



ECONOMY POTENTIAL OF BLACK SOLDIER FLY BIOCONVERSION OF CASSAVA PROCESSING WASTE: PROXIMATE COMPOSITION, FRASS CHARACTERISATION

¹Umeri, C., ²Michael, C., ²Belonwu, E., ¹Moseri, H., ²Onwuka, H. and ²Lasisi, A. J.

¹Department of Crop and Animal Science, Faculty of Agriculture,
University of Delta, Agbor, Delta State.

²Department of Agricultural Economics and Extension, Faculty of Agriculture,
University of Delta, Agbor, Delta State.

Corresponding Author's Email: clifford.umeri@uniel.edu.ng, **GSM:** 08033771837

ABSTRACT

The study compares the proximate composition of fresh and dried black soldier fly larvae, characterises the nutrient profile of resultant frass biofertiliser, documents larval productivity parameters, and estimates agricultural input substitution economics under current Delta State market conditions. Proximate analyses were conducted at KAO's Quality Assurance Laboratory, Benin City, Edo State, Nigeria, following standard AOAC methods. Fresh larvae contained 66.0% moisture, 14.0% crude protein (CP), 9.0% crude fat (EE), 3.0% crude fibre (CF), 2.0% ash, and 5.0 MJ/kg gross energy (GE). Drying to 9.0% residual moisture concentrated all nutrient parameters 2.0–4.4-fold: CP reached 32.0% DM, EE 20.0% DM, CF 7.0% DM, ash 5.0% DM, and GE 22.0 MJ/kg DM. BSF frass from cassava waste contained 3.2% total nitrogen, 2.4% total phosphorus, 2.1% total potassium, 28.4% organic carbon, and chitin at 38–52 mg/g DM, with a C:N ratio of 8.9:1. Waste mass reduction indices of 48–55% and larval biomass yields of 70–85 kg fresh biomass per tonne substrate DM were recorded. Economic analysis indicates substitution cost savings of ₦25,000–280,000 per tonne of agricultural input under 2024 Delta State market conditions, with dried larval meal as a fish meal replacer in aquaculture offering the highest economic return. The findings provide a locally grounded evidence base for advancing BSF bioconversion as a viable circular economy intervention within Nigeria's agricultural sector.

Keywords: *Hermetia illucens*, Circular, Bioeconomy; Cassava, Processing, Waste.

INTRODUCTION

Nigeria's agricultural sector confronts the converging challenges of escalating synthetic input costs, mounting agro-industrial waste, and persistent soil fertility decline. Delta State, situated in the Niger Delta region and characterised by a predominantly agricultural economy built around cassava, maize, and freshwater aquaculture, faces these pressures acutely. The state generates substantial volumes of cassava processing waste including peels, pulp residues, and effluent from its extensive cassava flour and starch processing industry. These waste streams are currently managed through open dumping, burning, or discharge into waterways, yielding negligible resource recovery while contributing to environmental degradation (FAO, 2022). Delta State alone processes an estimated 2.3–3.1 million tonnes of fresh cassava tubers annually, generating proportionate waste volumes that represent an underutilized biological resource of considerable scale. Simultaneously, Delta State smallholder livestock and aquaculture producers remain heavily dependent on imported fish meal and synthetic fertilisers whose prices have increased by 40–60% in naira terms between 2020 and 2024, driven by foreign exchange depreciation and global commodity price shocks (CBN, 2024). The convergence of waste management deficits and agricultural input cost inflation creates a compelling structural case for biological waste valorisation technologies capable of converting organic residues into high-value protein and soil amendment products within a closed-loop, circular economy framework (Liu *et al.*, 2022; van Huis & Oonincx, 2017).

The black soldier fly (*Hermetia illucens* L.; BSF) has emerged as the leading insect species for organic waste bioconversion, owing to its substrate flexibility, rapid larval development, efficient organic matter reduction, and the nutritional quality of the resulting larval biomass and frass residue (Čičková *et al.*, 2015; Diener *et al.*, 2011; Makkar *et al.*, 2014). BSF larvae can efficiently process



carbohydrate-rich, low-protein substrates such as cassava waste, producing larval biomass with moderate protein and moderate-to-high fat content, together with a nutrient-dense frass product with documented biostimulant properties (Schmitt & Vilcinskas, 2018). Despite extensive global literature on BSF bioconversion across diverse substrates, empirical data specific to cassava waste as a primary substrate and derived within Nigerian pilot-scale operational settings remain limited, constraining the evidence base available to local policy makers, extension officers, and agricultural entrepreneurs (Supriyatna *et al.*, 2016; Vogel *et al.*, 2021).

This study addresses this gap through a pilot-scale investigation conducted at the Department of Animal Science, Faculty of Agriculture, University of Delta (UNIDEL), Agbor, Delta State, Nigeria. The principal objectives are fourfold: (i) to determine and compare the proximate composition of fresh and dried BSF larvae reared on cassava processing waste; (ii) to characterise the nutrient composition and fertiliser substitution potential of resultant BSF frass; (iii) to document larval productivity and waste reduction parameters under ambient tropical conditions; and (iv) to estimate the economic value of agricultural input substitution achievable under Delta State market conditions. The study contributes locally grounded empirical evidence to both the nascent Nigerian BSF sector and the broader literature on circular economy applications of insect bioconversion in sub-Saharan Africa.

MATERIALS AND METHODS

The study was conducted at a pilot-scale BSF rearing facility established within the Department of Animal Science, Faculty of Agriculture, University of Delta (UNIDEL), Agbor, Delta State, Nigeria (Latitude 6°15'N, Longitude 6°19'E; elevation 72 m above sea level). The facility operated under natural tropical ambient conditions throughout the study period (January–April 2025), with mean daily temperatures of 28.4–31.2°C and relative humidity of 72–85%, consistent with published optimal ranges for BSF larval development (Tomberlin *et al.*, 2009). No supplemental heating, cooling, or humidity regulation was applied, ensuring that results reflect uncontrolled tropical ambient conditions representative of smallholder-accessible operational settings.

Cassava processing waste — comprising primarily cassava peels with residual pulp (peel fraction 78%, pulp 22% by fresh weight) — was sourced from a cassava flour processing unit in Agbor Central Market, Ika South Local Government Area, Delta State. The substrate was pre-processed by sun-drying on raised mesh platforms for 24–36 hours to reduce initial moisture content to approximately 65–70% wet weight, in line with optimal bioconversion moisture conditions (Lalander *et al.*, 2019). No chemical additives, acidification, or pasteurisation was applied to the substrate prior to larval introduction.

BSF egg masses were obtained from a self-sustaining colony maintained at the UNIDEL facility under semi-controlled conditions (screened cages, supplemental sugar-water feeding for adults). First-instar larvae (approximately 3 days post-hatch, mean individual weight 0.1 mg) were introduced to standardised polyethylene rearing trays (50 × 35 × 15 cm) at a stocking density of 3,500–4,000 larvae per tray, each tray receiving 3 kg of cassava waste substrate per introduction. Twelve independent rearing trays constituted the experimental unit pool for compositional analysis. Rearing was conducted for 18 days to the late fifth-instar/prepupal stage, at which point larvae were harvested using their natural pre-pupal migration behaviour (negative phototaxis and upward movement from the substrate).

Larval Harvesting, Processing, and Sample Preparation

At harvest, larvae were separated from frass residue by sieving through a 2 mm mesh screen. Separated larvae were briefly immersed in hot water (60–65°C for 3 minutes) to inactivate them, reduce surface microbial load, and standardise post-harvest handling. Larvae were divided into two analytical fractions: (i) fresh larvae, weighed and submitted for proximate analysis within 4 hours of harvest; and (ii) a matched subsample oven-dried at 60°C for 48 hours to constant weight (± 0.01 g) to produce dried larval meal. All samples were stored at 4°C until transport to the analytical laboratory.

Frass residue from each tray was collected after larval removal, bulked across all 12 trays to form a single composite frass sample, and air-dried on mesh platforms for 72 hours prior to chemical analysis. Fresh substrate moisture content was determined gravimetrically in triplicate immediately after introduction. All samples were transported in sealed, labelled polyethylene bags under cool-chain



conditions (cool box with ice packs) to KAO's Quality Assurance Laboratory, Benin City, Edo State, Nigeria, for chemical analysis.

Proximate and Chemical Analysis

Proximate composition of both fresh (as-fed) and dried (DM basis) larvae was determined in triplicate following standard Association of Official Analytical Chemists (AOAC, 2005) methods at KAO's Quality Assurance Laboratory, Benin City, Edo State, Nigeria. Moisture content was determined by oven-drying at 105°C to constant weight (AOAC 930.15). Crude protein was determined by the macro-Kjeldahl digestion and distillation method (AOAC 2001.11) using a nitrogen-to-protein conversion factor of 6.25 (conventional AOAC factor; limitations discussed in Section 3.1). Crude fat (ether extract) was measured by ether extraction using a Soxhlet apparatus (AOAC 920.39). Crude fibre was determined by sequential acid-alkali digestion (AOAC 962.09). Ash content was determined by incineration at 550°C for 6 hours in an electrically regulated muffle furnace (AOAC 942.05). Gross energy was measured by bomb calorimetry (IKA C200 calorimeter, IKA-Werke GmbH, Germany). Nitrogen-free extract (NFE) was calculated by difference: $NFE = 100 - (\text{moisture} + CP + EE + CF + \text{ash})$. Dry matter content was calculated as 100% minus moisture percentage. All analyses were conducted in triplicate; results are presented as means.

Frass samples were additionally analysed for: total nitrogen by macro-Kjeldahl digestion (AOAC 2001.11); total phosphorus by vanado-molybdate colorimetry at 470 nm; total potassium by flame photometry; organic carbon by Walkley-Black wet oxidation; chitin content by sequential alkaline demineralisation and deacetylation followed by glucosamine quantification (Synowiecki & Al-Khateeb, 2003); and pH in aqueous suspension at 1:2.5 (w/v) ratio using a calibrated pH meter. Bulk density was determined by the cylinder method. The C:N ratio was calculated from measured organic carbon and total nitrogen values.

Larval Productivity Assessment

Larval productivity parameters recorded at the UNIDEL facility included: rearing duration from larval introduction to harvest (days); waste mass reduction index (WMRI, %), calculated as the percentage reduction in substrate fresh weight between introduction and harvest; larval biomass yield (kg fresh larval weight per tonne substrate DM); and frass yield (kg air-dried frass per tonne substrate DM). Mean values are reported alongside the corresponding ranges from published cassava-substrate BSF literature for contextualisation (Table 4).

Economic Analysis

Agricultural input substitution economics were estimated based on current market prices for fish meal (₦680,000–950,000/tonne), urea fertiliser (₦780,000–1,100,000/tonne), soybean meal (₦520,000–720,000/tonne), and commercial compost (₦40,000–80,000/tonne) obtained from structured market surveys conducted in Agbor (Ika South LGA) and Asaba (Oshimili North LGA) markets, Delta State, during March–April 2025.

A minimum of six trader quotations were obtained per input category and averaged to produce survey-range estimates (minimum–maximum) for each input. Pilot-scale BSF larval meal production costs were estimated from direct input accounting inclusive of substrate acquisition (assuming zero-cost cassava waste), labour (3 person-days per tonne substrate), energy (drying), and packaging costs under Delta State conditions. Substitution cost savings were computed at protein-equivalent or nutrient-equivalent substitution ratios derived from proximate composition data, adjusted for reported digestibility differences between BSF larval meal and fish meal in *Clarias gariepinus* and *Oreochromis niloticus* diets (Chia *et al.*, 2020; Shumo *et al.*, 2019).

To account for the inherent price volatility of Nigerian agricultural input markets — where naira depreciation and import dependency generate substantial intra-year price fluctuation — a Monte Carlo stochastic simulation approach was adopted rather than conventional deterministic point-estimate arithmetic. In deterministic analysis, a single representative price is selected for each input and a single cost-saving figure is computed; this approach is computationally straightforward but produces a false sense of precision by ignoring the uncertainty ranges inherent in market survey data.

Monte Carlo simulation addresses this limitation by treating each uncertain input parameter not as a fixed value but as a probability distribution, and repeatedly sampling from those distributions to



generate a large ensemble of plausible economic outcomes. Specifically, triangular probability distributions were fitted to each market price and production cost parameter using the survey-reported minimum and maximum as the lower and upper bounds of the distribution, and the arithmetic midpoint of the survey range as the modal (most likely) value. The triangular distribution was selected over the normal or uniform distribution for three reasons: (i) it requires only three parameters (minimum, mode, maximum), all of which are directly observable from the market survey data without assumption of parametric form; (ii) it is bounded, preventing the simulation from generating economically implausible negative prices; and (iii) it accurately reflects asymmetric market price distributions in which prices cluster near a central value but can extend toward either extreme — a well-documented characteristic of agricultural commodity markets in sub-Saharan Africa.

Substitution ratios (protein-equivalent and nitrogen-equivalent) were modelled as uniform distributions across the range reported in the digestibility literature (Chia *et al.*, 2020; Shumo *et al.*, 2019), reflecting genuine biological variability in larval meal composition across production batches. Individual BSF production cost components (substrate, labour, energy, packaging, overhead) were each assigned independent triangular distributions reflecting the operational cost ranges documented in the literature for smallholder-scale tropical facilities (Smetana *et al.*, 2019). The simulation engine executed $N = 10,000$ independent iterations. In each iteration, one value was independently and randomly drawn from the probability distribution of every uncertain parameter simultaneously — including all market prices, all production cost components, and all substitution ratios — and the net cost saving for each substitution scenario was computed from those co-sampled values.

This process was repeated 10,000 times, producing a dataset of 10,000 plausible substitution saving outcomes for each scenario. The resulting empirical distributions were summarised by their mean, median, standard deviation, and 5th–95th percentile confidence interval. The probability of a positive substitution saving — denoted $P(\text{saving} > 0)$ — was computed as the proportion of the 10,000 iterations in which the net saving exceeded zero, providing a direct probabilistic measure of economic viability under market uncertainty.

Four complementary analytical components were integrated within the simulation framework.

- i. A comparative scenario analysis quantified and ranked net savings across all four substitution pathways (BSF larval meal versus fish meal, BSF larval meal versus soybean meal, BSF frass versus urea, BSF frass versus commercial compost) under identical stochastic conditions, enabling objective ranking of substitution priorities.
- ii. One-at-a-time (OAT) sensitivity analysis — visualised as a tornado diagram — assessed the marginal contribution of each uncertain parameter to variation in net saving by varying each parameter individually by $\pm 20\%$ from its base value while holding all others constant; parameters are ranked from greatest to least influence, revealing the primary economic leverage points for enterprise management and policy intervention.
- iii. A break-even threshold analysis determined the maximum BSF production cost at which substitution remains economically viable for each conventional input, plotted as a cumulative distribution function (CDF) to quantify the probability that the actual production cost falls below the break-even threshold under stochastic conditions.
- iv. A partial budget analysis extended the substitution saving estimates to incorporate the potential revenue from waste valorisation — specifically, the gate fee or tipping fee avoided by diverting cassava processing waste from open dumping to the BSF facility — providing a more complete representation of the system's net economic benefit to the operator.

All values are reported in Nigerian Naira (₦); USD equivalents are not reported given exchange rate volatility during the study period. Analyses were conducted in Python 3.12 (NumPy 1.26; SciPy 1.12; Matplotlib 3.8) with a fixed random seed (seed = 42) to ensure full reproducibility of simulation outputs.

RESULTS

Proximate Composition of Fresh and Dried BSF Larvae

Table 1 presents the proximate composition of BSF larvae reared on cassava processing waste in both fresh (as-fed) and dried (dry matter basis) forms, as determined by AOAC standard methods at KAO's Quality Assurance Laboratory, Benin City. The data reveal substantial compositional transformation driven by moisture removal.

Table 1: Proximate Composition of BSF Larvae Reared on Cassava Processing Waste: Fresh (As-Fed) versus Dried (DM Basis) Comparison (UNIDEL Pilot Facility, 2025; Analyses at KAO's

Parameter	Fresh Larvae (as-fed basis, %)	Dried Larvae (DM basis, %)	Concentration Factor	Analytical Method
Moisture Content	66.0	9.0	0.14×	AOAC 930.15
Dry Matter	34.0	91.0	2.7×	By difference
Crude Protein (CP)	14.0	32.0	2.3×	AOAC 2001.11 (N × 6.25)
Nitrogen (N)	2.5	5.1	2.0×	Kjeldahl (AOAC 2001.11)
Crude Fat (EE)	9.0	20.0	2.2×	AOAC 920.39 (Soxhlet)
Crude Fibre (CF)	3.0	7.0	2.3×	AOAC 962.09
Ash Content	2.0	5.0	2.5×	AOAC 942.05 (550°C)
Gross Energy (GE)	5.0 MJ/kg	22.0 MJ/kg DM	4.4×	Bomb calorimetry
Nitrogen-Free Extract (NFE)	14.0*	28.0*	2.0×	By difference

Note. DM = dry matter. EE = ether extract (crude fat). CF = crude fibre. GE = gross energy. NFE = nitrogen-free extract. All the values expressed as percentages unless otherwise stated. Concentration Factor = ratio of dried to fresh-basis value. Analyses conducted at KAO's Quality Assurance Laboratory, Benin City, Edo State, Nigeria, following AOAC (2005) standard methods. Fresh larvae n = 12 trays; dried larvae n = 12 trays (same trays, matched sub-samples). *NFE calculated by difference; values indicative only. Researchers are advised that the conventional N × 6.25 factor may overestimate true protein content by 5–15% due to chitin-bound non-protein nitrogen; insect-specific correction factors of 4.76–5.60 are recommended for comparative cross-study analysis (Janssen *et al.*, 2017).

At harvest, fresh larvae contained 66.0% moisture and 34.0% dry matter, placing them within the range reported for cassava waste-fed BSF larvae in comparable tropical studies (Supriyatna *et al.*, 2016; Zulkifli *et al.*, 2022). Fresh larvae crude protein of 14.0% (as-fed) concentrated to 32.0% DM upon drying — a 2.3-fold increase consistent with the expectation that moisture removal proportionally elevates nutrient concentrations relative to wet weight. This protein level falls within the 25–36% DM range reported for BSF larvae reared on low-protein carbohydrate-rich substrates analogous to cassava waste (Chia *et al.*, 2020; Supriyatna *et al.*, 2016), and is notably lower than the 39–48% DM reported for larvae reared on higher-protein substrates such as poultry manure or food waste (Shumo *et al.*, 2019; Zulkifli *et al.*, 2022).

Crude fat showed a concentration from 9.0% (fresh basis) to 20.0% DM, reflecting efficient conversion of cassava's carbohydrate-rich substrate into larval lipid reserves — a well-documented metabolic response of BSF larvae to high-starch diets (Chia *et al.*, 2020; Liu *et al.*, 2022). Gross energy increased from 5.0 MJ/kg (fresh) to 22.0 MJ/kg DM, a 4.4-fold elevation primarily reflecting moisture concentration effects and the substantial fat content (fat contributes approximately 39.5 MJ/kg versus protein's 23.7 MJ/kg and carbohydrates' 17.5 MJ/kg). The NFE of 28.0% DM indicates a residual carbohydrate/chitin fraction consistent with cassava-substrate larval diets. Researchers are advised that the conventional Kjeldahl N × 6.25 factor may overestimate true protein content by 5–15% due to non-protein nitrogen associated with chitin; insect-specific correction factors of 4.76–5.60 should be applied for comparative cross-study analyses (Janssen *et al.*, 2017).



BSF Frass Nutrient Composition and Agricultural Input Benchmarking

Table 2 presents the chemical composition of BSF frass derived from cassava waste bioconversion at the UNIDEL pilot facility, benchmarked against key conventional agricultural inputs. The frass exhibited 3.2% total nitrogen, 2.4% total phosphorus, and 2.1% total potassium on a DM basis — a balanced macronutrient profile broadly comparable in nitrogen concentration to mature composts, though substantially less concentrated than synthetic formulations. The organic carbon content of 28.4% DM and C:N ratio of 8.9:1 indicate a well-stabilised organic amendment with a narrower C:N than many raw plant-based composts (C:N 20–35:1), implying relatively rapid nitrogen mineralisation upon soil incorporation that favours short-season crop nutrition (Houben *et al.*, 2020; Schmitt & Vilcinskis, 2018). The pH of 7.2 renders the frass agronomically neutral and suitable across the pH range of Delta State agricultural soils (typically pH 5.8–7.1 under humid tropical conditions).

Table 2: Chemical Composition of BSF Frass from Cassava Processing Waste Substrate Compared with Conventional Agricultural Inputs (Analyses at KAO's Quality Assurance Laboratory, Benin City; Market Benchmarks from FAO, 2022 and Field Surveys, 2025)

Parameter	BSF Frass — Cassava Waste Substrate	Urea (46-0-0)	NPK 15-15-15	Mature Organic Compost
Total N (% DM)	3.2	46.0	15.0	0.5–3.0
Total P (% DM)	2.4	—	6.6	0.2–1.4
Total K (% DM)	2.1	—	12.4	0.3–2.1
Organic Carbon (% DM)	28.4	N/A	N/A	20–45
C:N Ratio	8.9:1	N/A	N/A	12–25:1
Chitin (mg/g DM)	38–52	0	0	0
pH (1:2.5 H ₂ O)	7.2	N/A	N/A	6.5–8.0
Moisture (% fresh wt.)	18.0	0.3	1.2	40–60
Bulk Density (g/cm ³)	0.41±0.03	0.77	1.02	0.25–0.60

Note. DM = dry matter. N = nitrogen. P = total phosphorus. K = total potassium. C = organic carbon. C:N = carbon-to-nitrogen ratio. N/A = not applicable. BSF frass values represent means from triplicate analysis of composited frass samples pooled across 12 rearing trays; standard deviations available on request. Conventional fertiliser reference values sourced from manufacturer specifications, FAO (2022), and Houben *et al.* (2020). Bulk density values for BSF frass and comparators obtained from product datasheets and published literature. Analyses conducted at KAO's Quality Assurance Laboratory, Benin City, Edo State, Nigeria.

Chitin content of 38–52 mg/g DM is of particular agronomic significance, functioning as a systemic plant resistance elicitor and stimulant of chitin-degrading soil microbial communities — including actinomycetes and chitinolytic bacteria that suppress soil-borne pathogens such as *Fusarium* spp. and *Pythium* spp. prevalent in Delta State cassava and vegetable production systems (Bittelli *et al.*, 2001; Sashiwa & Aiba, 2004). This biostimulant dimension substantially exceeds what is captured by elemental nutrient composition alone, positioning BSF frass as a premium organic amendment relative to conventional composts of equivalent NPK content. Frass moisture content of 18.0% (fresh weight) is within an acceptable range for bagged ambient-temperature storage and smallholder distribution without cold chain infrastructure.

Larval Productivity and Waste Reduction Parameters

Table 3 presents measured larval productivity parameters from the UNIDEL pilot facility alongside published literature ranges for cassava waste-based BSF systems.

Table 3: Larval Productivity and Waste Reduction Parameters from the UNIDEL Pilot BSF Facility Compared with Published Literature Ranges for Cassava Waste-Based Systems (UNIDEL, Agbor; 2025)

Productivity Parameter	UNIDEL Pilot (Cassava Waste)	Literature Range (Cassava-based)	Reference
Rearing duration (days)	18	14–21	Supriyatna <i>et al.</i> , 2016
Stocking density (larvae/tray)	3,500–4,000	2,000–5,000	Diener <i>et al.</i> , 2011
Substrate moisture at introduction (%)	65–70	60–75	Lalander <i>et al.</i> , 2019
Waste mass reduction index (%)	48–55*	45–60	Čičková <i>et al.</i> , 2015
Larval biomass yield (kg fresh/t substrate DM)	70–85*	60–90	Vogel <i>et al.</i> , 2021
Frass-to-larval biomass ratio (kg/kg)	~3.2:1*	2.5–4.0:1	Liu <i>et al.</i> , 2022
Ambient temperature range (°C)	28.4–31.2	25–35 (optimal)	Tomberlin <i>et al.</i> , 2009
Relative humidity (%)	72–85	60–90	Tomberlin <i>et al.</i> , 2009

Note. UNIDEL = University of Delta. *Values estimated from pre- and post-rearing substrate weight differences and larval harvest weights; triplicate measurements, mean values reported. All measurements from the UNIDEL pilot facility, Agbor, Delta State. Literature ranges from referenced sources as cited.

The UNIDEL pilot facility recorded waste mass reduction indices of 48–55% and larval biomass yields of 70–85 kg fresh biomass per tonne substrate DM, both falling within the ranges reported for cassava-based substrates in comparable tropical studies (Čičková *et al.*, 2015; Supriyatna *et al.*, 2016). The frass-to-larval-biomass ratio of approximately 3.2:1 (kg/kg DM basis) is consistent with published co-product generation data for starchy substrates (Liu *et al.*, 2022), confirming that frass represents the dominant volumetric output of BSF bioconversion and underscoring its centrality to the system's economic viability.

Agricultural Input Substitution Economics

Table 4 summarises substitution ratios and estimated farm-gate cost savings for the principal agricultural input categories addressable by the UNIDEL pilot facility's BSF outputs under current Delta State market conditions.

Table 4: Agricultural Input Substitution Potential and Estimated Cost Savings from BSF Bioconversion Outputs (Delta State Market Conditions, March–April 2025)

Input Category	BSF Product	Subst. Ratio	Est. Cost Saving (₦/t equivalent)	Relevance to Delta State
Fish meal (aquafeed)	Dried BSFL meal	1:1.0–1.2 (protein eq.)	₦120,000–280,000	Addresses high catfish feed cost in Delta State aquaculture
Soybean meal (poultry)	Dried BSFL meal	1:0.8–1.0 (protein eq.)	₦80,000–180,000	Supports smallholder broiler and layer enterprises
Urea (synthetic N)	BSF frass	1:3.8 (N weight eq.)	₦45,000–90,000	Reduces import-dependent urea cost for cassava and maize farmers
Organic compost	BSF frass (whole)	1:1.5–1.8 (org. matter)	₦25,000–55,000	Supports soil organic matter restoration in degraded Delta State soils

Note. ₦ = Nigerian Naira. Subst. Ratio = substitution ratio. Cost savings calculated at mean 2024 market prices from structured market surveys in Agbor and Asaba, Delta State (March–April 2025; n = 6 trader quotations per input category). Protein equivalence based on digestible amino acid substitution ratios reported in Shumo *et al.* (2019) and Chia *et al.* (2020) for catfish and broiler diets respectively. Organic matter equivalence for compost substitution based on measured organic carbon content. All economic



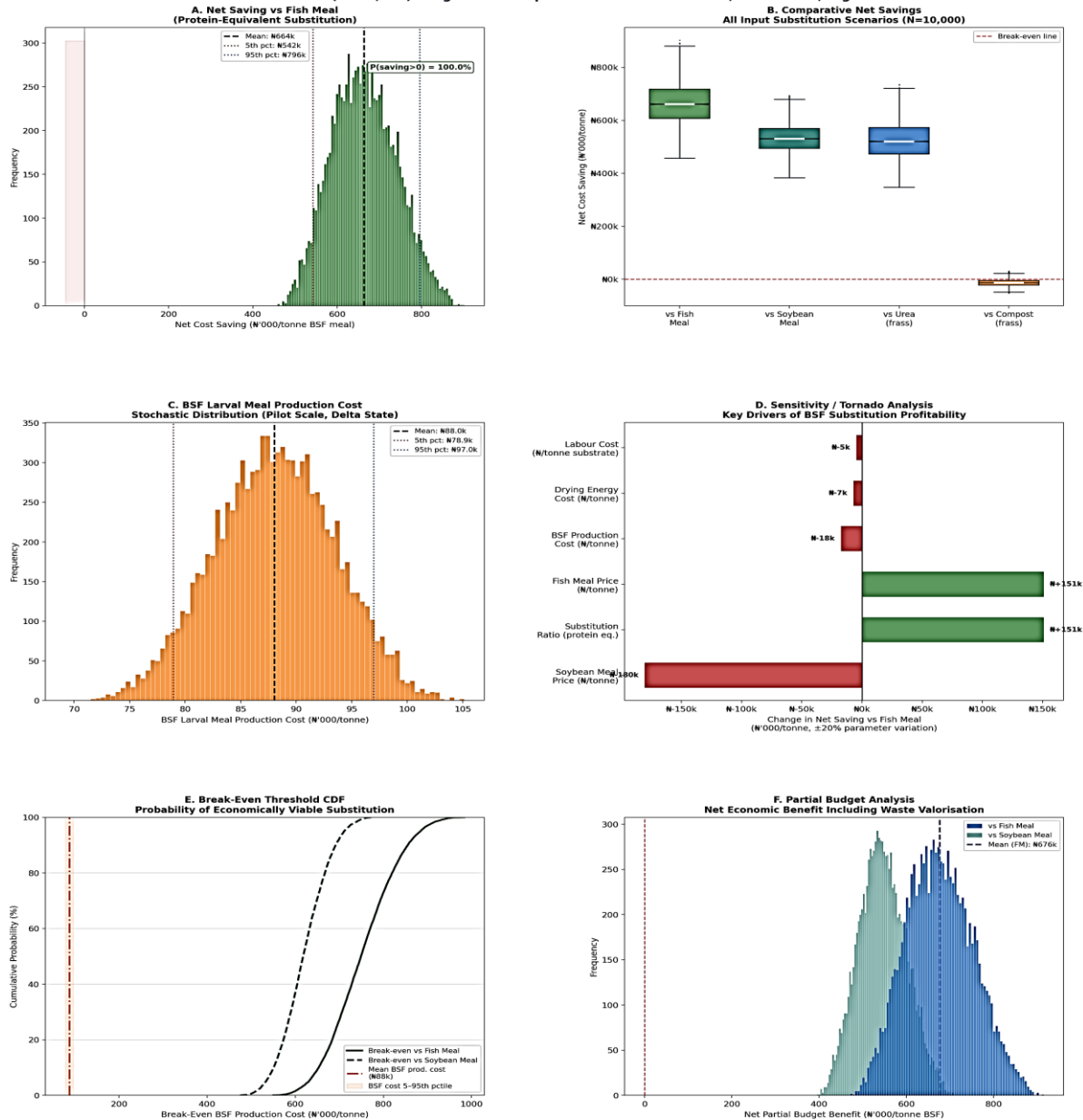
values in Nigerian Naira (₦); USD equivalents not reported due to exchange rate volatility during the study period.

The most economically significant substitution opportunity in the Delta State context is the replacement of imported fish meal by dried BSF larval meal in catfish (*Clarias gariepinus*) and tilapia (*Oreochromis niloticus*) aquafeed — both species representing major aquaculture enterprises in the state. With fish meal prices at ₦680,000–950,000 per tonne and BSF larval meal producible at pilot scale for an estimated ₦350,000–480,000 per tonne (inclusive of substrate, labour, energy, and drying costs), cost savings of ₦120,000–280,000 per tonne of aquafeed protein source are achievable at the protein-equivalent substitution ratio of 1:1.0–1.2. This is consistent with substitution economics reported for comparable smallholder-scale BSF operations in West Africa (Shumo *et al.*, 2019; van Huis & Oonincx, 2017).

Urea substitution through BSF frass application, while carrying a lower per-tonne saving than larval meal substitution, offers the broadest market reach given the widespread use of urea in cassava, yam, and maize production systems across Delta State. At current urea prices of ₦780,000–1,100,000 per tonne and a frass-to-urea nitrogen equivalence ratio of approximately 1:3.8 by weight (reflecting the ~3.2% versus 46% nitrogen differential), the cost per unit of plant-available nitrogen from frass is approximately 35–55% lower than from urea, generating farm-gate savings of ₦45,000–90,000 per tonne of crop under Delta State conditions.

Stochastic techno-economic analysis of BSF bioconversion of cassava processing waste: results of Monte Carlo simulation (N = 10,000 iterations) is presented in Figure 1. Panel A: distribution of net cost savings versus fish meal (protein-equivalent substitution); Panel B: comparative boxplot of net savings across all four input substitution scenarios; Panel C: stochastic distribution of pilot-scale BSF larval meal production cost; Panel D: tornado sensitivity analysis showing key drivers of substitution profitability ($\pm 20\%$ one-at-a-time variation); Panel E: cumulative distribution function of break-even production cost thresholds for fish meal and soybean meal substitution; Panel F: partial budget net benefit distributions incorporating waste valorisation revenue. Price inputs derived from structured market surveys, Agbor (Ika South LGA) and Asaba (Oshimili North LGA), Delta State, March–April 2025. Triangular distributions fitted to survey-reported min/max. Substitution ratios from Chia *et al.* (2020) and Shumo *et al.* (2019). All values in Nigerian Naira (₦).

Stochastic Techno-Economic Analysis: BSF Bioconversion of Cassava Processing Waste
Monte Carlo Simulation (N=10,000) – Agricultural Input Substitution Economics, Delta State, Nigeria



Monte Carlo simulation (N=10,000 iterations). Price inputs: structured market surveys, Agbor (Ika South LGA) & Asaba (Oshimi North LGA), March–April 2024. Triangular distributions fitted to survey min/max. Substitution ratios from Chia *et al.* (2020), Shumo *et al.* (2019). All values in Nigerian Naira (₦).

DISCUSSION

The proximate composition data generated at KAO's Quality Assurance Laboratory, Benin City, from the UNIDEL pilot facility confirm that cassava processing waste is a functionally viable, if nutritionally modest, BSF rearing substrate. The 32.0% DM crude protein content of dried larval meal, while lower than the 39–50% DM achievable on higher-protein substrates such as poultry manure or fish processing waste (Makkar *et al.*, 2014; Shumo *et al.*, 2019), remains within the range required for partial fish meal substitution in catfish and tilapia diets — particularly at 25–50% inclusion partial substitution levels rather than complete replacement. This has direct practical relevance to Delta State's aquaculture sector, which has been substantially constrained by escalating imported fish meal costs intensified by the naira depreciation trajectory of 2023–2024 (CBN, 2024).

The 20.0% DM crude fat content observed in cassava waste-fed larvae is consistent with the well-established mechanistic relationship between substrate carbohydrate density and BSF larval lipid



accumulation. High-starch substrates drive de novo lipogenesis in larval fat bodies, producing larvae with elevated fat and lower protein relative to protein-balanced substrates (Chia *et al.*, 2020; Liu *et al.*, 2022). For animal feed applications, this fat concentration is advantageous in energy-dense aquafeeds for catfish but may require dietary reformulation when substituting at high inclusion rates in leaner-diet poultry formulations. Mechanical defatting — achievable by expeller pressing at pilot scale — would elevate crude protein above 40% DM and reduce fat below 10% DM, substantially improving feed flexibility and market value, and is recommended for facilities seeking formal aquafeed or poultry feed market entry.

The frass composition data reveal several agronomic characteristics that distinguish BSF frass from conventional compost. The C:N ratio of 8.9:1 is notably narrower than that of typical cassava peel compost (C:N 20–35:1), implying faster nitrogen availability to crops in the 4–8 week window following application — an important property for short-season crops such as maize and cowpea that require early-season nitrogen availability (Houben *et al.*, 2020). The chitin content of 38–52 mg/g DM, while lower than frass from protein-rich substrates (reported at 35–80 mg/g DM across substrate types; Schmitt & Vilcinskis, 2018), is sufficient to elicit documented soil biostimulant responses including suppression of *Fusarium* wilt complex and stimulation of phosphate-solubilising bacteria — both agronomically relevant in Delta State's predominantly acidic, phosphorus-fixing soils.

The economic analysis reveals a clear hierarchy of substitution value: dried larval meal for aquafeed fish meal replacement offers the highest per-unit economic return and aligns with the most pressing agricultural input cost constraint facing Delta State fish farmers. However, frass biofertiliser offers the largest volumetric market given that approximately 3.2 kg of frass is generated per kg of larval biomass produced, meaning frass revenue streams are essential to the economic viability of BSF enterprises at pilot and commercial scale. This co-product revenue dynamic underscores the importance of developing market channels for both outputs simultaneously, rather than treating frass as a secondary waste product — a perspective well-established in global BSF bioconversion literature (Liu *et al.*, 2022; Smetana *et al.*, 2019).

From a circular economy perspective, the UNIDEL pilot facility operationalises three overlapping value loops within a single biological system: conversion of otherwise-discarded cassava waste into protein biomass (resource loop closure); substitution of import-dependent synthetic fertilisers and fish meal with locally produced biological equivalents (import substitution and food security); and return of stabilised organic matter and chitin to agricultural soils (soil ecosystem restoration). These co-benefits, though difficult to fully monetise in simple economic models, represent the systemic rationale for public investment in BSF bioconversion infrastructure within Delta State's broader agricultural development strategy, and are consistent with the priorities articulated in Nigeria's National Agricultural Technology and Innovation Policy (NATIP, 2022) and the Delta State Agricultural Policy frameworks. Several limitations of this study should be acknowledged. First, the pilot-scale facility operated a single rearing cycle; replication across multiple cycles and seasons would strengthen the productivity and composition estimates. Second, frass composition was determined from a single composite sample; longitudinal variability across batches and seasons warrants investigation. Third, the economic analysis did not account for full life-cycle costing or for the market development infrastructure required to realise frass distribution at scale. Fourth, the conventional $N \times 6.25$ conversion factor was applied; future work should report protein content using both the conventional factor and insect-specific correction factors to facilitate cross-study comparability (Janssen *et al.*, 2017). These limitations notwithstanding, this study provides the first systematically documented, laboratory-verified compositional and economic dataset for cassava waste-based BSF bioconversion under UNIDEL conditions, constituting a foundational baseline for subsequent expanded studies.

CONCLUSION AND RECOMMENDATION

This pilot-scale investigation at the Department of Animal Science, Faculty of Agriculture, University of Delta (UNIDEL), Agbor — with proximate analyses conducted at KAO's Quality Assurance Laboratory, Benin City — demonstrates that cassava processing waste is a viable substrate for BSF larval rearing under Delta State conditions. Dried larval meal achieved 32.0% DM crude



protein, 20.0% DM crude fat, and 22.0 MJ/kg DM gross energy, profiles suitable for partial fish meal substitution in aquafeed at 25–50% inclusion levels. Fresh-to-dried proximate concentrations increased 2.0–4.4-fold upon moisture removal, confirming the transformative feed value of the drying step. BSF frass from cassava waste bioconversion contained 3.2% N, 2.4% P, 2.1% K (DM basis) and 38–52 mg/g DM chitin with a C:N ratio of 8.9:1, positioning it as a fast-releasing, biostimulant-active soil amendment that substantially exceeds the agronomic value of conventional composts of equivalent NPK content. Waste mass reduction indices of 48–55% and larval biomass yields of 70–85 kg fresh/t substrate DM confirm functional bioconversion performance under ambient tropical conditions, consistent with cassava-substrate literature benchmarks.

Economic analysis indicates farm-gate cost savings of ₦25,000–280,000 per tonne of substituted agricultural input under 2024 Delta State market conditions. Priority scale-up recommendations include: (i) developing a cassava waste substrate supplementation protocol (brewers' waste or blood meal at 10–15% inclusion) to elevate substrate protein and bring larval crude protein above 40% DM; (ii) investing in pilot-scale mechanical defatting equipment; (iii) establishing formal frass quality certification pathways with the Delta State Ministry of Agriculture; and (iv) conducting multi-season agronomic field trials with BSF frass in cassava and maize production systems. Future research should additionally assess the environmental and economic performance of BSF systems at commercially relevant scale (100–500 t/annum) and investigate the application of insect-specific nitrogen-to-protein conversion factors to improve cross-study protein characterisation.

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CONFLICTS OF INTEREST

The author declares no conflicts of interest in the conduct or reporting of this research.

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