Application of Edible insects as Novel Protein Sources in Burundi: Nutritional Characterization and Potential for Food Fortification

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Abstract

Global food insecurity is exacerbated by population growth, climate change, and pressure on natural resources, with sub-Saharan Africa being disproportionately affected. In Burundi, diets are largely based on starchy staples that provide sufficient energy but remain deficient in high-quality protein and essential micronutrients, contributing to persistent malnutrition. Edible insects represent a sustainable, culturally accepted, and nutrient-dense alternative protein source that could support food fortification strategies. The nutritional, mineral, and functional quality of four edible insects was examined. The four edible insects were crickets (Acheta domesticus), locusts (Locusta migratoria), black soldier fly larvae (Hermetia illucens), and bee larvae (Apis mellifera). The proximate composition, chitin level, mineral content, and some physicochemical attributes of the insects were determined. High inter-species variation was found. Crickets had the highest protein (approximately 57% dry matter), thus their suitability as nutritional supplements. Black soldier fly and bee larvae had high lipid and energy values, whereas locusts were found to have extremely high calcium levels. Bee larvae also showed relatively high iron and zinc values. Variability in chitin and biochemical composition affected the functional properties. In conclusion, the data illustrate the complementary, species-specific nutritional values of entomophagy products as sources of protein and micronutrients that can be integrated into meals based on staples in order to optimize the nutritional efficiency of diets in Burundi.

1 Introduction

1.1 Global and African food security challenges

Global food security is becoming more and more threatened by urbanization, population increase, climate change, and resource depletion [1], [2], [3]. Access to reasonably priced, varied, and nutrient-rich foods is severely restricted in low- and middle-income nations, especially in sub-Saharan Africa [4], [5]. Growth, cognitive development, immunity, and productivity are all compromised by protein-energy malnutrition and micronutrient deficiencies, which are particularly common in children and women of reproductive age [6], [7]. Sustainable, locally accessible, nutrient-dense foods that can either replace or enhance conventional animal proteins are needed to address these issues. Due to greenhouse gas emissions, land, water, and feed consumption, conventional livestock production has a significant negative impact on the environment [8]. As a result, research and policy debates are focusing more on alternative protein sources that have less of an impact on the environment [9], [10].

1.2 Edible insects as nutritional and techno-functional food ingredients

With their great nutritional value and little environmental impact, edible insects are becoming more widely acknowledged as acceptable substitute proteins [11], [12]. Insects offer culturally acceptable options for sustainable diets and are traditionally consumed by around two billion people, particularly in Africa, Asia, and Latin America [7], [11]. Insects consume less space and water, produce less greenhouse gases, and have a higher feed conversion efficiency than animals [11], [13]. Insects have amino acid profiles that either meet or surpass FAO/WHO criteria and are high in protein (40–70% DM) [14], [15], [16]. Additionally, they provide polyunsaturated fats, dietary fiber (mostly chitin), and vital minerals like calcium, magnesium, potassium, iron, and zinc [14], [17]. They are useful for treating deficits in both macronutrients and micronutrients because of these qualities [18], [19]. Insect-derived proteins affect composite meals' functional qualities, such as their ability to hold water, emulsification, texture, and matrix stability, in addition to their nutritional value [20], [21], [22]. The main structural polysaccharide found in insect exoskeletons, chitin, has texturizing, immunomodulatory, and prebiotic properties. [23], [24]. However, too much chitin might decrease mineral bioavailability and protein digestibility, highlighting the need of species selection and processing optimization. [25], [26], [27].

1.3 Knowledge gaps and justification for the Burundian context

Insects are barely included in official nutrition programs, despite the fact that entomophagy is common throughout sub-Saharan Africa, including Burundi. Malnutrition is made worse by Burundian diets' heavy reliance on starchy staples like cassava, maize, and sweet potatoes, which supply energy but are deficient in protein and minerals [7], [11]. Improving nutritional intake through the use of insect flours in staple-based diets is a practical and socially acceptable approach. Due to their accessibility and high nutrient content, locally accessible species such as locusts (Locusta migratoria), black soldier flies larvae (Hermetia illucens), bee larvae (Apis mellifera), and crickets (Acheta domesticus) seem especially promising. But nutritional profiles are greatly influenced by species, developmental stage, substrate, and raising conditions [10], [25], [28]. Particularly in Africa, the majority of research to date has been on proximate composition, with little comprehensive comparative evaluations of protein, mineral, chitin, and biochemical or physicochemical properties [13], [29].

In this regard, the current study seeks to offer a thorough and comparative assessment of four edible insect species that are frequently eaten in Burundi as novel and sustainable sources of protein for food fortification: Acheta domesticus, Locusta migratoria, Hermetia illucens larvae, and Apis mellifera larvae. In particular, the study looks into their proximate composition, mineral profiles, chitin content, carbon partitioning, and important physicochemical and biological parameters, such as zeta potential, particle size distribution, and FTIR spectrum features. This work aims to determine the best insect candidates and complementary combinations for the fortification of staple foods like cassava-based products by clarifying species-specific nutritional and techno-functional characteristics. This will contribute evidence-based strategies to address protein and micronutrient deficiencies in Burundi in line with the Sustainable Development Goals (SDGs 2, 3, 12, and 13) .

2 Materials and Methods

2.1 Insect Samples and Preparation

Based on their established nutritional value and local availability in Burundi, four edible insect species were chosen: locusts (Locusta migratoria), bee larvae (Apis mellifera), black soldier fly (BSF) larvae (Hermetia illucens), and crickets (Acheta domesticus). In order to capture intra-species heterogeneity, crickets and locusts were gathered from various natural settings, whereas bee larvae and BSF were obtained from local insect producers. The selection of sampling locations was based on habitat representativeness, reported consumption trends, and accessibility.

Each specimen was cleaned, dried in an oven at 105°C for 24 hours until it reached a consistent weight, then ground in a stainless-steel grinder and sieved to create particles smaller than 500 µm. Until analysis, powders were kept in sealed containers at -20°C. For proximate, carbon, particle size, and zeta potential investigations, three separate samples per species were prepared; for mineral tests, two duplicates were utilized; and because the spectra were very reproducible, FTIR spectra were recorded in a single run per species. Seasonality, substrate variations, and raising circumstances are recognized and described as limitations.

2.2 Proximate Composition Analysis

Standard analytical techniques were used to determine the approximate composition. Using nitrogen-to-protein conversion coefficients of 5.23 for crickets, locusts, and bee larvae and 4.76 for black soldier flies larvae, as suggested by Janssen et al. (2017), the crude protein content was determined using the Kjeldahl technique. Soxhlet extraction with hexane as the solvent was used to measure the amount of lipid. Following consecutive defatting, demineralization, and deproteinization, the chitin content was ascertained. Moisture content was determined by difference, and ash content was determined by burning at 550°C.

2.3 Mineral Analysis

Atomic absorption spectrophotometry (AAS) was used to measure essential minerals (Ca, Fe, Zn, Mg, Cu, Na, K, and Mn) after samples were acid digested using a mixture of HNO_3 and $HClO_4$. The dry matter basis was used to express the mineral concentration.

2.4 Carbon Content Determination

The Dumas method of elemental combustion was used to determine the concentrations of total carbon, organic carbon, and inorganic carbon. The overall biochemical content and level of mineralization of the insect samples were evaluated using these measures.

2.5 FTIR Spectroscopy

An ATR-equipped spectrophotometer was used to record Fourier-transform infrared (FTIR) spectra spanning the 4000–400 cm^{-1} range, with 32 scans per sample and a resolution of 4 cm^{-1}. Amide I (1630–1650 cm^{-1}), Amide II (1520–1540 cm^{-1}), aliphatic CH_2/CH_3 stretching vibrations (2800–2950 cm^{-1}), and polysaccharide-related bands (1000–1150 cm^{-1}) were identified as the main absorption bands.

2.6 Particle Size and Zeta Potential Analysis

Using a Zetasizer device, dynamic light scattering (DLS) was used to quantify the particle size distribution and zeta potential. To assess colloidal stability and dispersion behavior, powdered samples were dispersed in distilled water at a concentration of 0.1% (m/v) and examined at 25°C [21].

2.7 Chitin Extraction and Quantification

Chitin was extracted through chemical treatment involving demineralization with 1 M HCl followed by deproteinization with 1 M NaOH. Chitin yield was calculated as a percentage of dry weight and correlated with characteristic FTIR spectral bands [21].

2.8 Statistical Analysis

Statistical analysis was conducted using a Python 3.10 computing environment. Descriptive statistics and data processing were done using the Pandas library. The normality of data distributions was assessed using D'Agostino's K-squared test, which is implemented in SciPy. Pearson's correlation coefficient (r), with statistical significance set at $p < 0.05$, was calculated to evaluate linear relationships between continuous variables.

Graphical representations, including correlation matrices and histograms, were produced using Matplotlib and Seaborn. As needed for additional visualization, publication-quality figures were produced using Sigma Plot 11.0.

3 Results and Discussion

Table 1
Proximate nutritional composition of selected edible insect species (mean ± SD, n = 3; dry matter basis)

Type of insects	Protein (%)	Chitin	Lipid (%)	Ash (%)	Dry matter (%)	Moisture (%)	Carbohydrates (%)
Crickets	56.81 ± 2.32a	7.3 ± 1.75a	11.12 ± 0.50	8.70 ± 0.14	93.68 ± 0.43	6.32 ± 0.43	9.75
Bee larvae	33.84 ± 1.37b	5.4 ± 1.49b	26.03 ± 0.61	4.23 ± 0.11	83.56 ± 0.08	16.44 ± 0.08	14.06
BSF	37.16 ± 1.97b	3.98 ± 1.6c	45.78 ± 3.22	6.65 ± 0.07	94.04 ± 0.61	5.94 ± 0.61	0.47
Locusts	37.04 ± 2.91b	8.96 ± 1.19a	7.54 ± 0.51	4.33 ± 0.11	93.9 ± 0.00	6.1 ± 0.00	36.03

3.1 Interspecific variability in proximate composition and implications for protein fortification

The mean ± standard deviation is used to express all compositional data. One-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) post hoc test were used to examine differences between insect species. At $p < 0.05$, differences were deemed statistically significant. Values that share distinct superscript letters (a–c) in Tables 1 and 2 differ considerably.The proximate makeup of the four edible bug species varied significantly ($p < 0.05$), as Table 1 illustrates, indicating strong interspecific heterogeneity. The highest protein content was found in crickets (Acheta domesticus) (56.81 ± 2.32% DM), which was much higher than that of locusts, bee larvae, and black soldier fly (BSF) larvae (≈ 33–37% DM). These results are in line with earlier research that found orthopterans (especially crickets) to be among the edible insects with the highest protein content.[14], [30].This protein level is very important for food fortification from a nutritional standpoint. For instance, adding 10% cricket flour to cassava flour would raise the protein content by about 5.7 g per 100 g of product, potentially meeting ~ 11–14% of an adult's daily protein needs (based on FAO recommendations of 40–50 g/day). This demonstrates the concrete impact of cricket-based fortification on Burundi's protein-deficient diets that are primarily composed of cassava and other starchy staples.

The lipid contents of BSF and bee larvae, on the other hand, were considerably greater (45.78 ± 3.22% and 26.03 ± 0.61% DM, respectively), confirming their categorization as energy-dense matrix as opposed to protein-focused components. These patterns have significant implications for improving taste and caloric density in fortified foods and are compatible with their larval metabolism.[14], [19], [29].

3.2 Chitin content: nutritional benefits and functional constraints

Locusts (8.96 ± 1.19% DM) and crickets (7.30 ± 1.75% DM) had the highest levels of chitin ($p < 0.05$), while BSF larvae (3.98 ± 1.60% DM) had the lowest. These changes fall within ranges documented in the literature and represent differences in exoskeletal development and sclerotization between adult orthopterans and larval insects [26], [30].

In terms of nutrition, chitin is becoming more widely acknowledged as an insoluble dietary fiber with possible prebiotic, immunomodulatory, and lipid-lowering properties [24]. However, by physically trapping proteins and chelating divalent minerals like calcium and iron, too much chitin may decrease mineral bioavailability and protein digestibility [25], [26], [27].

These findings imply the existence of an ideal chitin window from a formulation perspective. As seen in BSF larvae, low-to-moderate chitin levels may enhance composite flours' texture, dispersion, and protein accessibility. On the other hand, in order to maintain nutritional efficiency while retaining functional benefits, the greater chitin levels of crickets and locusts require careful management of inclusion rates (e.g., ≤ 10–15%) or the adoption of processing techniques like fermentation or partial de-chitinization.

3.3 Mineral Composition

Table 2
Mineral composition of selected edible insect species (mg/100 g dry matter; mean ± SD).

Mineral	Crickets	BSF	Bee Larvea	Locusts
Mg	17.63 ± 1.12	35.55 ± 0.76	21.76 ± 1.39	28.75 ± 12.02
Fe	10.24 ± 0.33	10.73 ± 0.14	11.27 ± 0.04	9.13 ± 0.12
Zn	1.23 ± 1.04	3.79 ± 0.28	5.47 ± 0.19	2.97 ± 0.014
Cu	1.2 ± 0.47	20.86 ± 0.33	0.45 ± 0.65	4.03 ± 0.014
Ca	41.61 ± 3.35	843.10 ± 10.13	150.0 ± 7.26	1845.92 ± 128.71
Na	366.95 ± 2 .71	328.41 ± 3.00	381.48 ± 34.02	345.22 ± 0.64
K	559.04 ± 0.60	615.93 ± 6.73	381.59 ± 391.12	288.76 ± 73.35
Mn	6.7 ± 19.17	14.68 ± 17.52	3.25 ± 0.62	1.49 ± 1.82

The complementing micronutrient potential of the examined species was highlighted by the significant interspecific heterogeneity found in the mineral analysis (Table 2). Locusts showed remarkably high calcium concentrations (1845.92 mg/100 g DM), which were compatible with significant exoskeletal mineralization and on par with or higher than those of calcium sources obtained from dairy [31], [32]. Incorporation of 5% locust flour into cassava flour could provide approximately 90 mg of calcium per 100 g, representing ~ 9% of adult daily requirements, a highly relevant contribution in low-dairy diets.

The highest concentrations of iron (11.27 mg/100 g DM) and zinc (5.47 mg/100 g DM), two micronutrients that are severely lacking in many sub-Saharan African communities, were found in bee larvae. Depending on age and physiological state, a fortified food with 10% bee larvae flour might provide about 1.1 mg iron and 0.5 mg zinc per 100 g, meeting 6–10% of daily iron requirements [14]. Magnesium, potassium, and copper were especially abundant in BSF larvae, confirming previous findings of effective mineral accumulation in larval insects based on substrate and metabolic activity[10], [15]. Overall, these results support the idea that edible insects are not nutritionally homogenous ingredients but rather species-specific micronutrient reservoirs.

Table 3
Main FTIR spectral features (Amide I and Amide II bands) of protein powders from selected edible insect species.

Insect Species	Amide I (cm^{-1})	Amide II (cm^{-1})	Structural Observations	References
Crickets	1650.0	1550.0	High β-sheet content, tendency to aggregate	[32]
Locusts	1652.0	1552.0	Similar profile to crickets, stable secondary structures	[32]
Bee larvae	1648.0	1548.0	More flexible structures, lower aggregation tendency	[32], [33]
BSF	1645.0	1545.0	Slightly more open protein conformation, protein absorption dominant	[32], [33]

Notes:

- Variations in the secondary structure and content of amino acids are reflected in slight alterations in the locations of the Amide I and II bands.
- By reducing lipid interference, hexane defatting makes it possible to see protein bands more clearly.
- Additional signals (≈ 1375–1420 cm^{-1}) may be produced by chitin, however they are typically obscured in protein-rich defatted powders.

Interpretation:

- All insect protein powders have noticeable Amide I and II bands, which is in line with their high protein concentration.
- Locusts and crickets have greater β-sheet structures, indicating post-processing aggregation tendencies.
- The proteins of bee larvae seem more flexible than those of BSF larvae, which may have an impact on the functional qualities of meal formulations.
- Protein signals are made clearer by the defatting process, which also lessens interference caused by lipids.

The substantial protein content of all insect protein powders was confirmed by FTIR analysis (Table 3), which showed distinct Amide I and II bands. Higher β-sheet structures were found in crickets and locusts, suggesting a stronger propensity for post-processing protein aggregation, which could affect the texture and water-holding characteristics of composite flours [33]. Bee and BSF larvae, on the other hand, displayed more variable protein conformations, which would enhance matrix homogeneity and emulsification [34].

Functional appropriateness was further explained by the lipid-to-protein (L/P) ratio. Locusts and bee larvae had greater ratios (> 0.60), which were linked to better mouthfeel and energy density, whereas crickets had the lowest ratio (0.42), indicating that they were lean, protein-oriented elements. The intermediate profile of BSF larvae demonstrated their adaptability in meal preparation [21].

Table 4
Protein and lipid contents and lipid-to-protein (L/P) ratios of edible insect powders (dry matter basis). The samples were sorted from the highest relative protein content to the highest relative lipid content. The proportions and computed lipid-to-protein (L/P) ratios are summarized as follows:

Sample	Protein (%)	Lipid (%)	L/P Ratio
Crickets	70.6%	29.4%	0.42
BSF	64.3%	35.7%	0.56
Locusts	61.1%	38.9%	0.64
Bee Larvae	62.1%	37.9%	0.61

The lipid-to-protein (L/P) ratio proved a useful integrative indicator of the functional suitability of insect ingredients. Because they had the lowest L/P ratio (0.42), crickets were categorized as a lean, protein-focused ingredient. Conversely, larger ratios (> 0.60) were seen in locusts and bee larvae, indicating lipid-rich matrices that may enhance taste, energy density, and fat-soluble vitamin delivery.

The intermediate profile (L/P = 0.56) of BSF larvae demonstrated flexibility for both protein and energy increases. These differences are crucial for food formulation because the protein-lipid balance influences the emulsification capacity, water-holding behavior, texture development, and shelf stability of composite food systems [20], [21], [34].

3.4 Carbon partitioning and biochemical composition

The four edible bug species' carbon content profiles showed clear biochemical differences affecting their nutritional value and processing capacity. According to research showing that larval insects typically have higher nutritional density and metabolic efficiency than adult orthopterans, bee and Black Soldier Fly (BSF) larvae showed the highest and most stable organic carbon fractions, reflecting their concentration of proteins, lipids, and energy-rich macromolecules. [11].

Consistent with other assessments of orthopteran biochemical profiles, crickets and locusts displayed lower and more variable quantities of organic carbon, probably as a result of changes in feeding, developmental stage, or cuticular structure [29].

Their higher inorganic carbon content, particularly in crickets, corresponds to elevated exoskeletal mineralization, including calcium and ash [1], [32].

Because of their consistent organic carbon content, BSF and bee larvae seem to be a good fit for standardized, scalable food and feed formulations [13], [19], However, in order to minimize variability and guarantee constant nutritional outputs, crickets and locusts may need controlled rearing circumstances even if they provide vital minerals [24], [27]. These findings provide credence to the widely held belief that while orthopterans may require more standardization, larval species are most suited for creating nutrient-rich, industrially scaled insect products [6].

3.5 Implications for food fortification strategies in Burundi

The recent research clearly demonstrates that no single insect species can meet all dietary needs when taken as a whole. Instead, each species has special advantages that can be thoughtfully applied to food fortification programs. Crickets are the greatest candidates for protein enrichment, locusts for calcium fortification, bee larvae for iron and zinc supplementation, and BSF larvae for energy and lipid augmentation.

Adding insect flours, either separately or in combination, is an environmentally sustainable, culturally acceptable, and scientifically sound strategy to improve nutritional quality in Burundi, where diets are dominated by cassava and other starchy staples. This approach aligns with FAO recommendations on sustainable protein diversification and immediately helps achieve SDGs 2, 3, 12, and 13.

3.6 Study limitations and future perspectives

While this study provides trustworthy species-specific nutritional data, additional research is necessary because to variations in raising conditions, seasonal availability, and processing methods. The sensory acceptability, protein digestibility, and amino acid bioavailability of insect-fortified meals under real-world consumption conditions should be evaluated in future research. Furthermore, controlled intervention trials are needed to determine the actual nutritional impact of insect-based fortification on vulnerable populations.

4 Conclusion

This study clearly demonstrates that Burundian edible insects are high-potential nutritional resources for food fortification due to their distinct and complementary nutritional profiles. Crickets are particularly helpful for supplementing staple diets with protein, even though locusts are an excellent provider of calcium. While bee larvae appear to be well suited for iron and zinc supplementation, black soldier flieslarvae are distinguished by their substantial lipid and energy content as well as their rather stable biochemical makeup.

The importance of selecting insect species according to specific nutritional objectives is highlighted by the notable interspecific diversity in protein, mineral, chitin, and carbon composition. Instead of using a single-species approach, combining several insect flours into cassava-based and other basic food products could maximize macro- and micronutrient intake while retaining cultural acceptance and environmental sustainability.

Through the production of species-specific data under local conditions, this effort provides a strong scientific basis for the development of context-appropriate insect-based fortification approaches in Burundi. Ultimately, it contributes to the achievement of the Sustainable Development Goals, particularly those related to sustainable protein diversification, improved nutrition and health, climate action, and zero hunger.

Declarations

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Ethics declarations

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Figures

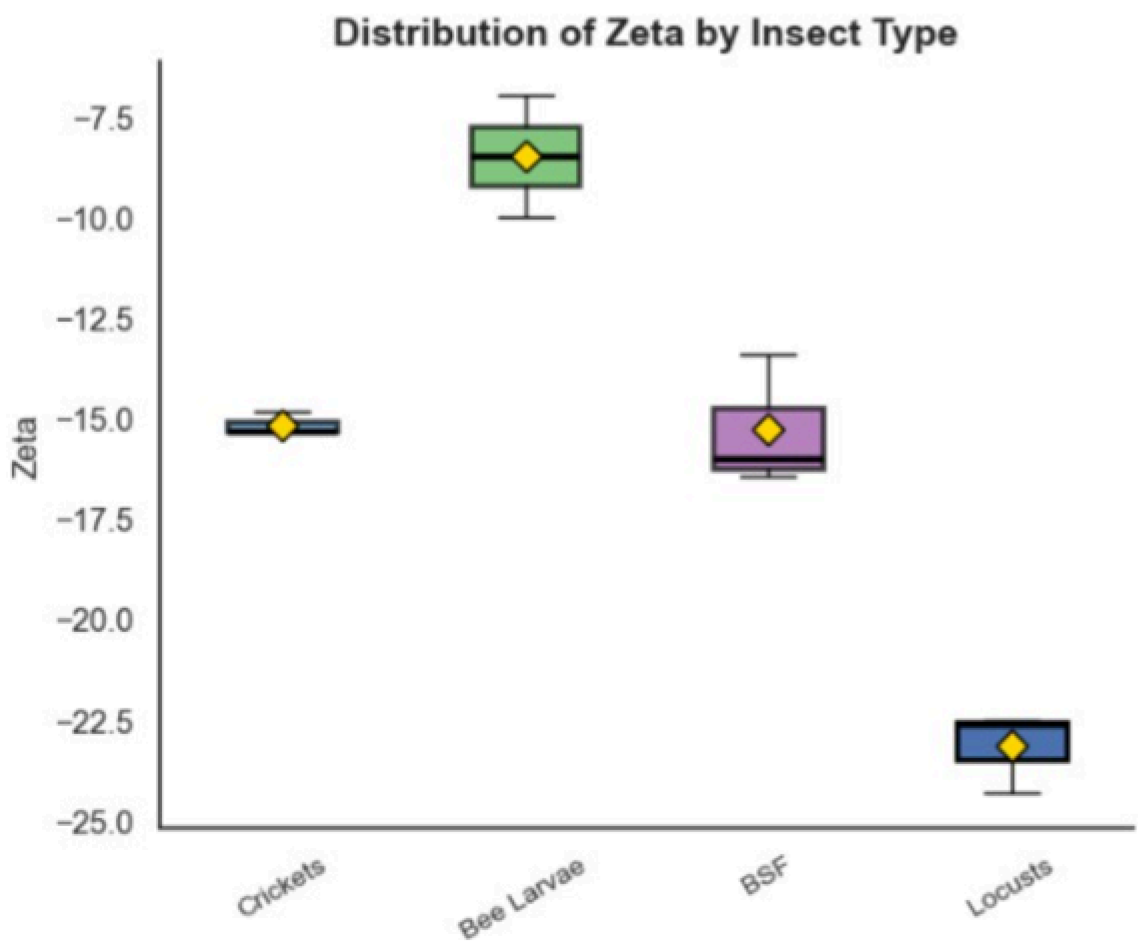

Figure 1

Zeta potential of powders derived from different edible insect species.

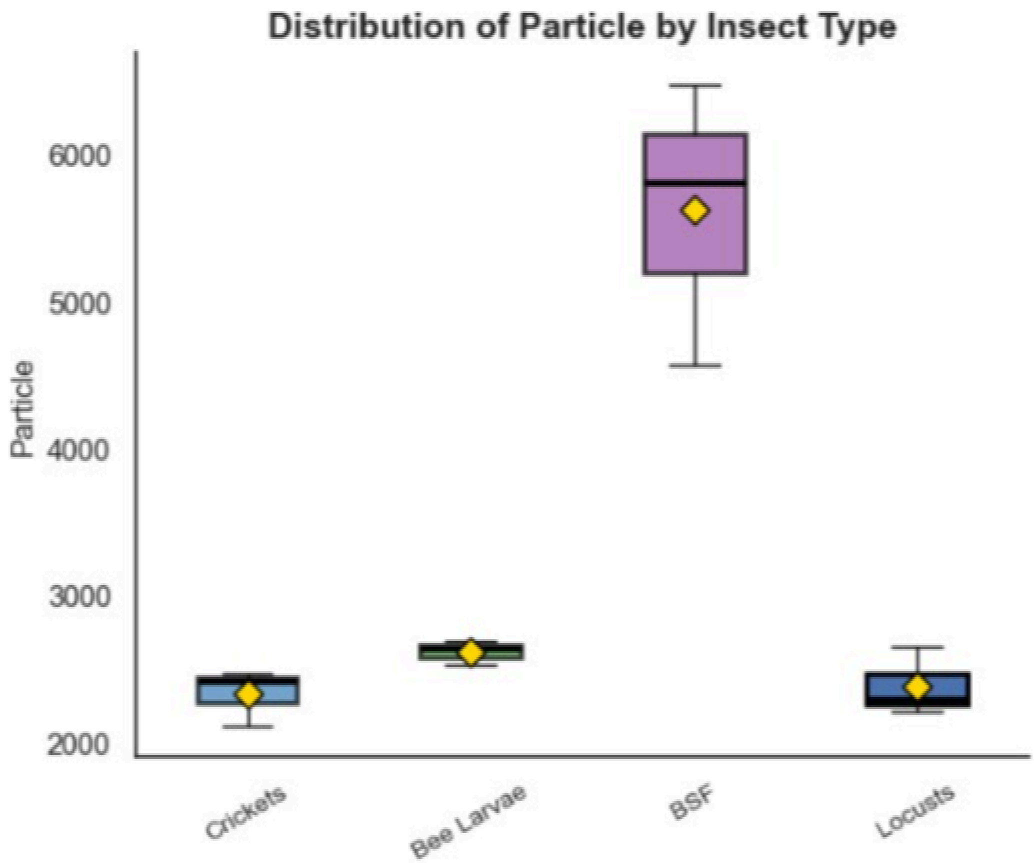

Figure 2

Comparative biochemical and physicochemical properties of the four edible insect species consumed in Burundi

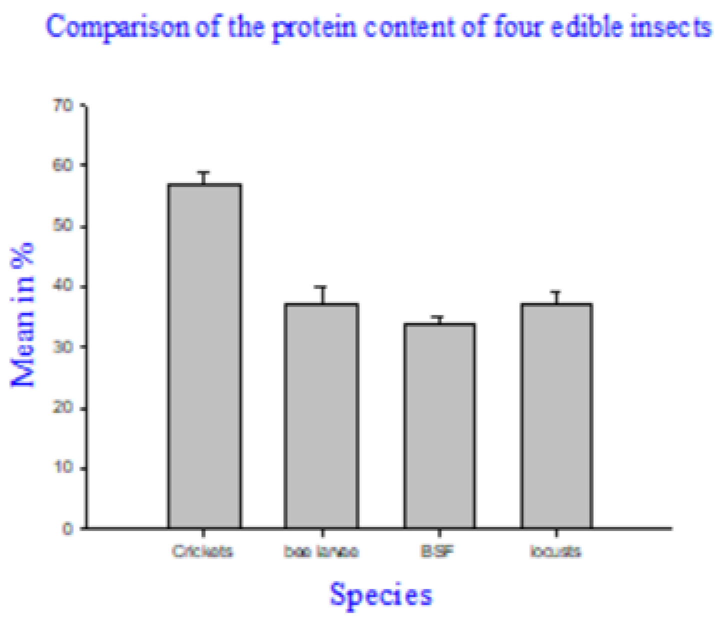

Figure 3

Comparison of protein content (% dry matter) across the four edible insect species

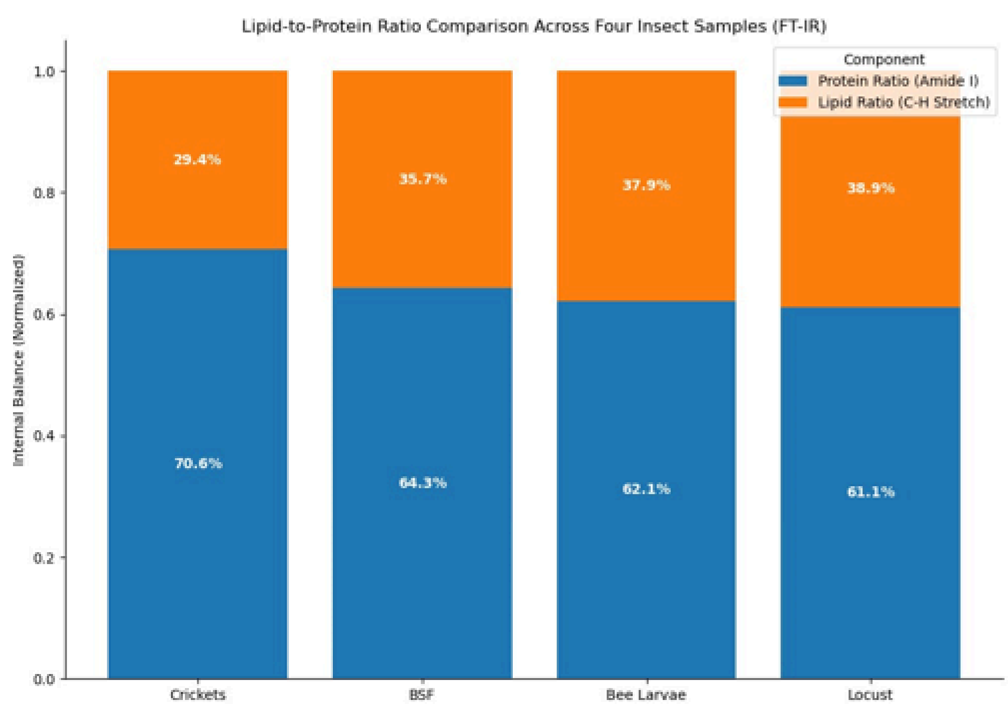

Figure 4

Lipid to Protein comparison across four insect samples (FTIR)

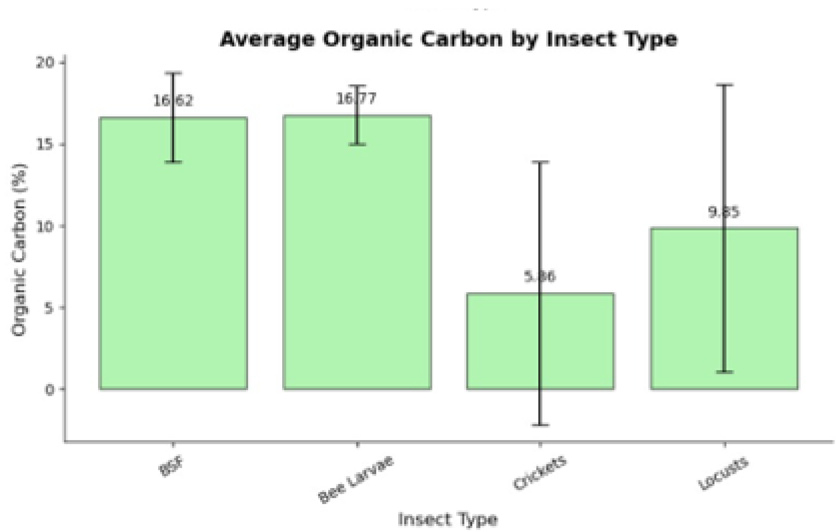

Figure 5

Carbon partitioning in the four edible insect species: (a) organic carbon

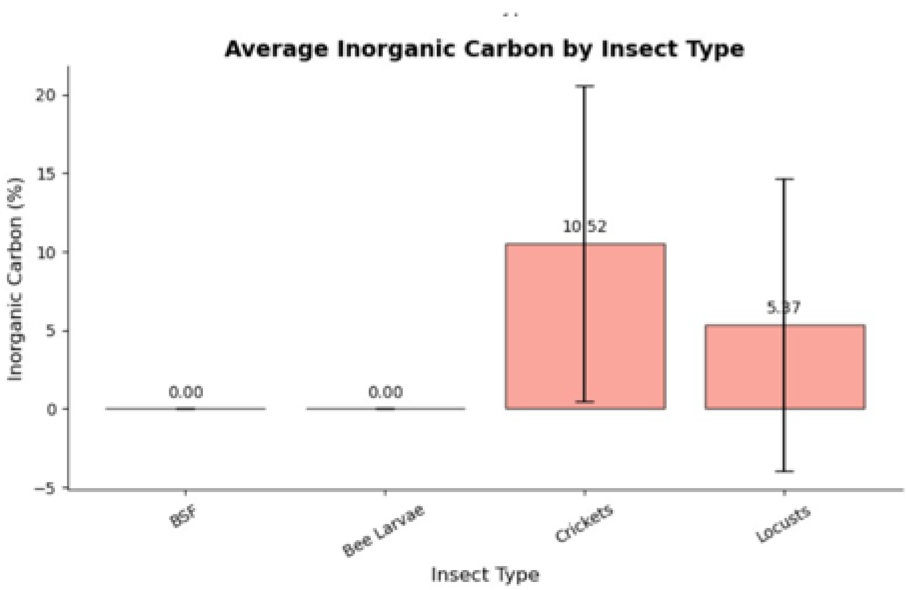

Figure 6

Carbon partitioning in the four edible insect species: (b) inorganic carbon