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Supplementation of maize bran with either sunflower or oil palm seed cakes improves growth and nutritional value of the edible house cricket (*Acheta domesticus*)

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Abstract

The house cricket, *Acheta domesticus* (Linnaeus) (Orthoptera: Gryllidae) is one of the major insects successfully domesticated for food around the world. However, expensive feed is still a major challenge in the production of the insect, leading to low returns. This study aimed at developing an alternative diet for mass rearing of *A. domesticus*. We tested five diets, namely commercial chicken mash (CCM; control diet), maize bran supplemented with 50% sunflower seed cake (SFC50), 50% shea seed cake (SBC50), 50% oil palm seed cake (POC50), and 25% maize bran + 25% of each of the oil seed cakes (MSSP25). The experiment was arranged as a randomized unreplicated block design with 50 blocks, each containing one replicate of each diet treatment. Survival of *A. domesticus* fed on maize bran supplemented with either sunflower seed cake or oil palm seed cake was comparable to that of those fed on the control diet. However, emerging adults on oil seed supplemented diets (SFC50 and POC50) were heavier than their counterparts raised on the control diet. The shortest development time was observed among *A. domesticus* fed on 50% sunflower seed cake compared to all other diets. *Acheta domesticus* fed on the control diet was richer in protein, while those reared on maize bran supplemented with either sunflower seed cake or oil palm seed cake contained higher levels of fat, minerals (sodium, calcium, and iron) and polyunsaturated fatty acids (PUFAs). We conclude that supplementation of maize bran with 50% of either sunflower seed cake or oil palm seed cake improves survival and weight gain of *A. domesticus* and shortens their development time. In addition, these diets modify the nutritional composition of *A. domesticus*, especially lipids, minerals, and PUFAs. We recommend the use of SFC50 and POC50 as alternative diets to commercial chicken mash in the mass production of *A. domesticus*.

KEYWORDS

circular economy, dietary supplementation, fatty acids, mass production, minerals, nutritional composition, nutritional profile, oil seed cake, orthoptera, proximate composition

INTRODUCTION

Over the past seven decades, the global population has experienced a remarkable increase from 2.6 to 8 billion and is predicted to rise to 9.74 billion people by 2050 (United Nations, 2023). This population growth poses a significant increase in the demand for food, especially protein-rich foods (Okello et al., 2022; Siddiqui

et al., 2024). Africa and Asia are already experiencing a deficit in essential food intake, especially proteins. In 2022, the daily per capita protein intake was lowest in Africa (64.4 g) followed by Asia (81.8 g) (FAOSTAT, 2022). A similar pattern was observed in fat consumption, with the lowest levels being in Africa (54.0 g) and Asia (79.5 g) (Omuse et al., 2024). Consequently, the production of food must increase in order to match the population

growth. However, as the population increases, the per capita land available for agriculture decreases, hence limiting output from conventional crop and animal production (Wade & Hoelle, 2020). In addition, conventional food production systems are associated with challenges such as the emission of greenhouse gases, which are the major causes of climate change (Wade & Hoelle, 2020). Houzer and Scoones (2021) reported that the livestock industry alone produces between 8% and 15% of the planet's greenhouse gas emissions, which is more than the total combined emissions from transportation. In response to these challenges, there has been a tremendous move in recent years to seek alternative food sources, especially protein sources, and insects are one of the potential alternatives (van Huis et al., 2013). Compared with livestock production, insect production systems are more sustainable due to several attributes, including high feed conversion efficiency (Barroso et al., 2014; Bawa et al., 2020; Broeckx, 2021; Oonincx et al., 2015). Additionally, they can be reared on organic waste, emit few greenhouse gases, require a small rearing space, and take a small fraction of feed and water (Govorushko, 2019; van Huis et al., 2013; van Huis & Oonincx, 2017).

The house cricket, *Acheta domesticus* (Linnaeus) (Orthoptera: Gryllidae), is one of the edible insects that have gained popularity as human food due to its rich nutritional profile. It contains 56%–76% proteins, lipids (6%–10%), essential mineral elements, monounsaturated fatty acids (MUFA; 31%), polyunsaturated fatty acids (PUFA; 27%), and energy (12%–18%) of dry matter (DM) (Bawa et al., 2020; Boulos et al., 2020; Magara et al., 2021; Oonincx et al., 2015; Pastell et al., 2021). Furthermore, *A. domesticus* has a high feed conversion efficiency; hence, it can be easily reared on agricultural and food industry side streams (Bawa et al., 2020; Oonincx et al., 2015; Sorjonen et al., 2022). Compared with other edible insect species, the global market for *A. domesticus* is higher and is expected to increase due to increased consumer acceptability in the Western world where insect consumption is not a tradition (Reverberi, 2020). For example, in America and Europe, there are over 20 brands of cricket energy bars on the market (Reverberi, 2020). In the tropics, consumption of *A. domesticus* is still low; however, there are many countries in the region that have long traditions for utilizing edible insects; hence, acceptability of *A. domesticus* is high (van Huis et al., 2013).

Farming of *A. domesticus* has progressively developed in the different parts of the world with large, medium, and small-scale production systems, and it is becoming an integral component of livestock production (Orinda et al., 2017). There are over 200 cricket farmers in Thailand, several cricket farming companies in America and Europe (Reverberi, 2020) and about 378 cricket farmers in Kenya and 140 farmers in Uganda (Tanga et al., 2021). However, the major feed used by large and small cricket farmers is chicken mash, which is very competitive and makes cricket production expensive (Oloo et al., 2020). Durst and

Hanboonsong (2015) reported that feed is the most expensive input in cricket rearing systems; hence, the use of local vegetable remains or other food industry by-products has been proposed to reduce costs in cricket production.

In the recent years, enormous efforts have been made to find cost-effective alternative diets for feeding *A. domesticus*, with several trials undertaken on different side streams from the food and beverage industries and agricultural fields (Jucker et al., 2022; Morales-Ramos et al., 2020; Oloo et al., 2020). In a study by Sorjonen et al. (2022), spent brewery's grains and rapeseed cake improved the survival, development time, and weight gain of *A. domesticus*. Oonincx et al. (2015) tested beet molasses, potato steam peelings, bread remains, spent grains, and cookie remains, and found that these by-products improved the growth parameters (survival, weight gain, and development time) and the nutritional composition of *A. domesticus*. Morales-Ramos et al. (2020) and Oloo et al. (2020) also tested dry cabbage, brewery waste, peanut hull kales, sweet potato leaves, and banana peels on the growth performance of *A. domesticus* and recommended them as efficient and potential diets used in large-scale production systems. However, there is still a need to develop more alternative diets utilizing locally available side streams in the different regions around the world, as some of the recommended by-products are rare in certain regions. Moreover, by-products such as sweet potato leaves and banana peels are also utilized in conventional livestock production, which limits their availability (Oloo et al., 2020).

Oil seed by-products (oil seed press cakes) are often undervalued and usually discarded by oil factories; however, they can be exploited for feeding insects due to their rich nutritional profile (Almeida Sá et al., 2021; Vinayashree & Vasu, 2021). Hoc et al. (2021) and Georgescu et al. (2022) reported that the inclusion of linseed cake, soybean cake, sunflower seed cake, rapeseed cake, and hempseed cake in *H. illucens* (Linnaeus) larval diet, improved both larval weight and fatty acid profile of the larvae. Sorjonen et al. (2022) also demonstrated that a rapeseed cake-based diet enhanced the survival and weight gain of *A. domesticus*. According to Škvorová et al. (2024), a rapeseed cake-based diet increased the content of crude protein and polysaturated fatty acids in *Gryllus assimilis* (Fabricius). These studies provide a basis for investigating more oil seed by-products as alternative diets or diet ingredients in the mass production of *A. domesticus*.

In Uganda, there are both small and large-scale oil factories and domestic oil processors, which utilize oil seeds including sunflower seeds, oil palm seeds, and shea seeds. These factories and domestic processors produce large quantities of oil seed by-products (sunflower seed cake, oil palm seed cake, and shea seed cake), which are currently underutilized because they have not been tested for useful applications. These by-products contain nutrients such as proteins, lipids, minerals, and fatty acids (Almeida Sá et al., 2021), and they can be used as feed or feed

ingredients in rearing insects. This study aimed to evaluate the effect of supplementing maize bran with sunflower seed cake, shea seed cake, and oil palm seed cake on the survival, weight gain, development time, and nutritional profile of *A. domesticus*.

MATERIALS AND METHODS

Study population

Five hundred *A. domesticus* nymphs of the same cohort from two broods at the last nymphal stages were obtained from a farmer in Masaka district, Uganda. They were transported in an adequately aerated rectangular plastic container (60 cm length × 32 cm width × 45 cm height; Thermopack, Nairobi, Kenya) to the multifunctional research laboratory at Gulu University. Six pieces of egg cartons were placed vertically in the container to act as hide-outs for the crickets. *Acheta domesticus* nymphs were reared to adults at 25–28°C, 55%–65% relative humidity, and L12:D12 photoperiod. They were fed on commercially available chicken starter mash put in two Petri dishes, supplemented with fresh leaves of milk weed, cassava, and pumpkin (Ssepuuya et al., 2020). Two Petri dishes filled with moist cotton wool were placed in the rearing container to provide drinking water; both feed and water were provided *ad libitum*. Balls of moist cotton wool were provided for laying eggs upon hearing mating songs and collected after every 3 days. Cotton balls containing eggs were put in round plastic containers (8 cm diameter × 6 cm height; Thermopack) and kept moist by sprinkling water until the eggs hatched.

Experimental diets

Three oil seed by-products, namely sunflower seed cake, oil palm seed cake, and shea seed cake, were used to supplement maize bran. These by-products were selected because they are nutritious and locally obtainable from large- and small-scale oil factories in Uganda, and they are readily available, especially sunflower and shea seed cakes in Northern and oil palm seed cake in central Uganda. Maize bran is the major constituent of the diet commonly used in the commercial farming of *A. domesticus*. The oil seed by-products were collected from local factories, dried in an oven (Memmert, UN260 Schwabach FRG, Germany) at 60°C for 24 h, and ground into fine powder using a heavy-duty blender (Master Electro-EM-BL-1069, China) and sieved through a 1-mm sieve. Maize bran was purchased from Gulu central market in Gulu city and sieved using the same sieve. Four diets of 500 g each were constituted, three of which were 50:50 combinations of maize bran and each of the oil seed by-products, and one was 25% of maize bran + 25% of each of the oil seed by-products (Table 1). These diets were tested alongside commercial

TABLE 1 Composition of the four oil seed-based diet treatments.

Diet treatment	Oil seed by-product inclusion (%)	Maize bran inclusion (%)
SFC50	50	50
SBC50	50	50
POC50	50	50
MSSP25	75 (25% of each by-product)	25

Note: SFC50 = 50% sunflower seed cake + 50% maize bran, SBC50 = 50% shea seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each by-product.

chicken mash (control diet), which was purchased from poultry feed stores in Gulu city, Uganda. After constituting the diets, a sample of 30 g was immediately picked in triplicate from each diet for nutritional analysis, and both the stock and samples were kept in a freezer at −20°C.

Experimental design

The experiment was arranged as a complete randomized unreplicated block design where each block contained one replicate of the experimental diets (Malinga et al., 2022). The setup was maintained at 25–28°C, 50%–60% relative humidity, and L12:D12 photoperiod. One-day-old nymphs were individually reared in plastic containers (21 cm high, 19 cm diameter; Thermopack) with the opening covered by a netting cloth. Each container was randomly subjected to one of the five diet treatments with 50 replicates. The containers were arranged as 50 blocks (i.e., separate locations in the laboratory room), each containing one replicate of each diet treatment (Malinga et al., 2022). The randomized block design aimed to control for potential sources of environmental variability in the laboratory and to ensure that observed changes in the growth performance and nutritional composition of *A. domesticus* were due to differences in diets only. In each container, a 2 cm × 2 cm piece of egg tray carton was placed to provide a hideout for the insects and food was placed on a piece of paper (Ssepuuya et al., 2020). A piece of moist cotton wool was placed in each container to provide drinking water and to humidify the air, and it was kept moist by spraying with potable water daily. Diets and water were provided *ad libitum*, and they were replenished after 2–3 days. To determine survival, observations were made daily until adult molting to detect dead nymphs. For individuals that survived to adults, weights were taken using a digital weighing scale (Model kern PCB350-3) with a precision of 0.0001 g. Development time was calculated as the number of days between hatching of the nymph from eggs and adult emergence. Adults that emerged from each diet treatment were harvested after 2 weeks and kept in the freezer at −20°C until nutritional analysis. The experiment was kept running until there were no more surviving individuals and the emergence of adults from all the treatments.

Nutritional analyses

The nutritional composition of the diets and adult *A. domesticus* from each diet treatment was analyzed, except for SBC50, because the number of adults from this diet could not make the 50 g required for nutritional analysis. Dry matter (DM), total ash, crude fiber, crude fat, crude protein, carbohydrates, minerals, and fatty acids for diets and adult *A. domesticus* from each diet treatment were determined in triplicates. Analyses were performed on samples dried at 60°C for 24 h in an oven (Memmert; UF110), except for DM, and all samples were ground using a mortar and pestle. All analyses were performed at the Centre of Expertise Sustainable biomass and Chemistry, Thomas More University of Applied Sciences, Belgium.

Proximate analysis

Dry matter determination

Dry matter content was determined by drying the sample in an oven (Memmert; UF110) at 105°C for 24 h. DM percentage was calculated based on the weight loss of the sample (Noyens et al., 2023).

$$\% \text{ DM} = \frac{m_{\text{dried sample}}}{m_{\text{sample}}} \times 100.$$

Total ash determination

Total ash was determined by drying the sample at 105°C for 24 h and incineration in a muffle furnace (Nabertherm; L9/11/SKM) at 550°C for 4 h. Percentage ash was calculated from weight loss by incineration (Noyens et al., 2023).

$$\% \text{ Ash} = \frac{m_{\text{incinerated sample}}}{m_{\text{dried sample}}} \times 100$$

Crude protein determination

Crude protein was determined by analyzing the nitrogen present in the samples using the Kjeldahl method BN EN ISO 5983-1 (2005). A general N to P factor of 6.25 was used to calculate the protein content of diets and 5.33 for the insect samples (Boulos et al., 2020; Noyens et al., 2023).

Crude fat determination

Crude fat was determined with ethyl acetate using Soxhlet extraction equipment. Approximately 5 g of each sample was placed in an extraction thimble and covered with ceramic wool to prevent sample loss. The sample was extracted overnight with 350 mL of ethyl acetate; the extract was cooled down, and the organic solvent was

removed and recovered via rotary evaporation (Büchi; R-300) at 153 mbar and 50°C. Flasks containing fat were put in a fume hood for 12 h to eliminate all the solvent and were weighed on an analytical balance (Noyens et al., 2023).

Crude fiber determination

The fiber bag method of Gerhardt was used to determine crude fiber; 1 g of the sample was placed in a dedicated fiber bag (Gerhardt; CF bag) and glass spacer. The fiber bag was filled with the sample, defatted with petroleum ether (BP 40–60°C), and dried for 2 min in a fume hood. The defatted sample was first extracted in an acidic solution of 0.13 M sulphuric acid for 30 min at boiling temperature. The extracted fiber bag with the sample was rinsed three times with boiling demineralised water and subsequently extracted in a solution of 0.23 M potassium hydroxide for 30 min. The extracted fiber bag with the sample was rinsed again three times with boiling demineralised water and dried for 12 h at 105°C. The dried bag with fiber residue was weighed on an analytical balance and incinerated at 550°C for 4 h in a muffle furnace. Ashes were weighed and fiber content was calculated based on the weight loss from the incinerated sample (Noyens et al., 2023).

Carbohydrate determination

Total carbohydrate content was determined by the method of difference following the procedures of the Food and Agriculture Organization (FAO, 2003).

$$\begin{aligned} \% \text{ carbohydrate} &= 100 - (\% \text{ moisture} + \% \text{ crude fiber} \\ &\quad + \% \text{ ash} + \% \text{ crude protein} + \% \text{ crude fat}) \end{aligned}$$

Mineral analysis

Samples were prepared as described by Broeckx (2021), and the mineral profile was determined using inductively coupled plasma-optical emission spectrometry (ICP-OES) (Optima 4300™ DV ICP-OES; Perkin Elmer, Massachusetts, USA). Quantification was done by use of a calibration curve drawn using certified standard solutions (Chem-Lab NV, Zedelgem, Belgium) (Noyens et al., 2023).

Fatty acid analysis

Fatty acids were determined using gas chromatography coupled with mass spectrometry (GC–MS) (Agilent Technologies; 7820A GC system with 5977E MSD detector). Fatty acid methyl esters (FAMES) were prepared from the ether extracts after esterification in a methanolic KOH solution with the addition of 20% BF₃/MeOH solution

according to the method of Joseph and Ackmannt (Joseph & Ackman, 1992). Fatty acids were identified by comparing their retention times with a 37 FAME-mix standard (Chemlab) and by comparing their MS spectrum with online libraries from the NIST database. A qualitative analysis was performed by calculating the area percentage of a peak relative to the total peak area of the chromatogram (Noyens et al., 2023).

Statistical analysis

A generalized linear mixed-effects model (with a binary logistic distribution of the response) was used to determine the effects of diet treatments on the nymphal survival (i.e., the number of individuals that survived to adults compared to those that died [fixed factor]). In this model, block was specified as a random factor. Model goodness-of-fit and the significance of the explanatory variable were assessed with the Hosmer–Lemeshow test and type III Wald chi-squared tests, respectively (Hosmer et al., 2013; Malinga et al., 2022). For individuals that survived to the adult stage, we analyzed the effects of diet, sex, and their interaction on the adult fresh weight and development time using linear mixed models (type III sum of squares). In all models, diet treatment, sex, and diet treatment $\times$ sex interaction were included as fixed factors and block as a random factor. If significant differences were found among treatments, least significant difference (LSD) pairwise tests were performed to determine which treatments were significantly different. The model's fit was checked by inspecting the distribution of the residuals. We tested differences in the content of proteins, crude fat, DM, ash, crude fiber, carbohydrates and minerals in *A. domesticus* among each diet treatment using one-way analysis of variance (ANOVA) followed by LSD post-hoc test to determine differences between all diet treatments. Levene's normality test was conducted to confirm the normality of data before running ANOVA. SPSS software (version 20, Armonk, NY) was used to perform these analyses at a significant level of $\alpha = 0.05$.

We tested differences in the composition of fatty acids (i.e., the proportions of fatty acids) in *A. domesticus* fed on the four diets, using permutational multivariate analysis of variance (PERMANOVA; type III sums of squares and 999 permutations) (Anderson et al., 2008). When significant differences were found, pairwise comparisons were run to determine differences in the different pairs of treatments. A Monte Carlo test was used for both main and pairwise tests because we had only three replicates for each treatment (Anderson et al., 2008). We visualized patterns in the composition of fatty acids among diet treatments using non-metric multidimensional scaling (NMDS). For clarity, distances among centroids of each treatment were shown. We evaluated the degree of variability in the proportion of fatty acids in *A. domesticus* among each treatment using the permutational multivariate dispersion test (PERMDISP)

(Anderson et al., 2008). PERMDISP tests the homogeneity of multivariate dispersions within factor groups based on deviations from the group centroid. The fatty acids with the highest contribution to observed dissimilarities between pairs of diet treatments were determined using a similarity percentages routine (SIMPER) (Clarke & Warwick, 2001). We tested for differences in the contents of saturated fatty acids (SFAs), MUFAs, and PUFAs among *A. domesticus* reared on the four diets using univariate PERMANOVA (using Euclidian distance as a similarity measure, type III sum of squares, 999 permutations). Whenever significant differences were found, we performed pairwise PERMANOVA tests to determine differences between levels of each diet treatment. Additionally, using the routine RELATE (Clarke & Gorley, 2006), we tested the degree of similarity between the two resemblance matrices: diets and *A. domesticus* fed on the diets. These analyses were conducted in PRIMER-E software, version 6 (Clarke & Gorley, 2006) and the PERMANOVA+ add-on package (Anderson et al., 2008), based on the Bray–Curtis similarity matrix computed from untransformed fatty acid composition data. An exception was the univariate PERMANOVA, which was run on the Euclidean similarity matrix from untransformed data (Anderson et al., 2008).

RESULTS

Effect of diet on survival of *A. domesticus* nymphs to adults

Survival of *A. domesticus* nymphs to adults was significantly different among the diets ($F_{4,245} = 23.718, p = 0.001$). The highest survival was observed in *A. domesticus* fed on the 50% sunflower seed cake (SFC50: 96%), 50% oil palm seed cake (POC50: 94%) and the commercial chicken mash control diet (CCM: 94%), while the lowest survival (30%) was among those reared on 50% shea seed cake (SBC50) (Figure 1).

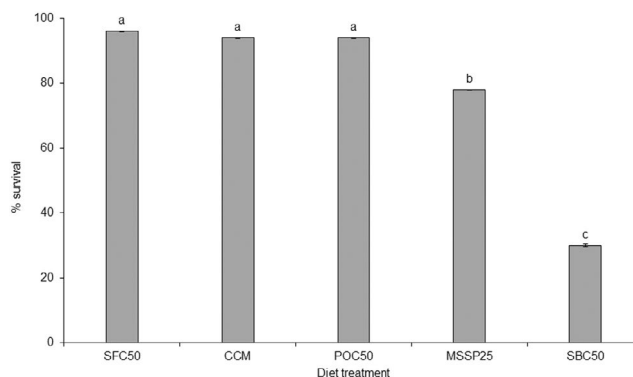


FIGURE 1 Survival (%) of *Acheta domesticus* nymphs to adults on five diets. Columns with the same letters are not significantly different ($p > 0.05$). Error bars indicate standard error of the mean (SEM). SFC50 = 50% sunflower seed cake + 50% maize bran, CCM = commercial chicken mash (control diet), POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each of the seed cakes.

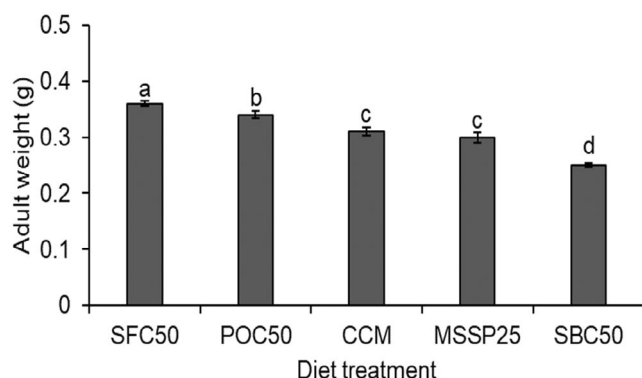


FIGURE 2 Mean adult weight (g) of *Acheta domestica* on five diets. Columns with the same letters are not significantly different ($p > 0.05$). Error bars indicate standard error of the mean. SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, CCM = commercial chicken mash (control diet), MSSP25 = 25% maize bran + 25% of each of the seed cakes, SBC50 = 50% shea seed cake + 50% maize bran.

Effect of diet on weight of *A. domestica* adults

Adult weight of *A. domestica* was significantly different among diets ($F_{4,144.37} = 19.96$, $p = 0.001$). *Acheta domestica* reared on the 50% sunflower seed cake (SFC50) were significantly heavier than those fed on other diets (Figure 2). The treatment $\times$ sex interaction was not significant ($F_{3,165.98} = 1.07$, $p = 0.362$), females were significantly heavier (Marginal mean $0.35 \pm \text{SE } 0.01$ g) than males (0.29 ± 0.01 g) ($F_{1,170.78} = 91.83$, $p = 0.001$).

Effect of diet on development time (from 1-day-old nymph to adult) of *A. domestica*

Development of *A. domestica* from hatching to adults was significantly different among diets ($F_{4,179} = 5.75$, $p = 0.001$), with individuals reared on the 50% shea seed cake (SBC50) taking a significantly longer time (67 days) to develop compared to other diets (Figure 3). The development time of *A. domestica* reared on the 50% sunflower seed cake (SFC50; 56 days) was comparable to those fed on the control diet (56 days). The treatment $\times$ sex interaction was not significant ($F_{3,179} = 1.95$, $p = 1.123$) and there was no significant difference among males and females ($F_{1,182} = 1.08$, $p = 0.301$).

Nutritional composition of experimental diets

The content of crude protein was highest in diets with 50% sunflower seed cake SFC50 (16.3%), followed by the diet with 25% maize bran and 25% each of the seed cakes (MSSP25) (15.5%), while crude fat was highest in all oil seed by-products-based diets compared to the control diet

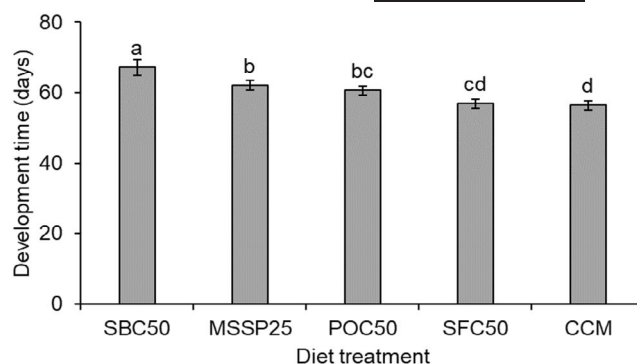


FIGURE 3 Mean development time (days) of *Acheta domestica* on five diets. Bars with the same letters are not significantly different ($p > 0.05$). Error bars indicate standard error of the mean. CCM = commercial chicken mash (control diet), SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each seed cake, SBC50 = 50% shea seed cake + 50% maize bran.

(Table 2). Nine essential minerals (phosphorus, magnesium, potassium, sodium, calcium, zinc, copper, iron and manganese) were detected in all the diets in varying proportions. The content of phosphorus, magnesium, calcium, and sodium was highest in the control diet, while potassium, zinc, copper, iron, and manganese were highest in oil seed by-products-based diets compared to the control diet. The most predominant fatty acids in all diets were oleic acid (18:1), palmitic acid (16:0), linoleic acid (18:2), and stearic acid (18:0). The saturated fatty acids in the test diets were about double the value in the control diet. Polyunsaturated fatty acids were significantly higher in the control diet than in any of the test diets. Monounsaturated fatty acids were lowest in the 50% oil palm seed cake but were comparable among all the other diets.

Proximate composition of *A. domestica* fed on four diets

The content of DM, ash, crude fiber, and carbohydrate was not significantly different among *A. domestica* fed on all four diets (Table 3). The content of protein was significantly higher in *A. domestica* fed on the control diet, while the content of crude fat was significantly higher among *A. domestica* fed on the three oil seed by-product-based diets compared to the control diet.

Mineral content of *A. domestica* fed on four diets

All the nine essential minerals found in the diets were also observed in *A. domestica* fed on the four diets. The content of phosphorus, magnesium, potassium, and zinc was significantly higher in *A. domestica* fed on the control diet, while the content of sodium, calcium, and iron was significantly higher in *A. domestica* fed on oil

TABLE 2 Proximate, mineral and fatty acid composition of experimental diets (mean $\pm$ standard error of the mean).

	Diet treatment				
	CCM	SFC50	SBC50	POC50	MSSP25
Proximate (% dry matter)					
Dry matter	90.9 $\pm$ 0.1	94.6 $\pm$ 0.3	92.1 $\pm$ 0.2	92.1 $\pm$ 0.2	93.8 $\pm$ 0.2
Total ash	10.6 $\pm$ 0.7	4.8 $\pm$ 0.2	5.1 $\pm$ 0.1	13.2 $\pm$ 0.3	8.8 $\pm$ 0.2
Crude fiber	10.9 $\pm$ 0.5	16.8 $\pm$ 0.6	12.7 $\pm$ 0.3	13.9 $\pm$ 0.3	13.9 $\pm$ 0.3
Crude fat	7.7 $\pm$ 0.3	36.6 $\pm$ 0.5	23.2 $\pm$ 0.2	17.8 $\pm$ 0.6	24.5 $\pm$ 0.1
Crude protein	13.5 $\pm$ 0.1	16.4 $\pm$ 0.2	12.5 $\pm$ 0.1	14.9 $\pm$ 0.1	15.5 $\pm$ 0.3
Carbohydrate	48.3 $\pm$ 1.4	19.9 $\pm$ 0.6	38.5 $\pm$ 0.5	32.3 $\pm$ 0.4	31.2 $\pm$ 0.5
Minerals (mg/100 g dry matter)					
P	747.97 $\pm$ 59.17	553.1 $\pm$ 16.44	543.91 $\pm$ 48.37	461.22 $\pm$ 9.43	486.85 $\pm$ 27.18
Mg	406.01 $\pm$ 11.72	224.94 $\pm$ 4.93	248.51 $\pm$ 15.18	248.02 $\pm$ 7.55	232.51 $\pm$ 8.75
K	716.95 $\pm$ 21.01	642.82 $\pm$ 8.51	1236.55 $\pm$ 9.23	905.79 $\pm$ 9.25	1014.65 $\pm$ 5.35
Na	83.43 $\pm$ 3.31	55.83 $\pm$ 4.92	57.15 $\pm$ 5.22	32.89 $\pm$ 5.20	66.49 $\pm$ 6.97
Ca	798.82 $\pm$ 63.62	214.94 $\pm$ 20.66	352.9 $\pm$ 6.02	355.44 $\pm$ 7.29	458.13 $\pm$ 9.59
Zn	5.21 $\pm$ 0.55	4.5 $\pm$ 0.31	3.75 $\pm$ 0.47	5.46 $\pm$ 0.52	3.71 $\pm$ 0.24
Cu	0.83 $\pm$ 0.07	1.03 $\pm$ 0.04	0.47 $\pm$ 0.05	4.95 $\pm$ 0.38	2.96 $\pm$ 0.42
Fe	167.84 $\pm$ 13.84	79.85 $\pm$ 4.43	28.81 $\pm$ 1.16	974.91 $\pm$ 34.64	480.05 $\pm$ 4.34
Mn	4.01 $\pm$ 0.37	3.67 $\pm$ 0.29	3.05 $\pm$ 0.39	8.89 $\pm$ 0.57	6.14 $\pm$ 0.12
Fatty acids (% of 100 g crude fat)					
Myristic acid (C14:0)	0.1 $\pm$ 0.01	0.1 $\pm$ 0.01	7.8 $\pm$ 0.1	0.6 $\pm$ 0.3	0.3 $\pm$ 0.01
Palmitic acid (C16:0)	11.4 $\pm$ 0.4	8.7 $\pm$ 0.1	40.1 $\pm$ 0.4	34.4 $\pm$ 0.4	13.5 $\pm$ 0.2
Palmitoleic acid (C16:1)	0.4 $\pm$ 0.01	0.1 $\pm$ 0.01	39.5 $\pm$ 0.2	0.2 $\pm$ 0.01	0.2 $\pm$ 0.03
Stearic acid (C18:0)	4.04 $\pm$ 0.2	29.3 $\pm$ 0.8	10.4 $\pm$ 0.3	6.9 $\pm$ 0.2	17.9 $\pm$ 0.2
Oleic acid (C18:1)	38.8 $\pm$ 0.6	36.9 $\pm$ 1.2	0.4 $\pm$ 0.1	32.9 $\pm$ 0.9	38.1 $\pm$ 0.3
Linoleic acid (C18:2)	41.8 $\pm$ 0.7	23.6 $\pm$ 0.7	1. $\pm$ 0.02	21.5 $\pm$ 0.5	26.2 $\pm$ 0.4
Alpha linolenic acid (C18:3)	0.8 $\pm$ 0.03	0.35 $\pm$ 0.01	0.2 $\pm$ 0.2	0.6 $\pm$ 0.02	0.3 $\pm$ 0.02
Arachidic acid (C20:0)	0.6 $\pm$ 0.1	1.2 $\pm$ 0.1	0.21 $\pm$ 0.04	0.7 $\pm$ 0.1	0.8 $\pm$ 0.02
Eicosanoic acid (C20:1)	0.4 $\pm$ 0.01	0.4 $\pm$ 0.1	1.38 $\pm$ 0.03	0.3 $\pm$ 0.03	0.2 $\pm$ 0.02
Behenic acid (C22:0)	0.4 $\pm$ 0.01	0.4 $\pm$ 0.04	0.22 $\pm$ 0.01	0.3 $\pm$ 0.04	0.6 $\pm$ 0.03
Lignoceric acid (C24:0)	0.3 $\pm$ 0.02	0.3 $\pm$ 0.02	0.21 $\pm$ 0.04	0.4 $\pm$ 0.02	0.3 $\pm$ 0.01
SFA	16.9 $\pm$ 0.6	39.9 $\pm$ 0.8	49.71 $\pm$ 0.6	43.6 $\pm$ 0.5	33.4 $\pm$ 0.1
MUFA	39.5 $\pm$ 0.6	37.4 $\pm$ 1.2	39.51 $\pm$ 0.7	33.4 $\pm$ 0.9	38.6 $\pm$ 0.2
PUFA	42.6 $\pm$ 0.7	23.9 $\pm$ 0.7	10.83 $\pm$ 0.4	22.1 $\pm$ 0.5	26.5 $\pm$ 0.4

Note: CCM = commercial chicken mash (control diet), SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each seed cake, SBC50 = 50% shea seed cake + 50% maize bran.

Abbreviations: MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid.

seed by-product-based diets compared to the control diet (Table 4). The content of copper and manganese was not different among all diet treatments.

Fatty acid composition of *A. domesticus* fed on four diets

Eight fatty acids were found in *A. domesticus* fed on the four diets (SFC50, POC50, MSSP25, and the control diet). These included four SFAs (palmitic acid, stearic acid,

myristic acid and arachidic acid), two MUFAs (oleic acid and palmitoleic acid), and two PUFAs (linoleic acid and Alpha linolenic acid) (Table 5). The most predominant fatty acids were SFAs (36%–40%) followed by PUFAs (28%–36%).

The composition of fatty acids in *A. domesticus* differed significantly among the four diets (PERMANOVA Pseudo- $F_{3,8}$ = 205.26, p = 0.001). According to the pairwise comparisons, the composition of fatty acids in *A. domesticus* reared on all diets differed significantly from each other as illustrated by the NMDS ordination (Figure 4). There was

TABLE 3 Dry matter (% on fresh matter), total ash, crude fiber, crude fat, crude protein, and carbohydrates (% on dry matter basis) of *Acheta domesticus* fed on four diets.

Proximate	Diet treatment				df	F	p-Value
	CCM	SFC50	POC50	MSSP25			
Dry matter	36.5 ± 0.7 ^a	37.7 ± 0.7 ^a	36.6 ± 0.5 ^a	35.2 ± 0.6 ^a	3	2.39	0.14
Total ash	6.9 ± 0.3 ^a	5.3 ± 0.3 ^a	5.1 ± 0.6 ^a	4.2 ± 0.1 ^a	3	9.34	0.07
Crude fiber	8.9 ± 0.6 ^a	7.2 ± 0.4 ^a	8.2 ± 0.3 ^a	7.4 ± 0.2 ^a	3	4.15	0.07
Crude fat	24.4 ± 0.6 ^a	35.4 ± 0.1 ^b	32.4 ± 0.7 ^b	35.3 ± 0.9 ^b	3	68.52	<0.001
Crude protein	58.1 ± 0.2 ^a	45.7 ± 0.5 ^b	51.9 ± 0.9 ^c	51.3 ± 1.4 ^c	3	32.76	<0.001
Carbohydrate	10.6 ± 0.8 ^a	13.6 ± 0.8 ^a	10.6 ± 0.9 ^a	9.3 ± 1.9 ^a	3	2.32	0.52

Note: Values within the same row with same letters are not significantly different (mean ± standard error of the mean, One-way ANOVA, $\alpha = 0.05$). CCM = commercial chicken mash (control diet), SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each seed cake. SBC50 was not included because no adults emerged.

TABLE 4 Mineral content (mg/100 g dry matter basis) of *Acheta domesticus* fed on four diets.

Mineral	Diet treatment				df	F	p-Value
	CCM	SFC50	POC50	MSSP25			
P	716.6 ± 63.98 ^a	621.8 ± 10.53 ^b	622.43 ± 0.52 ^b	655.11 ± 2.21 ^c	3	144.62	0.01
Mg	74.31 ± 0.91 ^a	60.71 ± 0.84 ^b	63.84 ± 0.49 ^b	48.96 ± 0.77 ^c	3	182.78	0.01
K	979.45 ± 0.98 ^a	832.32 ± 0.77 ^b	875.27 ± 0.77 ^d	880.18 ± 1.35 ^e	3	3912.52	0.01
Na	331.98 ± 1.15 ^a	327.81 ± 1.17 ^a	341.21 ± 1.16 ^b	352.95 ± 1.64 ^b	3	112.48	0.01
Ca	85.78 ± 0.59 ^a	80.66 ± 1.15 ^b	113.64 ± 0.98 ^d	132.91 ± 1.19 ^e	3	593.71	0.01
Zn	18.94 ± 0.66 ^a	14.08 ± 0.19 ^b	14.48 ± 0.19 ^b	12.02 ± 0.59 ^b	3	39.97	0.01
Cu	1.37 ± 0.17 ^a	1.62 ± 0.14 ^a	1.73 ± 0.27 ^a	1.8 ± 0.17 ^a	3	0.91	0.48
Fe	14.93 ± 0.52 ^a	10.27 ± 0.78 ^b	28.8 ± 0.29 ^c	19.07 ± 0.63 ^d	3	182.15	0.01
Mn	2.88 ± 0.18 ^a	2.51 ± 0.19 ^a	2.57 ± 0.22 ^a	2.55 ± 0.21 ^a	3	0.71	0.57

Note: Values within the same row with same letters are not significantly different (mean ± standard error of the mean, One-way ANOVA, $\alpha = 0.05$). CCM = commercial chicken mash (control diet), SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each seed cake. SBC50 was not included because no adults emerged.

TABLE 5 Fatty acid composition (% of 100 g crude fat) of *Acheta domesticus* fed on four diets.

Fatty acids	Diet treatment				df	Pseudo-F	p-Value
	CCM	SFC50	POC50	MSSP25			
Myristic acid (C14:0)	1 ± 0 ^a	1 ± 0 ^a	1.3 ± 0.3 ^a	20.7 ± 0.3 ^b	3	0.23	0.02
Palmitic acid (C16:0)	25.3 ± 0.3 ^a	19 ± 0.6 ^b	30.7 ± 0.7 ^c	1.3 ± 0.3 ^d	3	43.32	0.03
Palmitoleic acid (C16:1)	1.6 ± 0.1 ^a	1.4 ± 0.1 ^b	1.4 ± 0.1 ^b	0.5 ± 0.04 ^c	3	1.46	0.04
Stearic acid (C18:0)	9 ± 0 ^a	15.7 ± 0.9 ^b	8 ± 0 ^c	14 ± 0 ^d	3	2.76	0.02
Oleic acid (C18:1)	28.3 ± 0.2 ^a	25.3 ± 0.8 ^b	30.02 ± 0.5 ^c	33.8 ± 0.8 ^d	3	34.71	0.03
Linoleic acid (C18:2)	33.2 ± 0.2 ^a	36.6 ± 0.9 ^b	28.4 ± 0.4 ^c	29.7 ± 0.3 ^d	3	23.36	0.03
Alpha linolenic acid (C18:3)	0.3 ± 0.02 ^a	0.2 ± 0.01 ^b	0.4 ± 0.1 ^c	0.2 ± 0.03 ^b	3	0.37	0.04
Arachidic acid (C20:0)	0.3 ± 0.3 ^a	0.3 ± 0.3 ^a	0.3 ± 0.3 ^a	0 ± 0 ^a	3	1.74	0.17
SFA	36.6 ± 0.2 ^a	36.3 ± 1.6 ^b	40.5 ± 0.6 ^c	37.4 ± 0.5 ^d	3	57.12	0.04
MUFA	29.8 ± 0.3 ^a	26.7 ± 0.8 ^b	31.4 ± 0.6 ^c	34.3 ± 0.8 ^d	3	38.28	0.03
PUFA	33.8 ± 0.3 ^a	36.9 ± 0.9 ^b	28.8 ± 0.45 ^c	29.9 ± 0.3 ^c	3	39.44	0.04
ω -6/ ω -3	102.5 ± 7.2 ^a	231.1 ± 17.9 ^b	78.7 ± 8.3 ^c	165.1 ± 20.7 ^b	3	89.76	0.01

Note: Values within the same row with same letters are not significantly different (mean ± standard error, PERMANOVA, $\alpha = 0.05$). CCM = commercial chicken mash (control diet), SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each seed cake. SBC50 was not included because no adults emerged.

Abbreviations: MUFA, monounsaturated fatty acid; PFA, polyunsaturated fatty acid; SFA, saturated fatty acid.

no significant difference in the degree of variability in fatty acid composition of *A. domesticus* among diet treatments (PERMDISP: $F_{3,8}=3.64$, $p=0.224$). Three fatty acids (palmitic acid, linoleic acid, and myristic acid) made the strongest contribution to differences in the fatty acid composition of *A. domesticus* fed on the four diets (SIMPER analysis; Table 6).

The proportion of SFAs differed significantly among *A. domesticus* fed on the four diets (PERMANOVA Pseudo- $F_{3,8}=549.44$, $p=0.001$). Based on the pairwise comparisons, the four diets differed significantly from each other ($p<0.05$). The proportion of MUFAs in *A. domesticus* fed on the four diets was significantly different (PERMANOVA Pseudo- $F_{3,8}=32.402$, $p<0.001$). Based on the pairwise comparisons, the diets differed significantly from each other ($p<0.05$). Also, the proportion of PUFAs differed among diet treatments (PERMANOVA Pseudo- $F_{3,8}=42.91$, $p=0.001$). According to the pairwise comparisons, the diets differed significantly from each other ($p<0.05$) except for diet POC50 versus MSSP25 ($p=0.06$). In addition, the ω -6/ ω -3 ratio differed among diets (PERMANOVA

Pseudo- $F_{3,8}=21.43$, $p=0.001$). Based on the pairwise comparisons, the ω -6/ ω -3 ratio differed among all diet pairs except CCM versus POC50 ($p=0.097$) and SFC50 versus MSSP25 ($p=0.084$).

The resemblance matrix of fatty acid compositions of the four diets (CCM, SFC50, POC50 MSSP) did not correlate with that of *A. domesticus* fed on these diets (RELATE analysis; $\rho=0.11$, $p=0.216$).

DISCUSSION

This study demonstrated that supplementation of maize bran with 50% of either sunflower seed cake or oil palm seed cake improves survival and weight gain of *A. domesticus* and shortens their development time. Survival (neonate nymphs to adults) of *A. domesticus* fed on diets supplemented with either sunflower seed cake or oil palm seed cake was 2–4 times higher than their counterparts fed on a combination of spent grain, beer yeast, and cookie remains (27%) (Jucker et al., 2022; Oonincx et al., 2015). The differences in the survival of *A. domesticus* in previous studies and the current study could be due to the differences in nutritional composition of the diets tested. We observed the highest survival in diets, 50% sunflower seed cake (SFC50), 50% oil palm seed cake (POC50), and the control diet. The high survival among *A. domesticus* fed on these diets is attributed to higher content of proteins and minerals (iron and sodium), which are vital for insect survival (Ferrero et al., 2017; Hernández et al., 2012; Peterson et al., 2021). Our results concur with Oonincx et al. (2015) and Kaewtapee et al. (2024) who reported high survival of *A. domesticus* and *Gryllus bimaculatus* (DeGeer) fed on protein and mineral-rich diets. Whereas the protein and mineral (iron and sodium) content of diets consisting of shea seed cake (MSSP25 and SBC50) were comparable to the other diets, survival of *A. domesticus* fed on these diets was low compared to those fed on diets containing 50% sunflower seed cake, 50% oil palm seed cake, and the control diet. This could be because shea seed cake was unpalatable to *A. domesticus*, which led to low intake of diets where it was incorporated. It is also likely that shea seed cake contains antinutrients such as tannins, which could have

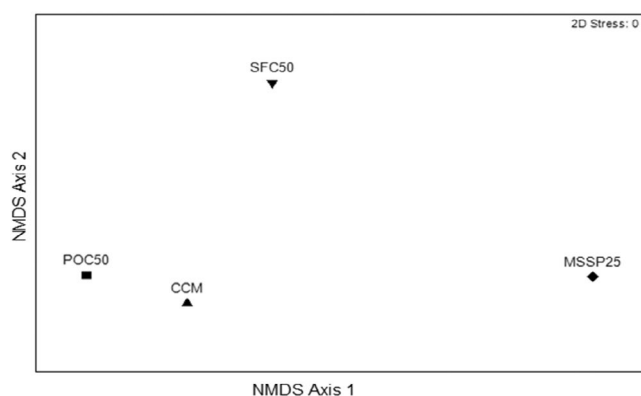


FIGURE 4 Patterns in the fatty acid composition of *Acheta domesticus* fed on the four diets, based on non-metric multidimensional scaling (NMDS). The centroids of each treatment are shown for clarity. The closer the treatments are in the ordination space, the more similar their fatty acid composition was. CCM = commercial chicken mash (control diet), SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each seed cake. SBC50 was not included because no adults emerged.

TABLE 6 Fatty acids in *Acheta domesticus* that contributed to the dissimilarity between different pairs of diet treatments (SIMPER analysis, % contribution).

Fatty acid	CCM and SFC50	CCM and POC50	CCM and MSSP25	SFC50 and POC50	SFC50 and MSSP25	POC50 and MSSP25
Linoleic acid	16.6	35.9	-	24.5	12.2	-
Oleic acid	14.6	13.01	9.3	14.1	15.1	6.2
Palmitic acid	32.8	35.4	41.4	34.2	31.6	48
Stearic acid	32.4	9.9	7.8	23.7	-	9.8
Myristic	-	-	33.4	-	35.6	31.9

Note: Fatty acids with the highest contribution are shown in bold. CCM = commercial chicken mash (control diet), SFC50 = 50% sunflower seed cake + 50% maize bran, POC50 = 50% oil palm seed cake + 50% maize bran, MSSP25 = 25% maize bran + 25% of each seed cake. SBC50 was not included because no adults emerged.

interfered with the digestibility of the feeds and utilization of nutrients in these diets. However, investigating the presence of antinutrients in shea seed cake is warranted to confirm this argument.

Adult weight of *A. domesticus* reared on diets, 50% sunflower seed cake, 50% oil palm seed cake was significantly heavier compared to those fed on the control diet and diets containing shea seed cake. This is because the high content of protein and fat in these diets enhanced weight gain of *A. domesticus*. Proteins are the body building blocks which translate into an increase in size while fats and excess carbohydrates are accumulated in the fat body of insects, hence increasing their biomass (Kim et al., 2020; Li et al., 2020). The adult weight of *A. domesticus* observed in this study is comparable to those fed on hen feed combined with grape marc (0.2–0.38 g), maize distiller (0.27–0.32 g) (Jucker et al., 2022) and a combination of rice bran and spent yeast (0.34 g) (Orinda et al., 2017). Our findings have revealed that maize bran supplemented with either 50% sunflower cake or oil palm cake can be used in large-scale production systems to produce *A. domesticus* of enhanced weight. The interaction between diet and sex was not significant, indicating that both sexes responded similarly to the different diets in terms of weight gain. However, females from all diets were heavier than males. This result aligns with the typical sexual dimorphism observed in many insect species, where females often grow larger than males, potentially due to reproductive roles and associated energy requirements (Esperk et al., 2007).

Acheta domesticus fed on 50% sunflower seed cake and the control diet developed faster than those fed on other diets (POC50, MSSP25, and SBC50). The development time of *A. domesticus* (from neonate nymphs to adults) observed in this study is comparable to those reared on fruit and vegetable waste (67 days), maize distiller (60 days) (Jucker et al., 2022), and a high protein, high fat diet (55 days) (Oonincx et al., 2015). The fast growth observed in *A. domesticus* fed on the control diet and 50% sunflower seed cake diet can be explained by the higher levels of protein and carbohydrates in these diets compared to the other oil seed by-product-based diets. Similarly, Bawa et al. (2020) and Oonincx et al. (2015) observed shorter development times among *A. domesticus* reared on high protein diets. Our findings align with Roeder and Behmer (2014) and Rho and Lee (2014), who reported that proteins and carbohydrates are crucial nutrients in insects development. Kim et al. (2020) also found that *Drosophila melanogaster* (Meigen) grew faster when fed on diets containing high levels of proteins and carbohydrates.

Previous studies have consistently reported that the proximate composition, mainly protein and fat, of *A. domesticus* is modified by diet (Bawa et al., 2020; Finke, 2002; Oonincx et al., 2019). In the present study, all proximate parameters except fat and protein were similar in *A. domesticus* fed on the four diets (SFC50, POC50, MSSP25, and control diet). The fat content of *A. domesticus* was greatly influenced by oil seed by-product diets due to their high

fat content. The content of fat found in *A. domesticus* reared on oil seed-based diets was higher than the 6%–19% that was found in *A. domesticus* fed on vegetable waste, cattle manure, garden waste, and horse manure (Harsányi et al., 2020). *Acheta domesticus* fed on the oil seed-based diets in the current study also had a higher fat content than those fed on formulated feed with varied protein composition (Yaemkong et al., 2024). The content of protein in *A. domesticus* fed on the three oil seed by-product-based diets was generally lower than that in those fed on the control diet. However, this protein content is comparable to the 52% protein reported by Oonincx et al. (2015) in *A. domesticus* reared on combinations of by-products from food industries. The content of fiber, ash, and carbohydrate found in our study falls within the ranges previously reported for *A. domesticus*, where fiber ranged from 4% to 8%, ash (3%–5%) and carbohydrate (1%–11%) (Amarender et al., 2020; Jino et al., 2021; Promkhan et al., 2020; Sihamala et al., 2018; Udomsil et al., 2019).

Results on the mineral content of *A. domesticus* showed that it proportionately accumulated all the nine minerals that were found in the diets. This observation aligns with the findings by Harsányi et al. (2020) for crickets fed on vegetable waste, garden waste, and animal manure. The contents of P, Mg, K, Na, Ca, Zn, Cu, and Mn found in the present study are within the ranges previously reported, that is, 225.00–1038.9, 22.60–136.58, 347.00–1211.1, 101.44–471.4, 27.50–210, 6.71–22.20, 0.51–4.86, and 0.89–4.40 mg/100 g, respectively (Barroso et al., 2014; Bawa et al., 2020; Finke, 2002; Magara et al., 2021; Payne et al., 2016a, 2016b; Rumpold & Schlüter, 2013; Udomsil et al., 2019; Williams et al., 2016). For the case of iron, its content was highest in *A. domesticus* fed on diets POC50 and MSSP25 and was above the range (1.9–11.23 mg/100 g) previously reported (Bawa et al., 2020; Magara et al., 2021). The high content of iron in *A. domesticus* fed on these diets is explained by the significantly high content of iron in the diets. Therefore, oil seed by-product-based diets can be used to produce *A. domesticus* rich in macro and micro minerals, notably diets POC50 and MSSP25, which yielded crickets containing an exceptionally high content of iron. The content of iron in crickets fed on POC50 is 12 times more than that of beef (2.4 mg/100 g) and 23 times more than that of chicken (1.2 mg/100 g) (Finke, 2002).

Our results revealed that the fatty acid composition of *A. domesticus* was influenced by the diets, which concurs with previous reports (Bawa et al., 2020; Oonincx et al., 2015). The most abundant fatty acids were oleic acid and linoleic acid, and they were highest in *A. domesticus* fed on diets MSSP25 and SFC50, respectively. These results are noteworthy since both oleic and linoleic acids are associated with a decrease in low-density lipoprotein and cholesterol; hence, they reduce the risk of cardiovascular diseases (Pilco-Romero et al., 2023; Shramko et al., 2020). The gradient in the fatty acid composition of *A. domesticus* corresponded with that of the diets on which they were raised, indicating that certain fatty acids, especially linoleic acid, are modified by diet,

which aligns with findings by Lehtovaara et al. (2017). The saturated fatty acids were the most predominant, and their content was highest in *A. domesticus* fed on diet POC50, which is reflected in this diet. Whereas monounsaturated fatty acids are reportedly higher than polyunsaturated fatty acids in *A. domesticus* and other orthopterans (Pilco-Romero et al., 2023; Udomsil et al., 2019), we found higher levels of PUFAs compared to MUFAs in crickets fed on the 50% sunflower seed cake and the control diet. However, in all diets, PUFAs were mainly contributed by linoleic acid, which greatly increased the ω -6/ ω -3 ratio. Foods with high levels of ω -6/ ω -3 ratio are associated with inflammatory, cardiovascular, and immunological disorders in humans (Russo, 2009). Therefore, while the oil seed by-product diets are potential alternative diets for mass production of *A. domesticus*, it is important to increase the content of alpha-linolenic acid in these diets to produce crickets with ω -6/ ω -3 ratio that is within the recommended range of 4:1 to 10:1 associated with more health benefits to humans (Russo, 2009; Ssepuuya et al., 2019).

CONCLUSION

In conclusion, our results demonstrated that supplementation of maize bran with 50% of either sunflower seed cake or oil palm seed cake enhances survival and weight gain of crickets and shortens their development time. Furthermore, these diets modify the nutritional composition of *A. domesticus*, notably fat, iron, and PUFA but not the ω -6/ ω -3 ratio. We recommend use of SFC50 and POC50 as alternative diets to commercial chicken mash in mass production of *A. domesticus*. However, future studies should focus on increasing the content of alpha-linolenic acid in these diets to produce crickets that are healthier for human consumption. Furthermore, evaluating the economic feasibility of using maize bran supplemented with either 50% sunflower cake or oil palm cake compared to the conventional feed (chicken mash) in mass rearing of *A. domesticus* is warranted.

AUTHOR CONTRIBUTIONS

Francis Sengendo: Writing – original draft; methodology; writing – review and editing; data curation; conceptualization; software; formal analysis; visualization. **James Peter Egonyu:** Supervision; writing – review and editing; methodology; validation. **Anu Valtonen:** Supervision; writing – review and editing; validation; methodology; formal analysis; visualization. **Isabelle Noyens:** Supervision; writing – review and editing; formal analysis. **Harriet Angwech:** Supervision; writing – review and editing. **Martha Franny Alaroker:** Writing – review and editing; data curation. **Philip Nyeko:** Supervision; writing – review and editing; validation. **Geoffrey Maxwell Malinga:** Visualization; supervision; project administration; funding acquisition; conceptualization; validation; writing – review and editing; investigation; methodology; resources.

Sabine Van Miert: Supervision; funding acquisition; writing – review and editing; project administration; validation; conceptualization; investigation; resources; visualization; methodology.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data will be available upon request from the corresponding author.

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REFERENCES

- Almeida Sá, A.G., da Silva, D.C., Pacheco, M.T.B., Moreno, Y.M.F. & Carciofia, B.A.M. (2021) Oilseed by-products as plant-based protein sources: amino acid profile and digestibility. *Future Foods*, 3, 100023.
- Amarender, R.V., Bhargava, K., Dossey, A.T. & Gamagedara, S. (2020) Lipid and protein extraction from edible insects—crickets (Gryllidae). *LWT - Food Science and Technology*, 6, 109222. Available from: <https://doi.org/10.1016/j.lwt.2020.109222>
- Anderson, M.J., Gorley, R.N. & Clarke, K.R. (2008) *PERMANOVA+ for PRIMER: guide to software and statistical methods*. Plymouth, UK: PRIMER-E.
- Barroso, F.G., de Haro, C., Sánchez-Muros, M.J., Venegas, E., Martínez-Sánchez, A. & Perez-Banon, C. (2014) The potential of various insect species for use as food for fish. *Aquaculture*, 422–423, 193–201. Available from: <https://doi.org/10.1016/j.aquaculture.2013.12.024>
- Bawa, M., Songsermpong, S., Kaewtapee, C. & Chanput, W. (2020) Effect of diet on the growth performance, feed conversion, and nutrient content of the house cricket. *Journal of Insect Science*, 2, 1–10. Available from: <https://doi.org/10.1093/jisesa/ieaa014>
- Boulos, S., Tännler, A. & Nyström, L. (2020) Nitrogen-to-protein conversion factors for edible Insects on the swiss market: *T. molitor*, *A. domesticus*, *L. migratoria*. *Frontiers in Nutrition*, 7, 89. Available from: <https://doi.org/10.3389/fnut.2020.00089>
- Broeckx, L. (2021) Growth of black soldier fly larvae reared on organic side-streams. *Sustainability (Switzerland)*, 13, 12953. Available from: <https://doi.org/10.3390/su132312953>
- Clarke, K.R. & Gorley, R.N. (2006) *PRIMER v6: user manual/tutorial*. Plymouth, UK: PRIMER-E.
- Clarke, K.R. & Warwick, R.M. (2001) *Change in marine communities: an approach to statistical analyses and interpretation*, 2nd edition. Plymouth: PRIMER-E.
- Durst, P. & Hanboonsong, Y. (2015) Small-scale production of edible insects for enhanced food security and rural livelihoods: experience from Thailand and Lao People's Democratic Republic. *Journal of Insects as Food and Feed*, 1, 25–31.
- Esperk, T., Tammaru, T., Nylin, S. & Teder, T. (2007) Achieving high sexual size dimorphism in insects: females add instars. *Ecological Entomology*, 32, 243–256.
- FAOSTAT. (2022) *Food security and nutrition*. Available from: <https://www.fao.org/faostat/en/#data> [Accessed 23rd June 2024].

- Ferrero, A., Torreblanca, A. & Garcerá, M.D. (2017) Assessment of the effects of orally administered ferrous sulfate on *Oncopeltus fasciatus* (Heteroptera: Lygaeidae). *Environmental Science, Pollution Research and Management*, 24, 8551–8561. Available from: <https://doi.org/10.1007/s11356-017-8546-z>
- Finke, M. (2002) Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo Biology*, 21, 269–285.
- Food and Agriculture Organisation (FAO). (2003) *Food energy—methods of analysis and conversion factors*. Available from: http://www.fao.org/uploads/media/FAO_2003_Food_Energy_02.pdf [Accessed 20th August 2024].
- Georgescu, B., Boaru, A.M., Muntean, L., Sima, N., Struti, D.I., Paapuc, T.A. et al. (2022) Modulating the fatty acid profiles of *Hermetia illucens* larvae fats by dietary enrichment with different oilseeds: a sustainable way for future use in feed and food. *Insects*, 13(9), 801. Available from: <https://doi.org/10.3390/insects13090801>
- Govorushko, S. (2019) Global status of insects as food and feed source: a review. *Trends in Food Science and Technology*, 91, 436–445.
- Harsányi, E., Juhász, C., Kovács, E., Huzsvai, L., Pintér, R., Fekete, G. et al. (2020) Evaluation of organic wastes as substrates for rearing *Zophobas morio*, *Tenebrio molitor*, and *Acheta domesticus* larvae as alternative feed supplements. *Insects*, 11(9), 604. Available from: <https://doi.org/10.3390/insects11090604>
- Hernández, L., Arcila, M., Todd, E.V., Miller, G.A. & Frederickson, M.E. (2012) Salt intake in Amazonian ants: too much of a good thing? *Insectes Sociaux*, 59, 425–432. Available from: <https://doi.org/10.1007/s00040-012-0237-7>
- Hoc, B., Franci, F., Carpentier, J., Mostade, L., Blecker, C., Purcaro, G. et al. (2021) Omega-3-enrichment of *Hermetia illucens* (L. 1758) prepupae from oilseed by-products. *Journal of the Saudi Society of Agricultural Sciences*, 20, 155–163.
- Hosmer, J.D.W., Lemeshow, S. & Sturdivant, R.X. (2013) *Applied logistic regression*, 3rd edition. Hoboken, NJ: John Wiley and Sons.
- Houzer, E. & Scoones, I. (2021) *Are livestock always bad for the planet? Rethinking the protein transition and climate change debate*. Brighton: PASTRES. Available from: <https://doi.org/10.19088/STEPS.2021.003>
- Jino, T., Surawang, S. & Wachirasir, K. (2021) Chemical composition and optimum condition of protein concentrate extraction from commercial crickets. *Thai Journal of Science and Technology*, 1, 64–73. Available from: <https://doi.org/10.14456/tjst.2021.5>
- Joseph, J.D. & Ackman, R.G. (1992) Capillary column gas chromatographic method for analysis of encapsulated fish oils and fish oil ethyl esters: collaborative study. *Journal of AOAC International*, 75(3), 488–506. Available from: <https://doi.org/10.1093/jaoac/75.3.488>
- Jucker, C., Belluco, S., Oddon, B., Ricci, A., Bonizzi, L., Lupi, D. et al. (2022) Impact of some local organic by-products on *Acheta domesticus* growth and meal production. *Journal of Insects as Food and Feed*, 6, 631–640.
- Kaewtapee, C., Triwai, P., Inson, C., Masmeatathip, R. & Sriwongras, P. (2024) Effects of protein levels on production performance, nutritional values, and phase feeding of two-spotted cricket. *Journal of Insect Science*, 2, 18. Available from: <https://doi.org/10.1093/jisesa/ieae039>
- Kim, K., Jang, T., Min, K.J. & Lee, K.P. (2020) Effects of dietary protein: carbohydrate balance on life-history traits in six laboratory strains of *Drosophila melanogaster*. *Entomologia Experimentalis et Applicata*, 168, 482–491. Available from: <https://doi.org/10.1111/eea.12855>
- Lehtovaara, V.J., Valtonen, A., Sorjonen, J., Hiltunen, M., Rutaro, K., Malinga, G.M. et al. (2017) The fatty acid contents of the edible grasshopper *Ruspolia differens* can be manipulated using artificial diets. *Journal of Insects for Food Feed*, 3(253), 262.
- Li, Y., Wang, S., Liu, Y., Lu, Y., Zhou, M., Wang, S. et al. (2020) The effect of different dietary sugars on the development and fecundity of *Harmonia axyridis*. *Frontiers in Physiology*, 11, 574851. Available from: <https://doi.org/10.3389/fphys.2020.574851>
- Magara, H.J.O., Niassy, S., Ayieko, M.A., Mukundamago, M., Egonyu, J.P., Tanga, C.M. et al. (2021) Edible crickets (Orthoptera) around the world: distribution, nutritional value, and other benefits—a review. *Frontiers in Nutrition*, 7, 537915. Available from: <https://doi.org/10.3389/fnut.2020.537915>
- Malinga, G., Acur, A., Ocen, P., Holm, S., Rutaro, K., Ochaya, S. et al. (2022) Growth and reproductive performance of edible grasshopper (*Ruspolia differens*) on different artificial diets. *Journal of Economic Entomology*, 115, 724–730. Available from: <https://doi.org/10.1093/jee/toac053>
- Morales-Ramos, J.A., Rojas, M.G., Dossey, A.T. & Berhow, M. (2020) Self-selection of food ingredients and agricultural by-products by the house cricket, *Acheta domesticus* (Orthoptera: Gryllidae): a holistic approach to develop optimized diets. *PLoS One*, 1, e0227400. Available from: <https://doi.org/10.1371/journal.pone.0227400>
- Noyens, I., Schoeters, F., Van Peer, M., Berrens, S., Goossens, S. & Van Miert, S. (2023) The nutritional profile, mineral content and heavy metal uptake of yellow mealworm reared with supplementation of agricultural side streams. *Scientific Reports*, 13, 11604. Available from: <https://doi.org/10.1038/s41598-023-38747-w>
- Okello, A.O., Otieno, D.J., Nzuma, J.M., Kidoido, M.M. & Tanga, C.M. (2022) Smallholder farmers' willingness to pay for commercial insect-based chicken feed in Kenya. *International Food and Agribusiness Management Review*, 26, 67–87. Available from: <https://doi.org/10.22434/IFAMR2022.0047>
- Oloo, J.A., Ayieko, M. & Nyongesah, J.M. (2020) *Acheta domesticus* (cricket) feed resources among smallholder farmers in Lake Victoria region of Kenya. *Food Science & Nutrition*, 8, 69–78.
- Omuse, E.R., Tonnang, H.E.F., Yusuf, A.A., Machekano, H., Egonyu, J.P., Kimathi, E. et al. (2024) The global atlas of edible insects: analysis of diversity and commonality contributing to food systems and sustainability. *Scientific Reports*, 14(1), 5045. Available from: <https://doi.org/10.1038/s41598-024-55603-7>
- Ooninx, D.G., Laurent, S., Veenbos, M. & Loon, J. (2019) Dietary enrichment of edible insects with omega 3 fatty acids. *Insect Science*, 27, 500–509. Available from: <https://doi.org/10.1111/1744-7917.12669>
- Ooninx, D.G., Van Broekhoven, S., Van Huis, A. & van Loon, J.J. (2015) Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS One*, 14, e144601. Available from: <https://doi.org/10.1371/journal.pone.0144601>
- Orinda, M.A., Mosi, R.O. & Ayieko, M.A. (2017) Effects of housing on growth performance of common house cricket (*Acheta domesticus*) and field cricket (*Gryllus bimaculatus*). *Journal of Entomology and Zoology Studies*, 5, 1138–1142.
- Pastell, H., Mellberg, S., Ritvanen, T., Raatikainen, M., Mykkänen, S., Niemi, J. et al. (2021) How does locally produced feed affect the chemical composition of reared house crickets (*Acheta domesticus*)? *ACS Food Science & Technology*, 1(4), 625–635. Available from: <https://doi.org/10.1021/acsfodsctech.0c00083>
- Payne, C.L.R., Scarborough, P., Rayner, M. & Nonaka, K. (2016a) A systematic review of nutrient composition data available for twelve commercially available edible insects, and comparison with reference values. *Trends in Food Science and Technology*, 47, 69–77. Available from: <https://doi.org/10.1016/j.tifs.2015.10.012>
- Payne, C.L.R., Scarborough, P., Rayner, M. & Nonaka, K. (2016b) Are edible insects more or less “healthy” than commonly consumed meats? A comparison using two nutrient profiling models developed to combat over- and undernutrition. *European Journal of Clinical Nutrition*, 3, 285–291. Available from: <https://doi.org/10.1038/ejcn.2015.149>
- Peterson, T.N., Welti, E.A.R. & Kaspari, M. (2021) Dietary sodium levels affect grasshopper growth and performance. *Ecosphere*, 12, 3392. Available from: <https://doi.org/10.1002/ecs2.3392>
- Pilco-Romero, G., Chisaguano-Tonato, A.M., María, E., Herrera-Fontana, M.E., Chimbo-Gándara, L.F., Sharifi-Rad, M. et al. (2023) House cricket (*Acheta domesticus*): a review based on its nutritional composition, quality, and potential uses in the food industry. *Trends in*

- Food Science and Technology*, 142, 104226. Available from: <https://doi.org/10.1016/j.tifs.2023.104226>
- Promkhan, S., Saithi, S. & Wongbasg, C. (2020) Effect of drying conditions and shelf life of crispy cricket product. *Khon Kaen Agriculture Journal*, 1, 1–12. Available from: [10.14456/kaj.2020.1](https://doi.org/10.14456/kaj.2020.1)
- Reverberi, M. (2020) Edible insects: cricket farming and processing as an emerging market. *Journal of Insects for Food and Feed*, 6, 211–220. Available from: <https://doi.org/10.3920/JIFF2019.0052>
- Rho, M.S. & Lee, K.P. (2014) Geometric analysis of nutrient balancing in the mealworm beetle, *Tenebrio molitor* L. (Coleoptera: Tenebrionidae). *Journal of Insect Physiology*, 71, 37–45. Available from: <https://doi.org/10.1016/j.jinsphys.2014.10.001>
- Roeder, K.A. & Behmer, S.T. (2014) Lifetime consequences of food protein-carbohydrate content for an insect herbivore. *Functional Ecology*, 28, 1135–1143. Available from: <https://doi.org/10.1111/1365-2435.12262>
- Rumpold, B.A. & Schlüter, O.K. (2013) Nutritional composition and safety aspects of edible insects. *Molecular Nutrition & Food Research*, 57, 802–823. Available from: <https://doi.org/10.1002/mnfr.201200735>
- Russo, G.L. (2009) Dietary n-6 and n-3 polyunsaturated fatty acids: from biochemistry to clinical implications in cardiovascular prevention. *Biochemical Pharmacology*, 77, 937–946.
- Shramko, V.S., Polonskaya, Y.V., Kashtanova, E.V., Stakhneva, E.M. & Ragino, Y., I. (2020) The short overview on the relevance of fatty acids for human cardiovascular disorders. *Biomolecules*, 8(8), 1127. Available from: <https://doi.org/10.3390/biom8081127>
- Siddiqui, S.A., Osei-Owusu, J., Yunusa, B.M., Rahayu, T., Fernando, I., Shah, M.A. et al. (2024) Prospects of edible insects as sustainable protein for food and feed – a review. *Journal of Insects for Food and Feed*, 10, 191–217.
- Sihamala, O., Saraboot, N., Chunthanom, P. & Bhulaido, S. (2018) Nutritional value of edible insects in Kalasin province King Mongkut's. *Agricultural Journal*, 2(98), 105.
- Škvorová, P., Kulma, M., Božik, M., Kurečka, M., Plachý, V., Slavíková, D. et al. (2024) Evaluation of rapeseed cake as a protein substitute in the feed of edible crickets: a case study using *Gryllus assimilis*. *Food Chemistry*, 441, 138254. Available from: <https://doi.org/10.1016/j.foodchem.2023.138254>
- Sorjonen, J.M., Karhapää, M., Holm, S., Valtonen, A. & Roininen, H. (2022) Performance of the house cricket (*A. domesticus*) on by-product diets in small-scale production. *Journal of Insects for Food and Feed*, 3, 289–294. Available from: <https://doi.org/10.3920/JIFF2021.0079>
- Ssepuuya, G., Sengendo, F., Ndagire, C., Karungi, J., Fiaboe, K.K.M., Efitre, J. et al. (2020) Effect of alternative rearing substrates and temperature on growth and development of the cricket *Modicogryllus conspersus* (Schaum). *Journal of Insects for Food and Feed*, 7, 163–172. Available from: <https://doi.org/10.3920/JIFF2020.0014>
- Ssepuuya, G., Smets, R., Nakimbugwe, D., Van Der Borght, M. & Claes, J. (2019) Nutrient composition of the long-horned grasshopper *Ruspolia differens* Serville: effect of swarming season and sourcing geographical area. *Journal of Food Chemistry*, 301, 125305.
- Tanga, C.M., Egonyu, J.P., Beesigamukama, D., Niassy, S., Emily, K., Magara, H.J.O. et al. (2021) Edible insect farming as an emerging and profitable enterprise in East Africa. *Current Opinion in Insect Science*, 48, 64–71. Available from: <https://doi.org/10.1016/j.cois.2021.09.007>
- Udomsil, N., Imsoonthornruksa, S., Goslawit, C. & Ketudat-Cairns, M. (2019) Nutritional values and functional properties of house cricket (*Acheta domesticus*) and field cricket (*Gryllus bimaculatus*). *Food Science and Technology Research*, 25, 597–605. Available from: <https://doi.org/10.3136/fstr.25.597>
- United Nations. (2023) *State of the world population*. Available from: <https://www.un-ilibrary.org/content/books/9789210027137> [Accessed 30th June 2024].
- van Huis, A. & Oonincx, D.G.A.B. (2017) The environmental sustainability of insects as food and feed. A review. *Agronomy for Sustainable Development*, 37, 43.
- van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G. et al. (2013) *Edible insects: future prospects for food and feed security*. Rome: Food and Agriculture Organization of the United Nations.
- Vinayashree, S. & Vasu, P. (2021) Biochemical, nutritional and functional properties of protein isolate and fractions from pumpkin (*Cucurbita moschata* var. Kashi Harit) seeds. *Journal of Food Chemistry*, 340, 128177. Available from: <https://doi.org/10.1016/j.foodchem.2020.128177>
- Wade, M. & Hoelle, J. (2020) A review of edible insect industrialization: scales of production and implications for sustainability. *Environmental Research Letters*, 15, 123013. Available from: <https://doi.org/10.1088/1748-9326/aba1c1>
- Williams, J.P., Williams, J.R., Kirabo, A., Chester, D. & Peterson, M. (2016) Nutrient content and health benefits of insects. Insects as sustainable food ingredients: production, processing and food applications. *Journal of Food Chemistry*, 2016, 61–84. Available from: <https://doi.org/10.1016/B978-0-12-802856-8.00003-X>
- Yaemkong, S., Incharoen, T., Rattanachak, N. & Jongjitvimol, T. (2024) Comparative analysis of diet effects on growth performance and nutrient composition in house cricket, *Acheta domestica* as an alternative protein source in Thailand. *Cogent Food & Agriculture*, 10(1), 2339543. Available from: <https://doi.org/10.1080/23311932.2024.2339543>

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