed to generate new scientific evidence on the combined protein and mineral optimization potential of multi-waste feed formulations within a circular bioeconomy framework. We hypothesize that moderate inclusion levels of BSF larvae meal and bone flour will produce nutritionally adequate pellets capable of supporting acceptable growth and improved cost efficiency compared to conventional feed. These findings are expected to fill a critical knowledge gap regarding integrated waste-based feed systems and provide a foundation for scalable, resource-efficient poultry nutrition strategies.

MATERIALS AND METHODS

This study employed a design-based research (DBR) framework (Barab and Squire, 2004; Cotton et al., 2009) adapted for environmental product innovation. The DBR process consisted of three major phases: (1) problem and context analysis, (2) design and development of pellet formulations, and (3) evaluation and refinement through laboratory analysis and short-term feeding trials. The DBR approach was selected for its iterative nature, allowing adjustments in formulation and process based on both empirical data and practical constraints in local poultry production systems.

Phase I: problem and context analysis

The initial phase focused on identifying constraints within local poultry production that could be addressed through waste-derived feed formulations. Field observations were conducted to document feeding practices, availability of feed resources, and production challenges faced by smallholder farmers. Informal interviews with farmers and food vendors provided insight into locally accessible waste streams, particularly post-consumption food waste and chicken feet bones. A preliminary assessment comparing commercial feed standards with the potential nutritional contribution of BSF larvae meal and chicken bone flour informed the feasibility and relevance of these materials. This phase established a clear practical need for low-cost, nutrient-rich feed alternatives derived from locally available waste resources.

Phase 2: design and development of pellet formulations

Collection and processing of raw materials

Post-consumer food waste was collected from household and small food service sources in the Malang region, East Java, Indonesia. The waste consisted primarily of rice, vegetable scraps, and residual cooked foods. After manual sorting to remove contaminants, the waste was homogenized and used as a substrate for the cultivation of (BSF; *Hermetia illucens*) larvae. The larvae were reared for 10–12 days under controlled conditions (27–30°C; 60–70% relative humidity) until reaching the prepupal stage. The harvested larvae were washed, blanched in hot water (≈90 °C for 5 min) to ensure microbial safety, sun-dried for 2–3 days, and ground into Maggot meal powder. The process of making BSF larvae flour can be seen in Figure 1.

Chicken feet bones were collected from local food stalls. The bones were washed, boiled to remove residual tissues and fat, sun-dried for 3–4 days, and mechanically ground using 8 mm and 4 mm sieves. The resulting material was then milled through a 60-mesh screen to produce fine bone flour, which served as a calcium–phosphorus source in the pellet formulations. The procedure for producing chicken feet bones flour is depicted in Figure 2.

Pellet formulation and production

An iterative DBR development cycle was used to refine the feed formulations. Preliminary small-batch mixtures were tested to evaluate binder performance, moisture balance, pellet cohesion, and durability. Adjustments were made to binder proportion, water content, and mixing duration to improve pellet stability and uniformity. Five experimental formulations (P1–P5) listed in Table 1 were designed by varying the inclusion levels of BSF larvae meal and chicken bone flour, while keeping rice bran, tapioca flour, and concentrate constant across treatments. A commercial factory-produced feed (P0) served as the control. Each formulation was mixed thoroughly, hydrated to a workable consistency, pelletized using a 4 mm die, and sun-dried for 6–8 hours over two consecutive days. The pellet-making process can be observed in Figure 3.

Poultry feeding trial

A 14-day feeding trial was conducted using semi-free-range chickens (*Gallus gallus*

Figure 1. Steps to create BSF larvae flour: (a) BSF larvae harvest; (b) BSF larvae drying; (c) dried BSF larvae; (d) BSF larvae flour

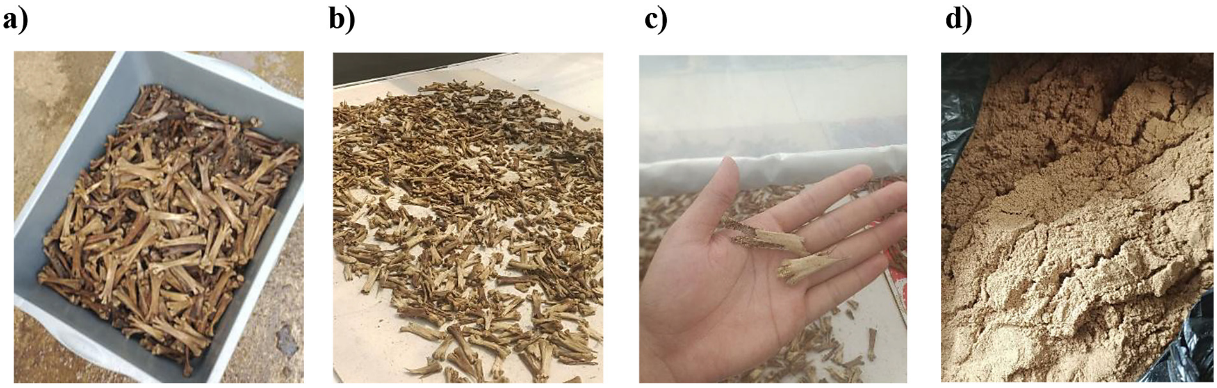

Figure 2. Steps to create chicken feet bones flour: (a) chicken feet bones; (b) bones drying; (c) dried bones; (d) chicken feet bones flour

domesticus) of comparable initial body weight. Birds were randomly assigned to treatment groups corresponding to the five pellet variants, with three replicates per treatment. Feed and water were provided ad libitum throughout the study period.

Daily feed intake was measured by recording the weight of feed offered and residual feed. Body weight measurements were taken on Day 0, Day 7, and Day 14. Mortality was monitored and used to calculate corrected feed conversion ratio (FCR). Growth performance parameters – including weight gain, feed intake, and FCR – were calculated for each treatment. Statistical analysis was conducted using one-way ANOVA, followed by pairwise t-tests at a significance level of $p < 0.05$.

Phase 3: DBR reflection and refinement

Laboratory nutritional analysis

Proximate analysis of each pellet variant was performed according to SNI 8173-1:2022 standards. Parameters assessed included crude protein, crude fat, crude fiber, moisture, ash, metabolizable energy, and carbohydrate content. The results were used to evaluate compliance with national poultry feed standards and to interpret the observed growth responses, particularly in relation to ash content, fiber levels, and energy density.

Economic feasibility analysis

Economic evaluation included raw material costs, processing labor, and energy inputs. The Economic Efficiency Index (EEI) was calculated as the ratio of feed cost to body-weight gain. Comparisons with commercial feed costs were used to determine the financial viability of each waste-derived formulation.

The final reflective phase synthesized laboratory data, feeding performance, and economic outcomes. Moderate inclusion levels of BSF larvae meal and bone flour provided the most balanced nutritional profile and favorable growth performance, while also reducing production costs. Higher bone-flour inclusion elevated ash levels and lowered metabolizable energy, indicating the need for further formulation

Table 1. Composition of Maggot plus pellet feed variants

Pellet code	BSF larvae meal (%)	Chicken feet bone flour (%)	Rice bran (%)	Tapioca flour (%)	Feed concentrate (%)	Description
P0	0	0	60	10	30	Commercial (factory-made) control feed — no waste-derived ingredients
P1	10	10	60	10	10	Initial formulation with low levels of BSF and bone flour
P2	15	10	55	10	10	Increased BSF proportion to enhance protein content
P3	20	10	50	10	10	Higher protein formulation with moderate mineral content
P4	20	15	45	10	10	Increased calcium–phosphorus contribution from bone flour
P5	25	15	40	10	10	Highest substitution level using waste-based materials (BSF + bone)

Figure 3. Steps to create five experimental formulations (P1–P5) pellets: (a) pellets formulation; (b) pellet grinding; (c) pellets drying

refinement. Insights from this phase informed recommendations for future iterations of waste-derived pellet development.

RESULTS AND DISCUSSION

The results of this study are presented according to the three iterative phases of the DBR approach. This structure clarifies how each finding is directly linked to the methodological actions undertaken, strengthening the reliability and interpretability of the outcomes.

Phase I: problem and context analysis

The initial DBR phase focused on diagnosing the nutritional, economic, and environmental challenges faced by smallholder poultry producers. As part of this assessment, the researchers conducted informal interviews with approximately 50 chicken farmers in the Gunungpati District of Semarang City, Indonesia. Most of them reported that feed costs were the dominant financial burden in their production system. Farmers consistently cited that the prices of rice bran and commercial poultry concentrate had increased significantly, making feed expenses difficult to sustain.

Complementing these interviews, field observations across multiple sub-districts and districts in Semarang City revealed that *mi ayam ceker* (chicken noodle with chicken feet) stalls are widely present and generate substantial amounts of post-consumption food waste and chicken feet bones. These waste materials are typically discarded without further use, despite their nutritional potential and steady availability. Together, the interview data and observational findings highlighted two key issues: (1) reliance on costly commercial feeds that limit profit margins for smallholder farmers, and (2) the presence of abundant, unutilized food waste and chicken feet bones that could serve as low-cost nutritional resources.

This situation established the need for a feed innovation capable of reducing production costs while utilizing locally available waste streams. BSF larvae meal and chicken feet bone flour was therefore identified as promising waste-derived ingredients suitable for protein and mineral supplementation. This diagnosis provided the foundation for the formulation strategy adopted in Phase II, where ingredient proportions were systematically varied to determine their impacts on nutritional composition and poultry performance.

Phase 2: design and development of pellet formulations

Nutritional composition of Maggot-based pellets

The Maggot Plus pellet feed was formulated using BSF larvae meal and chicken feet bone flour as the primary alternative protein and mineral sources, complemented with rice bran, tapioca flour, and a small portion of concentrate. The nutritional composition of the Maggot Plus pellet feed (P1–P5) was analyzed through laboratory testing following the standards of SNI 8173-1:2022 for poultry feed. Each formulation incorporated increasing proportions of BSF larvae meal and chicken feet bone flour, replacing portions of conventional feed ingredients. The cage preparation process and pellet codification can be seen in Figure 4.

The results of the proximate and energy analyses across the Maggot Plus variants (P1–P5) is summarized as can be seen in Table 2.

These results demonstrate that Maggot Plus pellets contain nutrient levels comparable to commercial poultry feed, with slightly higher ash content due to the inclusion of bone flour, which is advantageous for bone formation and eggshell quality.

Growth performance of chickens fed Maggot-based pellets

Growth data obtained over a 14-day period show clear treatment effects. The average live weights increased consistently from week to week across all treatments, though with varying growth rates as can be observed in Table 3.

The growth performance of chickens fed with different pellet formulations showed clear variations among treatments. The control group (P0), which received commercial feed, exhibited the highest body weight gain, with an average increase of 28.78% during the first week and 15.36% during the second week. This result reflects the balanced nutrient composition and high metabolizable energy content typically found in factory-produced feeds.

Chickens in the P1 group, which received feed partially substituted with BSF larvae meal and chicken feet bone flour, achieved satisfactory growth rates, indicating that partial inclusion of these waste-derived ingredients did not adversely affect feed utilization or animal performance. This suggests that moderate incorporation of BSF meal and bone flour can maintain productive growth while reducing dependence on conventional feed ingredients.

In contrast, the P2 to P5 groups showed a gradual decline in growth rate, particularly noticeable during the second week of observation. This reduction is consistent with the lower metabolizable energy and carbohydrate content identified in the nutritional analysis of these feed variants. As the proportion of M

Maggot meal and bone flour increased, energy-dense components such as rice bran and concentrate were reduced, which may have limited energy availability for optimal growth.

Despite the relatively slower weight gain, the Maggot-based feed formulations (P1–P5) demonstrate significant potential for feed cost reduction and organic waste valorization. These findings highlight the feasibility of utilizing locally sourced, waste-based materials – such as BSF larvae and chicken bone flour – as alternative feed ingredients. The adoption of such formulations supports the principles of a circular bioeconomy, promoting sustainable poultry production while reducing environmental burdens associated with feed manufacturing and food waste disposal. These findings affirm that the inclusion of BSF Maggot meal up to moderate levels (20–30%) can enhance growth rate and feed efficiency in semi-free-range poultry, consistent with previous studies on insect-based protein feed. The observed decline in performance at higher substitution rates (P4–P5) suggests that excessive mineralization

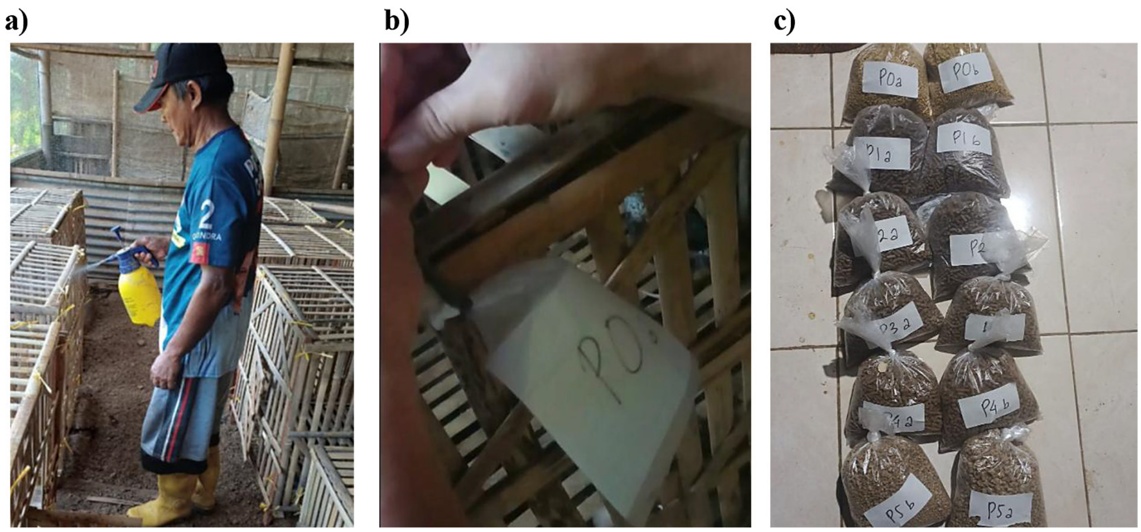

Figure 4. The preparation process for the chicken feed treatment using the research-produced pellets includes: (a) cage sterilization; (b) cage codification; and (c) pellet codification

Table 2. Nutritional composition of Maggot-based pellets

Parameter	(P1)	(P2)	(P3)	(P4)	(P5)	SNI 8173-1:2022 Standard	Remarks
Ash (%)	10.08	20.63	43.30	38.84	43.26	< 9%	All variants exceed SNI limit due to high bone flour content
Energy from fat (kcal/100 g)	1383	1241	1285	1179	1126	–	Meets energy standard when combined with total energy value
Total Fat (%)	15.37	13.80	14.28	13.10	12.51	> 4%	All variants meet SNI minimum standard
Moisture (%)	9.11	8.27	8.11	7.37	7.17	< 13%	All variants meet SNI moisture requirement
Metabolizable energy (kcal/100g)	3970	3523	2657	2806	2608	> 3200 kcal/kg	P3, P4, and P5 do not meet the minimum standard
Carbohydrate (%)	42.07	32.48	8.67	13.38	8.86	50–70%	All variants below standard due to substitution with protein and mineral materials
Crude protein (%)	22.62	24.68	21.13	27.38	21.86	> 18%	All variants meet SNI standard
Crude fiber (%)	23.85	14.93	14.38	6.63	3.04	< 5%	Only P5 meets the SNI standard

Table 3. Average percentage increase in chicken body weight during week 1 and week 2

Treatment code	Feed type	Average weight gain (%) – Week 2	Average weight gain (%) – Week 3	Description
(P0)	Commercial feed (control)	28.78%	15.36%	Highest overall weight gain; represents standard performance with factory-made feed
(P1)	Maggot + bone flour (low inclusion)	20.17%	11.06%	Slightly lower gain than control; good adaptation to maggot-based feed.
(P2)	Maggot + bone flour (moderate inclusion)	16.59%	1.96%	Noticeable drop in Week 2; possible effect of mineral excess or energy imbalance
(P3)	Maggot + bone flour (higher inclusion)	5.11%	6.32%	Moderate growth; stable adaptation after initial adjustment
(P4)	Maggot + bone flour (high inclusion)	4.65%	6.33%	Steady but low gain; birds may require higher energy supplementation
(P5)	Maggot + bone flour (maximum inclusion)	7.82%	2.42%	Slow growth due to reduced carbohydrate and energy content

from bone flour may impede optimal nutrient assimilation (Figure 5).

A one-way ANOVA test was conducted to evaluate the effect of different feed treatments (P0–P5) on the average body weight of chickens across three measurement periods. The results are summarized as in Table 4.

The ANOVA results show that there was a significant difference in chicken body weight among treatments during Week 1 ($p < 0.05$). This indicates that the feed formulations had an immediate impact on early growth performance. The higher mean values in treatments P1 and P3 suggest that partial substitution with BSF larvae meal and chicken bone flour supported efficient weight gain in the early phase. In contrast, during Week 2 and Week 3, the differences between treatments were not statistically significant ($p > 0.05$), although a slight trend was observed in Week 3 ($p \approx 0.096$). This suggests that as the experiment progressed, the chickens began to adapt to the Maggot-based formulations, reducing the initial growth variability observed earlier. The lack of significant differences in later weeks may also be attributed to the decline in metabolizable energy and carbohydrate levels in some feed variants (especially P2–P5), as identified in the nutritional analysis. Treatments with higher mineral content (due to chicken bone flour) but lower energy density may have limited subsequent growth potential compared to the commercial control feed (P0).

The results of the one-way ANOVA revealed that the type of feed had a significant effect on chicken body weight during the first week, but not in the subsequent weeks. This suggests that the inclusion of BSF larvae meal and chicken bone flour in the feed formulations influenced early growth performance, with treatments P1

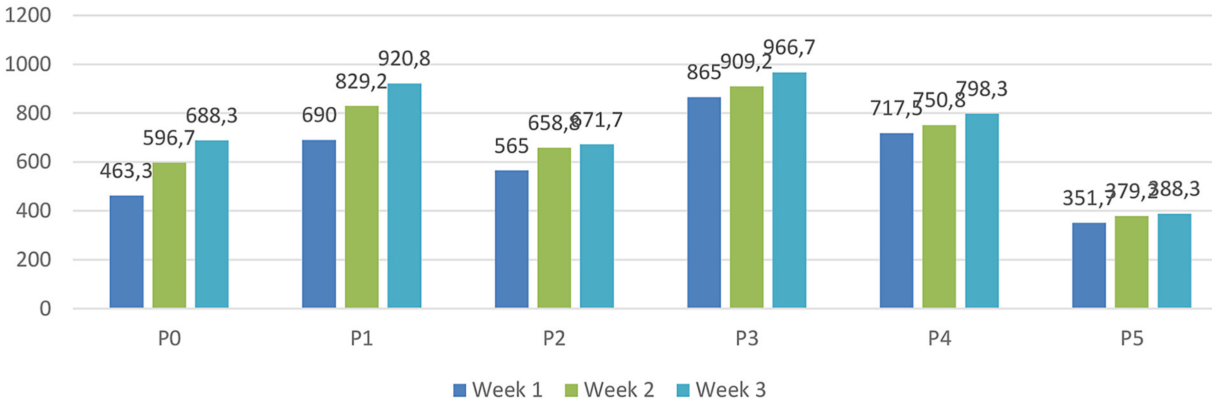

Figure 5. Chicken weight gain per treatment (P0–P5)

Table 4. Analysis of variance (ANOVA) results

Week (Mean)	F-statistic	p-value	Interpretation
Week 1 (Mean 1)	5.48	0.031	Significant difference among treatments
Week 2 (Mean 2)	2.91	0.113	No significant difference among treatments
Week 3 (Mean 3)	3.18	0.096	No significant difference among treatments (marginal trend)

and P3 showing the most promising results comparable to or even exceeding the commercial control (P0). However, by the second and third weeks, the differences among treatments were no longer statistically significant, indicating that the chickens had adapted to the Maggot-based diets over time. The reduced growth variation in later weeks may also be linked to lower metabolizable energy and carbohydrate levels in the higher inclusion treatments (P2–P5). Overall, the findings demonstrate that Maggot-based pellets can serve as a sustainable and cost-effective alternative feed source, capable of supporting satisfactory poultry growth while contributing to waste valorization and circular bioeconomy principles.

Economic feasibility and resource efficiency

Feed formulated with BSF larvae meal and chicken bone flour substantially reduced feed production costs compared to commercial poultry feed. As presented in Figure 6, the baseline cost of commercial feed was normalized to 100%, whereas the average cost of the waste-derived pellet formulations declined to approximately 75%. This represents a 25% reduction in feed cost, consistent with the ingredient-level pricing data and the cost structure described by farmers during Phase I. This reduction is attributed to two main factors. First, post-consumption food waste and chicken feet bones – acquired at zero or negligible cost from *mi ayam ceker* stalls across Semarang – replaced a significant portion of expensive commercial inputs such as rice bran and poultry concentrate. Second, the BSF larvae cultivation process converted these waste materials into a high-value protein source without requiring costly external feed ingredients.

The magnitude of this cost reduction becomes especially relevant when viewed in the context of the financial pressures described by the 50 interviewed farmers in Gunungpati. With commercial feed costing approximately IDR 8.000–10.000/kg (USD 0.50–0.63) and dedak costing IDR 4.000–5.000/kg (USD 0.25–0.32), feed routinely accounts for 60–70% of total production expenses. For a typical flock of 100 chickens consuming 1.5–2.0 kg/day, monthly feed expenditure reaches IDR 450,000–600,000 (≈ USD 28–38). A 25% reduction therefore translates into an estimated saving of IDR 112,500–150,000 per month (≈ USD 7–10) for small-scale farmers – an amount that meaningfully improves profitability under local economic conditions.

In addition to absolute cost reductions, the waste-derived formulations also demonstrated superior EEI performance when compared to commercial feed. The best-performing variant (P3) achieved the lowest EEI value – indicating the most favorable ratio of feed cost to body-weight gain – showing that chickens receiving P3 required

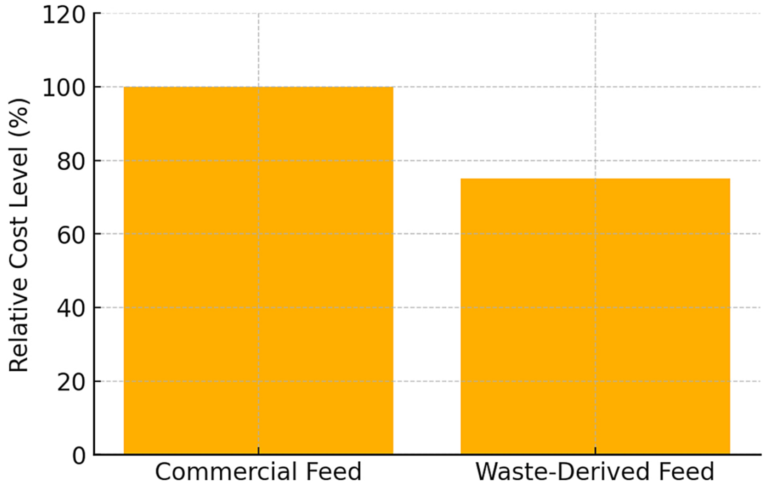

Figure 6. Cost comparison: Commercial feed vs waste-derived feed

less monetary input per kilogram of growth. This means the economic benefits of the waste-derived feed extend beyond ingredient pricing alone; they also reflect improved cost efficiency in biological conversion. The moderate inclusion level of BSF larvae meal in P3 reduced feed costs while maintaining acceptable growth efficiency, reinforcing the practicality and scalability of the waste-derived pellet system for smallholder farmers. Figure 6 visually emphasizes this gap between the two systems, highlighting the significant monetary advantage of adopting waste-derived formulations. By reducing dependence on market-priced components and improving cost-per-gain efficiency, the BSF–bone flour pellets align directly with the needs identified in Phase I and offer a viable pathway toward economic resilience for smallholder poultry production.

Phase 3: DBR reflection and refinement

The final DBR phase involved synthesizing the nutritional, biological, economic, and environmental findings to evaluate the performance of the developed formulations and identify refinement pathways for subsequent iterations. This reflective stage assesses how well the prototypes met the design intentions and where adjustments are required to optimize future versions.

Performance relative to existing alternative-protein feeds

Compared with other studies on alternative protein sources, the BSF–bone flour combination developed in this research demonstrated competitive or superior outcomes across several dimensions of feed performance. Crude protein levels in the best-performing variants were comparable to soybean- or fishmeal-based feeds, affirming the capacity of BSF larvae meal – derived through controlled bioconversion – to meet poultry protein requirements. At the same time, integrating chicken bone flour supplied essential calcium and phosphorus, reducing dependence on imported mineral supplements and supporting more locally resilient feed supply chains.

The short-term (14-day) feeding trial further validated the biological feasibility of the formulation. Growth performance patterns aligned with nutrient availability, reinforcing the functional value of BSF larvae in closed-loop nutrition systems common in tropical environments. These outcomes reflect the success of the design phase, while also guiding the adjustments needed for the next iteration.

Alignment with SNI (Standar Nasional Indonesia), national standards, and identified optimization needs

Some deviations from SNI standards – particularly elevated ash and fiber content in higher bone-flour variants – highlight areas requiring refinement. These deviations are consistent with the expected mineral density of bone-derived ingredients. They also point to the need for ratio adjustments or pre-treatment of bone flour to moderate excess minerals and improve bioavailability. Addressing these issues will be a key focus of the subsequent DBR cycle. Despite these limitations, the prototype formulations successfully demonstrated technical viability, meeting core proximate requirements such as protein, lipid, and moisture while remaining functionally appropriate for poultry feed (Table 5).

These results clearly show the trade-offs produced by varying ingredient proportions – information that is central to DBR-driven refinement.

Technical, economic, and ecological viability

The study affirmed that formulating poultry feed pellets from post-consumption food waste and chicken feet bone flour – processed through *Hermetia illucens* bioconversion – is a technically viable, nutritionally adequate, and economically feasible solution for sustainable livestock feed production. The literature further substantiates these findings, as BSF meal is widely recognized for its high crude protein content and efficient bioconversion performance (da-Silva et al., 2024; Gougbedji et al., 2022).

Economically, substituting commercial protein sources with locally available BSF meal and bone flour reduces feed production costs and dependency on imported inputs. The 25% cost reduction observed in this study aligns with prior analyses showing that localized insect-based feed systems typically improve economic resilience when substrate supply chains and labor inputs are optimized (Waithaka et al., 2022; Leipertz et al., 2024).

Environmentally, the integration of BSF bioconversion with bone-flour valorization demonstrates a strong fit within circular bioeconomy frameworks. This system diverts organic residues from food stalls and households – materials that would otherwise contribute to waste burdens – and reintegrates them into the livestock feed cycle. Such practices align with Sustainable Development Goals (SDG-2 and SDG-12) and correspond with evidence showing that BSF-based systems can reduce waste and lower greenhouse-gas emissions relative to landfill disposal (Beyers et al., 2023; Mangindaan et al., 2022).

Reflecting on the DBR process, several limitations emerged that must be addressed in subsequent iterations. The short duration of the feeding trial restricts the ability to draw conclusions about long-term growth trajectories, carcass characteristics, and reproductive performance, all of which may respond differently to waste-derived feed over extended periods. Moreover, previous meta-analyses have shown substantial variability in the nutritional and physiological responses to BSF meal across production stages and species (Martínez-Marín et al., 2023; da-Silva et al., 2024), underscoring the need for larger, more diverse, and longer-term trials. Mineral balance also requires refinement, particularly with respect to calcium–phosphorus ratios, to mitigate the elevated ash levels found in higher bone-flour formulations and to enhance mineral bioavailability. In addition, more comprehensive safety profiling – including microbiological assessments and amino-acid digestibility analyses—is needed to strengthen conclusions about feed completeness and consumer safety. Attention must also be given to pellet durability and storage stability, which have not yet been tested under real-world handling and supply-chain conditions.

To support scalability and practical adoption, the next DBR iteration should incorporate long-term and multi-breed feeding trials, systematic optimization of mineral ratios, and formal pellet durability testing to ensure physical stability during transport and storage. Environmental validation will also be essential; therefore, LCA and greenhouse-gas accounting should be undertaken to quantify the environmental benefits of integrating BSF bioconversion with bone-flour valorization (Beyers et al., 2023; Ramzy et al., 2025). Finally, collaboration with local feed manufacturers, municipal waste services, and farmer cooperatives is recommended to pilot commercial-scale production models, standardize processing protocols, and ensure regulatory compliance and

Table 5. Summary of key findings

Parameter	Best performing variant	Notable observation
Protein content	P5 (28.18%)	High, within or above standard
Moisture	P4–P5 (7–7.5%)	Ideal for storage stability
Weight gain	P3 (865–966 g)	Highest overall performance
Feed efficiency	P3 (FCR ≈ 1.8)	Most efficient feed utilization
Cost reduction	P3 (≈25%)	Lowest cost per kg weight gain
SNI compliance	Protein & moisture: ✓Ash & fiber: ✗	Requires ratio adjustment

market acceptance. Such efforts will help bridge the gap between experimental validation and practical implementation, enabling insect-based feed solutions to progress from research prototypes to viable industry practices.

CONCLUSIONS

The study confirmed that poultry feed pellets produced from post-consumption food waste and chicken bone flour via Black Soldier Fly larval bioconversion possess adequate nutritional composition, with crude protein, lipid, and moisture levels meeting general poultry feed standards. The inclusion of bone flour enriched the mineral content but also increased ash levels, highlighting the importance of maintaining an optimal balance between nutritional enhancement and feed palatability. Economic evaluation demonstrated the potential for cost reduction when partially replacing conventional protein sources with locally available insect meal and bone flour, particularly under conditions of efficient substrate management and production scaling. Environmentally, the integration of BSF bioconversion and bone-flour utilization contributes to waste minimization and resource circularity through the conversion of urban food and slaughter residues into valuable feed materials.

This study's limitations include the short experimental duration, which constrains interpretation of long-term production performance, carcass quality, and reproductive effects, as well as the absence of detailed microbiological and digestibility analyses. Future research is therefore directed toward extended feeding trials, optimization of mineral balance, evaluation of storage and pellet durability, and comprehensive life-cycle assessments to quantify the environmental impact and validate scalability. Overall, the findings indicate that the Maggot–bone flour pellet model offers a technically feasible, economically practical, and environmentally beneficial pathway for sustainable poultry feed development derived from waste-to-feed conversion systems.

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