

**NUTRIENT COMPOSITION OF TWO CRICKET
SPECIES (*Scapsipedus icipe* and *Gryllus bimaculatus*), AND
EFFECT OF EXTRUSION PROCESS OPTIMIZATION
ON NUTRITIONAL, FUNCTIONAL AND SENSORY
PROPERTIES OF MAIZE-CRICKET PORRIDGE
FLOUR**

DOROTHY KANORIO MURUGU

**DOCTOR OF PHILOSOPHY IN
FOOD SCIENCE AND NUTRITION**

**JOMO KENYATTA UNIVERSITY
OF
AGRICULTURE AND TECHNOLOGY**

2026

Nutrient Composition of Two Cricket Species (*Scapsipedus icipe* and *Gryllus bimaculatus*), and Effect of Extrusion Process Optimization on Nutritional, Functional and Sensory Properties of Maize-Cricket Porridge Flour

Dorothy Kanorio Murugu

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Food Science and Nutrition of the Jomo Kenyatta University of Agriculture and Technology

2026

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

Signature.....Date.....

Dorothy Kanorio Murugu

This thesis has been submitted for examination with our approval as University Supervisors:

Signature.....Date.....

Prof. Arnold Onyango, PhD

JKUAT, Kenya

Signature.....Date.....

Dr. Isaac Osuga, PhD

JKUAT, Kenya

Signature.....Date.....

Dr. Chrysantus Tanga, PhD

ICIPE, Kenya

DEDICATION

This thesis is dedicated to my parents, for their unwavering love, support, and endless encouragement throughout this journey and to my children, whose belief in me fueled my ambition and whose sacrifices made this achievement possible.

ACKNOWLEDGEMENT

This journey of research and writing would not have been possible without the support and guidance of many individuals and institutions.

First and foremost, I would like to express my deepest gratitude to my supervisors, Professor Arnold Onyango, Dr. Isaac Osuga and Dr. Chrysantus Tanga, for their invaluable guidance, insightful feedback, and unwavering encouragement throughout this process. Their expertise in the field of Food Science, Human Nutrition, Animal Nutrition and Entomology proved to be exceptionally instrumental in shaping the direction and focus of this thesis.

I am also grateful to the members of my host department through the leadership of Dr. Dorothy Othoo, the Head of Department, for their time, constructive criticism, and helpful suggestions during the faculty seminars which contributed to the development of this thesis. Their diverse perspectives enriched the research and strengthened the final product.

I would also like to express my heart felt gratitude to various institutions that provided funding support to my research work. These include International Center for Insect Physiology and Ecology (ICIPE), BioInnovate Africa and JICA. I deeply acknowledge the exceptional support by my supervisors in linking me with these funding opportunities that enabled data collection, performance of various experiments in Kenya and Uganda, and ultimately the laboratory analysis of generated research samples. Without this support, this thesis would not have been possible.

Furthermore, I would like to extend my special thanks to Dr. Sunday Ekesi of ICIPE for on-boarding me into the relevant funding project streams at ICIPE during the very initial stages of my research. This enabled me to access the insect material required for my research. Additionally, I acknowledge Professor Dorothy Nakimbugwe and the Food Science and Nutrition Faculty in Makerere University that hosted my research work in Uganda particularly for providing a stimulating and supportive research environment.

I am also particularly grateful to Dr. Norbert Wafula of Egerton University and Alex Ndiritu (my fellow PhD student) for their willingness to share their knowledge and expertise.

Above all, I sincerely express my gratitude to the Almighty God for making all provisions possible that enabled the completion of my PhD studies.

TABLE OF CONTENTS

DECLARATION.....	ii
DEDICATION.....	iii
ACKNOWLEDGEMENT	iv
TABLE OF CONTENTS.....	vi
LIST OF FIGURES	xix
LIST OF APPENDICES	xx
ACRONYMS AND ABBREVIATIONS.....	xxi
ABSTRACT	xxii
CHAPTER ONE	1
INTRODUCTION.....	1
1.1 Background of the Study	1
1.2 The Processing Challenge and Cereal Fortification	1
1.3 The Role of Extrusion Technology	2
1.4 Statement of the Problem	3
1.5 Justification	4
1.6 Objectives	5
1.6.1 Main objective	5
1.6.2 Specific objectives	5

1.7 Hypotheses of the Study	5
1.8 Significance of the Study	6
1.9 Scope and Delimitations.....	7
1.9.1 Scope of the Study	7
1.9.2 Delimitations.....	8
1.10 Operational Definition of Terms	8
CHAPTER TWO	10
LITERATURE REVIEW.....	10
2.1 Overview of the Nutrition Landscape for School Going Children in Kenya...	10
2.1.1 The Nutrition Crisis: Persistent PEM and Hidden Hunger.....	11
2.2 Maize as a Staple Food and its Nutritional Limitations	12
2.3 Nutrient Composition of Crickets	13
2.3.1 Protein Composition of Crickets	14
2.3.2 Amino Acids Composition of Crickets.....	14
2.3.3 Lipids Composition of Crickets.....	15
2.3.4 Minerals Composition of Crickets.....	15
2.3.5 Vitamins Composition of Crickets	16
2.3.6 Carbohydrate Composition of Crickets	16
2.4 Food Processing Technologies	17

2.4.1 Drying	17
2.4.2 Grinding and High-Pressure Processing	17
2.4.3 Fermentation	18
2.4.4 Extrusion	18
2.5 Effect of Extrusion on Nutritional and Functional Properties of Foods.....	19
2.5.1 Effect of Extrusion on Nutritional Properties of Edible Insects	19
2.5.2 Effects of Extrusion on Functional Properties of Foods	21
2.6 Optimization of Extrusion Processing Parameters	25
2.7 Incorporation of Insects into Food Products	25
2.8 Sensory Evaluation of Insect-Fortified Maize Products.....	27
2.9 Theoretical Review.....	28
2.9.1 Food and Nutrition Security Theory	28
2.9.2 Nutrition Optimization Theory	29
2.9.3 Edible Insect Utilization Framework.....	29
2.9.4 Food Processing and Fortification Theory.....	30
2.10 Literature Review Summary.....	30
2.10.1 Nutritional Profile of Edible Crickets	31
2.10.2 Maize-Based Diets and the Protein Gap	31
2.10.3 Extrusion Cooking: Mechanics and Matrix Interactions	31

2.10.4 Consumer Acceptance and Sensory Optimization.....	32
2.10.5 Conclusion of the Review	32
2.11 Research Gaps	32
2.12 Conceptual framework	33
CHAPTER THREE	37
NUTRIENT COMPOSITION OF CRICKET SPECIES <i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i> REARED IN KENYA	37
3.1 Introduction	37
3.2 Materials and Methods	39
3.2.1 Sample Collection and Preparation.....	39
3.2.2 Proximate Analysis	39
3.2.3 Determination of Amino Acid Composition	39
3.2.4 Determination of <i>In-Vitro</i> Protein Digestibility.....	40
3.2.5 Coupled Gas Chromatography–Mass Spectrometry (GC-MS) Analysis of Fatty Acids.....	41
3.2.6 Determination of Mineral Composition.....	42
3.2.7 Determination of Vitamins Composition.....	43
3.2.8 Data Analysis	45
3.3 Results and Discussion	45
3.3.1 Proximate Composition of <i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i> ...	45

3.3.2 Protein Digestibility	48
3.3.3 Amino Acid Composition.....	50
3.3.4 Fatty Acids Composition of Crickets, <i>S. icipe</i> and <i>G. bimaculatus</i>	57
3.3.5 Mineral Composition	64
3.3.6 Vitamins.....	69
3.4 Conclusions and Recommendation	74
CHAPTER FOUR.....	76
PHYSICOCHEMICAL CHARACTERIZATION OF EDIBLE CRICKETS’ (<i>Scapsipedus icipe</i> AND <i>Gryllus bimaculatus</i>) OILS AND THE ANTI- NUTRITIONAL PHYTOCHEMICAL PROFILE OF WHOLE GROUND CRICKET POWDER.....	76
4.1 Introduction	76
4.2 Materials and Methods	78
4.2.1 Sample Collection and Preparation.....	78
4.2.2 Extraction of cricket oil	78
4.2.3 Determination of Physicochemical Properties of Cricket Oil	79
4.2.4 Determination of Anti-Nutritional Phytochemical Profile	82
4.2.5 Data Analysis	84
4.3 Results and Discussion	84
4.3.1 Physicochemical Properties of Cricket Oils	84
4.3.2 Anti-Nutritional Phytochemical Properties of Ground Cricket Powder....	92

4.4 Conclusion.....	97
4.4.1 Synthesis of Lipid Benchmarks and Stability Profiles	98
4.4.2 Characterization of the Anti-Nutritional Phytochemical Profile	98
4.4.3 Comparative Assessment of <i>S. icipe</i> and <i>G. bimaculatus</i> :	99
4.4.4 Impacts of Extrusion on Physicochemical Lipid States	99
4.4.5 Enhanced Shelf-Life through Extrusion and Matrix Stability	99
4.4.6 Addressing the Knowledge Gap	100
4.4.7 Final Recommendations and Future Outlook	100
CHAPTER FIVE.....	102
EFFECT OF EXTRUSION PROCESSING ON SENSORY PROPERTIES OF A FORMULATED MAIZE – CRICKET PORRIDGE	102
5.1 Introduction	102
5.2 Materials and Methods	104
5.2.1 Materials Preparation.....	104
5.2.2 Porridge Flours Formulation.....	104
5.2.3 Extrusion.....	105
5.2.4 Porridge Preparation	105
5.2.5 Sensory Analysis.....	106
5.2.6 Data Analysis	106
5.3 Results and discussion.....	107

5.3.1 Maize-cricket formulation optimization	107
5.3.2 Effect of Extrusion Cooking On the Rating of Sensory Attributes	109
5.3.3 Effect of Cricket Substitution on Sensory Scores of Extruded and Non- Extruded Porridges	112
5.4 Conclusion.....	115
CHAPTER SIX	116
EFFECT OF EXTRUSION PROCESSING ON NUTRITIONAL AND FUNCTIONAL PROPERTIES OF A FORMULATED MAIZE – CRICKET PORRIDGE FLOUR USING EXISTING PROCESS CONDITIONS.....	116
6.1 Introduction	116
6.2 Materials and Methods	118
6.2.1 Sample Collection and Preparation.....	118
6.2.2 Formulation Optimization.....	118
6.2.3 Extrusion.....	119
6.2.4 Proximate Analysis	119
6.2.5 Functional Properties Analysis	120
6.2.6 Data Analysis	120
6.3 Results and Discussion.....	120
6.3.1 Effect of Extrusion on Nutritional Properties of <i>S. icipe</i> Enriched Maize Porridge Flour.....	120

6.3.2 Effect of Extrusion Processing and <i>S. icipe</i> Substitution Levels in Maize Porridge Flour on Proximate Composition.....	122
6.3.3 Effect of Extrusion on Functional Properties of Maize Porridge Flour Enriched with Crickets	125
6.3.4 Effect of Extrusion Processing and Substitution Level on Functional Properties of Maize-Cricket Flour at Different Substitution Levels	127
6.3.5 Effect of Extrusion on Pasting Properties of Maize Porridge Flour Enriched with Crickets.....	130
6.4 Conclusions	136
CHAPTER SEVEN.....	138
OPTIMIZATION OF EXTRUSION CONDITIONS FOR THE EXTRUSION OF A CRICKET ENRICHED MAIZE PORRIDGE FLOUR AND EFFECT ON NUTRITIONAL AND FUNCTIONAL PRODUCT QUALITIES.	138
7.1 Introduction	138
7.2 Methodology (Materials and Methods).....	140
7.2.1 Experimental Design.....	140
7.2.2 Statistical Modeling and Optimization: Optimization Process Steps	142
7.2.3 Statistical Analysis and ANOVA Structure.....	143
7.2.4 Visualizing the Optimization: Variation and 3D Plots	145
7.2.5 Extrusion Processing.....	145
7.2.6 Crude Protein determination.....	145
7.4 Results and Discussion	146

7.4.1 Effect of Optimizing Extrusion Conditions on Crude Protein of Blends Enriched with Different Cricket Species	146
7.5 Conclusion.....	152
CHAPTER EIGHT	153
CONCLUSION AND RECOMMENDATIONS.....	153
8.1 CONCLUSION	153
8.1.1 Nutrient Composition of Crickets <i>S. Icipe</i> and <i>G. Bimaculatus</i>	153
8.1.2 Physicochemical Characterization of Cricket Oils and Anti-Nutritional Phytochemical Profile of Whole Ground Cricket Powder	154
8.1.3 Effect of Extrusion on Sensory properties.....	156
8.1.4 Preliminary Effect of Extrusion Processing on Nutritional and Functional Properties of a Formulated Maize Cricket Porridge Flour Using Existing Extrusion Process Conditions.....	157
8.1.5 Optimization of a Tailored Extrusion Process for Maize-Cricket Porridge	160
8.2 Recommendations	161
8.2.1 Recommendations for Nutrition and Product Development.....	161
8.2.2 Recommendations for Food Industry	163
8.2.3 Recommendations for Future Research.....	163
8.2.4 Recommendations for Policy.....	164

REFERENCES..... 165

APPENDICES 213

LIST OF TABLES

Table 2.1: Integration of Core Theories in the Edible Insect Utilization Framework	33
Table 3.1: Proximate Composition of Crickets, <i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>	47
Table 3.2: Amino acid Profile of <i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i> (Mean \pm SE) in mg/g.....	54
Table 3.3: Comparative Distribution of Amino Acids in the Protein Fraction (% of Total Amino Acids) of Studied Insects against Recommended Amino Acid Values Based on FAO/WHO/UNU (2007) Consultation	56
Table 3.4: Composition of Fatty Acids (% of Total Fatty Acids *, (mg/100g) *) of <i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>	61
Table 3.5: Mineral Composition of Edible Cricket Species (<i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>) in Milligrams/100 grams on Dry Weight Basis ...	67
Table 3.6: Vitamin Composition of Edible Cricket Species (<i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>).....	71
Table 4.1: Physical and Chemical Characteristics of <i>Gryllus bimaculatus</i> and <i>Scapsipedus icipe</i> Oil	88
Table 4.2: Refractive Index Values for Selected Edible Insect Oils.....	88
Table 4.3: Comparative Analysis of Chemical Indices: Vegetable vs. Insect Oils...	92
Table 4.4: Phytochemical Composition (mg/100g) of <i>Gryllus bimaculatus</i> and <i>Scapsipedus icipe</i>	92
Table 4.5: Comparison between Maize, Beans and Crickets Anti-Nutrient Factor Density in (mg/100g)	96

Table 4.6: Maize Legume Blend versus Maize Cricket Blend: Impact of Anti-Nutritional Factors Concentration.....	97
Table 5.1: Mixture Design Extreme Vertices Model Optimizing Maize-Cricket Blend Ingredients.....	105
Table 5.2: Analysis of Variance for the Protein Optimization Model	107
Table 5.3: Effect of Extrusion Processing on Mean Scores of Sensory Attributes of Porridge from Maize Enriched with Cricket Meal.....	111
Table 5.4: The Effect of Substitution Level on the Mean Scores of Sensory Attributes of Maize Porridge Enriched with Cricket Meal	113
Table 6.1: Cricket Enriched Maize Flours Formulations.....	118
Table 6.2: Overall Effect of Extrusion Processing on Proximate Composition and Protein Digestibility of <i>S. icipe</i> Enriched Maize Porridge Flour	121
Table 6.3: Effect of Extrusion Processing and <i>S. icipe</i> Substitution Levels in Maize Porridge Flour on Proximate Composition	123
Table 6.4: Overall Effect of Extrusion Processing on Functional Properties of Maize-Cricket Flour	126
Table 6.5: Effect of Extrusion on Physical Properties of Maize-Cricket Flour at Different Substitution Levels	128
Table 6.6: Overall Effect of Extrusion Processing on Pasting Properties of Maize-Cricket Flour	132
Table 7.1: Box-Behnken Design Optimization Combinations of Extrusion Parameters and Insect Species	141
Table 7.2: The Box-Behnken Design (BBD) Experimental Matrix.....	144

Table 7.3: Analysis of Variance (ANOVA) of Extrusion Processing Conditions Optimization on Crude Protein of Blends Enriched with Different Insects Species.....	147
Table 7.4: Regression Equation for Optimizing Extrusion Processing Conditions on Crude Protein in Blends Enriched with Different Cricket Species	148

LIST OF FIGURES

Figure 2.1: Conceptual Framework	36
Figure 3.1: Comparative analysis of Percentage Crude Protein and Fat Content [On Dry Matter Basis – DM] of Crickets (<i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>), and Selected Plants and Animal Sources	48
Figure 3.2: Comparative Analyses of in Vitro Protein Digestibility of Crickets (<i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>) with Plant and Animal Food Sources.	50
Figure 3.3: Comparison of Selected Essential Amino Acids Content of Crickets (<i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>) with Conventional Animal And Plant-Based Sources	55
Figure 3.4: Representative Overlaid Total Ion Chromatogram of the Fatty Acid Profile	63
Figure 3.5: Comparison of Mineral Content of Crickets (<i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>), Animal and Plant-Based Sources	68
Figure 3.6: Folic Acid Content of <i>S. icipe</i> and <i>G. bimaculatus</i> Compared with Animal Source, Plant Source and Common Vegetables	73
Figure 5.1: Contour Plots Showing Interactive Effects of Individual Ingredients on Protein Content.....	108
Figure 5.2: Optimization Plot Showing Optimum Mixture Composition for the Corn-Cricket Blends	108
Figure 7.1: Effect of Extrusion Processing Conditions on the Optimization of Crude Protein in Blends Enriched with Crickets	150
Figure 7.2: Response Optimizer <i>Scapsipedus icipe</i> and <i>Gryllus bimaculatus</i>	151

LIST OF APPENDICES

Appendix I: Sample Collection Questionnaire	213
Appendix II: Sensory Evaluation Questionnaire	216
Appendix III: Informed Consent	217
Appendix IV: Photos of Cricket Species Used in This Study	219

ACRONYMS AND ABBREVIATIONS

ASTM	Advancing Standards Transforming Markets
AOAC	Association of Official Analytical Chemists
BD	Bulk Density
BT	Barrel Temperature
CP	Crude Protein
DHA	Docosahexaenoic acid
EPA	Eicosapentaenoic acid
FAO	Food and Agriculture Organization
FM	Feed Moisture
PCA	Principal Component Analysis
RDA	Recommended Dietary Allowance
RNI	Recommended Nutrient Intake
RSM	Response Surface Methodology
SFA	Saturated Fatty Acids
SS	Screw Speed
UFA	Unsaturated Fatty Acids
UNICEF	United Nations Children's Fund
WAI	Water Absorption Index
WFP	World Food Programme
WHC	Water Holding Capacity
WHO	World Health Organization
WSI	Water Solubility Index

ABSTRACT

Globally, there is growing interest in integrating cricket flour into plant-based foods to combat nutritional insecurity. However, data on the nutrient profiles of *Scapsipedus icipe* and *Gryllus bimaculatus*—the most widely consumed cricket species in Kenya—remains limited. Incorporating crickets into food matrices and using extrusion may impact the nutritional and functional properties of the formulated products. Optimal extrusion parameters for maximizing nutrient yield from various cricket species remain undefined. This study aimed to (i) determine the nutrient and anti-nutrient phytochemical composition of the two cricket species and compare them with published records of key animal and plant sources (ii) develop a nutritionally balanced maize-cricket formulation and evaluate the effect of extrusion on nutrient and functional properties of the formulated product using existing extrusion conditions (iii) determine the sensory attributes of porridges prepared with extruded and non-extruded maize-cricket flour blends and (iv) optimize the extrusion process parameters for attainment of optimal product in extruded maize-cricket porridge flour blends. Standard analytical methods were used to determine the nutrient composition of both cricket species. Maize-cricket blends were formulated using adult cricket powder, maize flour, and sugar. These were optimized using Minitab 20 software to meet the daily protein requirements of children aged 5-12 years. Three formulations containing 10%, 15%, and 20% cricket powder were prepared and processed both by extrusion and non-extrusion methods and samples subjected to nutritional and functional analysis. A semi-trained panel of 46 participants evaluated the sensory attributes of the porridge samples using a 9-point hedonic scale. Response Surface Methodology (RSM) through Box Benhenken design and the extreme vertices model of Mixture Design were employed to optimize extrusion process variables (barrel temperature, screw speed, and feed moisture) and formulation respectively, aiming to produce a porridge with significantly higher nutrient content from blends of *S. icipe* and *G. bimaculatus* with standard maize flour. Both cricket species, *S. icipe* and *G. bimaculatus*, demonstrated comparable protein content (56.8-56.9%) to animal sources and higher amino acid profiles to plant-based proteins. Their protein digestibility (80-88%) was similar to common plant foods but slightly lower than animal proteins. The cricket species were notably rich in essential minerals like iron, zinc, and potassium, significantly surpassing plant and animal sources. Calcium content was comparable to most sources, except kidney beans and eggs. Both cricket species offered higher levels of riboflavin, thiamine, and folic acid compared to conventional sources. Vitamin A was significantly higher in *S. icipe* compared to *G. bimaculatus*. Notable amounts of polyunsaturated fatty acids were found in (*S. icipe* (24.71%) and *G. bimaculatus* (19.16%), alongside saturated and monounsaturated fatty acids. Physicochemical properties of oils from both species revealed high similarity across most parameters, including refractive index, specific gravity, peroxide value, and saponification value ($P = 0.1047, 0.0774, 0.3581$ respectively). However, a highly significant difference was observed in acid values, with *S. icipe* (2.19 ± 0.36 mg KOH) exhibiting more than double the acidity of *G. bimaculatus* (1.10 ± 0.01 mg KOH; $P < 0.001$). Additionally, *G. bimaculatus* demonstrated a slightly higher solidification temperature range ($2-7^{\circ}\text{C}$) compared to *S. icipe* ($2-5^{\circ}\text{C}$). These results suggest that while the primary chemical stability and density of the two lipids are comparable, they differ significantly in their free fatty acid content and thermal

behavior. Analysis of anti-nutritional factors in *S. icipe* and *G. bimaculatus* revealed significant differences in most phytochemical markers ($P < 0.05$). *G. bimaculatus* contained significantly higher levels of phytates (10.33 ± 6.00 mg/100g vs. 3.85 ± 0.44 mg/100g; $P = 0.012$) and tannins (1.56 ± 1.08 mg/100g), which were not detected in *S. icipe* ($P = 0.003$). Conversely, *S. icipe* exhibited a significantly higher concentration of total polyphenols (65.00 ± 1.79 mg/100g) compared to *G. bimaculatus* (48.00 ± 4.49 mg/100g; $P = 0.021$). No significant difference was observed in oxalate concentrations between the two species ($P = 0.076$). These findings indicate that while *G. bimaculatus* possesses a more diverse anti-nutritional profile, *S. icipe* is richer in total polyphenolic content. Extruded porridge flours incorporating cricket powder were significantly more desirable in terms of appearance ($P = 0.003$), texture ($P = 0.001$), and mouthfeel ($P = 0.028$) compared to non-extruded counterparts. Consumer preference was most desirable with the addition of cricket powder at a 10% enrichment level. Taste, texture, and thickness were the most influential sensory attributes with a desirability rate of 21%, 26.6% and 17.2% respectively. The addition of cricket powder at different levels resulted in varying changes in the proximate composition, functional, and pasting properties of the porridge. While some properties like ash, dry matter, and P2 temperature remained unchanged ($P = 0.657$, $P = 0.295$, $P = 0.851$ respectively), protein digestibility increased at the 10% substitution level. Hydration properties improved, and bulk density decreased with increasing cricket powder levels. Extrusion reduced pasting properties, except for P2 temperature ($P = 0.851$). Optimal extrusion conditions were determined to be a barrel temperature of 120°C, a screw speed of 40 rpm, and a feed moisture content of 12%. Under these conditions, blends with *S. icipe* achieved a higher protein content (7.7%) with greater reliability (93.8% ($d=0.9377$)) compared to *G. bimaculatus* blends (5.8%) with a reliability of 43.5% (0.4347). In conclusion, both cricket species in this study were found to have significant levels of protein, minerals, fat and vitamins. When compared to conventional food sources using the Kenya Food Composition Tables, both species were shown to have either similar or higher values for protein, mineral, vitamins and fat. The extruded corn-cricket porridge evaluated in this study containing 16.52 g/100g of crude protein with an in vitro digestibility of 54.5%, provides 9.00 g of digestible protein per 100 g serving. Based on WHO/FAO (WHO/FAO/UNU, 2007) guidelines, this represents a substantial contribution to the daily requirements of school-going children, meeting approximately 49.1% of the RNI for a 5-year-old and 23.5% for a 12-year-old. Therefore, it is recommended to policy makers as a viable option to be added into the food basket for school meals in Kenya.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The global food system is currently under unprecedented anthropogenic pressure to meet the nutritional demands of a population projected to reach 9.7 billion by 2050 (Oluwole et al., 2023). Conventional livestock production, while a primary source of high-biological-value protein, is increasingly scrutinized for its intensive environmental footprint, characterized by extensive land degradation, high water-use indices, and significant greenhouse gas emissions (Steinfeld et al., 2006). Consequently, entomophagy—the consumption of insects—has gained international recognition as a sustainable strategy to mitigate the protein-energy malnutrition (PEM) crisis (Aidoo et al., 2023; Lisboa et al., 2024).

In Kenya, the rearing of crickets, specifically *Scapsipedus icipe* and *Gryllus bimaculatus*, has transitioned from a localized traditional practice to a strategic intervention for food security. For smallholder farmers, cricket cultivation represents a low-capital, high-yield venture that functions as both a nutritional safety net and a diversified income stream (Halloran et al., 2017). However, a critical research gap persists: while crickets are colloquially recognized for their dense protein and mineral profiles, comprehensive and standardized nutrient characterizations for whole crickets remain largely undocumented. Existing data are often fragmented, highly variable, or contingent upon specific rearing substrates, which precludes the establishment of reliable baseline nutritional values for industrial food formulation (Rumpold & Schlüter, 2013b).

1.2 The Processing Challenge and Cereal Fortification

The integration of entomophagous products into the mainstream food value chain is hindered by significant technical and socio-psychological barriers. Raw crickets are highly susceptible to microbial spoilage and enzymatic degradation. Furthermore, food neophobia—the consumer reluctance to ingest whole insects—remains a formidable

obstacle to market penetration (Deroy et al., 2015). To address these challenges, food scientists advocate for the conversion of insects into invisible powdered forms, which can be seamlessly incorporated into familiar food vehicles.

In Kenya, maize (*Zea mays*) serves as the primary staple cereal; however, its nutritional profile is intrinsically limited by a deficiency in essential sulfur-containing amino acids, specifically lysine and tryptophan (Goredema-Matongera et al., 2021; Ifie et al., 2026). Fortifying maize with cricket powder offers a synergistic opportunity to develop a complete protein source. Nevertheless, the development of such composite flours is currently constrained by the lack of precise biochemical characterization of the raw insect material. Without a standardized understanding of the nutrient composition of specific local species, the nutritional claims and formulation precision of fortified flours remain speculative.

1.3 The Role of Extrusion Technology

To ensure the microbiological safety, shelf-stability, and consumer convenience of composite flours, advanced thermal processing is required. Extrusion cooking, a High-Temperature Short-Time (HTST) technology, is uniquely suited for this application. It functions as a continuous-flow process that integrates mixing, cooking, shearing, and shaping into a single unit operation (Guy, 2001).

Extrusion provides several critical functional advantages. Firstly, extrusion achieves enhanced digestibility. The process facilitates the denaturation of proteins and the gelatinization of starches, resulting in instantized flours. It also mitigates the challenge of anti-nutritional compounds inherent in the food matrix. The high shear and temperature effectively inactivate heat-labile growth inhibitors and reduce phytic acid levels. Finally, extrusion improves nutrient bioavailability. Extrusion can enhance the bioaccessibility of essential minerals, such as iron and zinc, by disrupting the fiber-mineral matrix (S. Singh et al., 2007a).

Despite these benefits, the introduction of cricket-based proteins and lipids significantly alters the rheological behavior and expansion characteristics of the maize starch matrix. Currently, there is a dearth of empirical data regarding the interaction

between specific cricket nutrient profiles and extrusion parameters—such as melt temperature, screw speed, and feed moisture—on the nutritional, sensory and functional properties of the final product.

This study, therefore, seeks to fill these critical knowledge gaps by first establishing standardized nutrient characterizations for local cricket species and subsequently optimizing the extrusion process to produce a nutrient-dense, sensory-acceptable maize-cricket porridge flour that can be proposed for school meals initiative in Kenya.

1.4 Statement of the Problem

Despite the aggressive promotion of cricket farming in Kenya, a significant disconnect persists between production capacity and nutritional utilization. This research identifies three critical gaps:

First, a lack of standardized data hinders evidence-based nutrition. The Kenya Food Composition Tables (FCTs) (FAO/GOK, 2018b) currently lack comprehensive reference data on the nutrient profiles of locally reared cricket species. Consequently, households consume these insects without precise knowledge of their nutritional contribution, and industrial processors lack the empirical data required for accurate food formulation and labeling.

Second, the transition from subsistence rearing to a viable value chain is stalled by high post-harvest losses and consumer neophobia. Raw crickets are highly perishable, and the reluctance to consume whole insects limits market expansion. While cricket powder has shown promise in baked goods, there is insufficient research on its nutritional and functional behavior during extrusion cooking—a process critical for producing shelf-stable, ready-to-eat porridge flours.

Finally, there is a technical knowledge gap regarding the interaction between cricket-based fortificants and the maize starch matrix. Without understanding how extrusion parameters—specifically, melt temperature, screw speed, and feed moisture—interact with these composite blends, the industry cannot produce a standardized product. This results in products with inconsistent nutritional retention, poor functional performance

(such as, low solubility), and sub-optimal sensory appeal, particularly for the target demographic of school children (aged 5–12 years) who require both high nutrient density and palatable food vehicles.

1.5 Justification

This research is justified through its potential impact on public health nutrition, economic resilience, and food processing technology.

Public health and nutritional security: By providing the first detailed nutrient analysis of local cricket species for the National Food Composition Tables, this study will enable health practitioners and policymakers to quantify the role of insects in combating protein-energy malnutrition (PEM). Specifically, for school children aged 5 to 12 years, this research provides a technical pathway to deliver a complete protein source, rich in lysine and tryptophan—amino acids typically deficient in maize-based school feeding programs.

Economic empowerment and value addition: Developing a value-added, extruded porridge flour creates a stable, high-value market for surplus cricket harvests. This transforms a highly perishable commodity into a shelf-stable industrial ingredient, thereby reducing post-harvest losses and increasing the income security of subsistence farmers by integrating them into a formal agro-industrial value chain.

Technological advancement in food processing: Extrusion is a versatile High-Temperature Short-Time (HTST) technology that improves protein digestibility and ensures microbiological safety. Determining the optimal processing parameters for a maize-cricket blend provides a technical blueprint for food processors. This allows for the scalable production of nutrient-dense, instantized flours that are not only appropriate for household use but also for large-scale institutional school feeding programs.

1.6 Objectives

1.6.1 Main objective

To determine the nutrient composition of two cricket species (*Scapsipedus icipe* and *Gryllus bimaculatus*) and evaluate the effect of extrusion process optimization on nutritional, functional, and sensory properties of a formulated maize-cricket porridge flour.

1.6.2 Specific objectives

1. To determine nutrient composition of cricket species, *Scapsipedus icipe* and *Gryllus bimaculatus* from selected farms in Kenya.
2. To determine physicochemical properties of edible cricket oils of the two cricket species
3. To determine anti-nutrient phytochemical composition of whole ground cricket flour of the two cricket species
4. To determine the effect of extrusion processing on nutritional and functional properties of a formulated maize-cricket porridge flour using existing extrusion process conditions.
5. To determine the effect of extrusion processing on sensory properties of the formulated maize-cricket porridge
6. To develop the optimal extrusion process conditions for the extrusion of a cricket enriched maize porridge flour
7. To evaluate the effect of extrusion process development on selected product qualities.

1.7 Hypotheses of the Study

- 1 There is no difference in nutrient composition between cricket species *Scapsipedus icipe* and *Gryllus bimaculatus*.
- 2 There is no difference in the physicochemical properties of edible cricket oils of the two cricket species

- 3 There is no difference in anti-nutrient phytochemical composition of whole ground cricket flour of the two cricket species
- 4 Extrusion of maize flour enriched with cricket meal does not affect sensory properties of cricket enriched maize porridge formulations at different levels of cricket substitution.
- 5 Extrusion processing using existing extrusion process conditions has no effect on nutritional and functional properties of a formulated maize-cricket porridge flour.
- 6 Optimization of extrusion process conditions for an extruded cricket enriched maize porridge flour does not have effect on nutritional and functional properties of the resultant product.

1.8 Significance of the Study

This study is significant as it addresses the data scarcity in the National Food Composition Tables regarding edible insects. Furthermore, it provides a value-addition pathway for smallholder farmers, transforming a perishable harvest into a shelf-stable industrial ingredient, thereby bridging the gap between subsistence farming and the formal food industry. More specifically, this research holds multi-dimensional significance for public health, education, economic development, and food science innovation:

Contribution to national health and nutrition: By formulating a porridge specifically for children aged 5-12, this study addresses the hidden hunger prevalent in maize-dependent communities. It provides a technical solution to SDG 2 (Zero Hunger) and SDG 3 (Good Health and Well-being) by creating a food vehicle that delivers high-quality protein and essential minerals (Iron and Zinc) required for physical growth and cognitive development in school-aged children.

Educational impact through nutrition: There is a proven link between nutrition and academic performance. By improving the protein and micronutrient density of a common school-going meal (porridge), this study contributes to better educational outcomes. A well-nourished child has improved concentration and reduced absenteeism due to illness, directly supporting SDG 4 (Quality Education).

Economic empowerment of smallholder farmers: This study bridges the gap between subsistence cricket farming and the formal food industry. By establishing extrusion parameters for a shelf-stable flour, the research creates a value-addition pathway. This allows farmers to transition from selling perishable raw insects to supplying raw materials for a high-value industrial product, promoting rural industrialization and poverty reduction (SDG 1: No Poverty).

Policy and data advocacy: The detailed nutrient characterization of *S. icipe* and *G. bimaculatus* will provide the empirical evidence needed for the National Food Composition Tables (FCTs). This allows government bodies to formally recognize and regulate edible insects as a legitimate nutritional resource, paving the way for insect-based ingredients in national school feeding programs.

1.9 Scope and Delimitations

1.9.1 Scope of the Study

The scope of this research is defined by the following parameters:

Geographical Scope: The study was limited to crickets reared in Nyanza region, specifically focusing on farms utilizing standardized feed to ensure data consistency. The specific sampling locations were in Kisumu County, Siaya county and Homa Bay county. **Appendix 1** provides details gathered to standardize farms for sample collection.

Raw Materials: The research was limited to two species of crickets—*Scapsipedus icipe* and *Gryllus bimaculatus* —sourced from farms utilizing standardized cricket species. The standardization of cricket species was done by the International Centre for Insect Ecology and Physiology (ICIPE).

Nutritional Target: The study specifically focused on the nutritional requirements (Protein, Iron, and Zinc) of school-going children aged 5–12 years, using the WHO/FAO Recommended Dietary Allowances (RDAs)/ Recommended Nutrient Intakes (RNIs) as the primary benchmark for success.

Processing Technology: The study was restricted to extrusion cooking (specifically using a twin-screw extruder). It focused on the interaction between barrel temperature, screw speed, and feed moisture.

Product Formulation: The study focused on a maize-cricket flour intended for use as an instant or quick-cooking porridge.

1.9.2 Delimitations

The delimitations (or areas not covered by the study) of this study are declared in the paragraphs below.

Age Groups: While the product may be consumed by adults and children above the age of five years, this study did not evaluate its nutritional impact or sensory preference for children under 5, children 13 years and above or geriatric populations.

Clinical Trials: This research was limited to in-vitro protein digestibility and laboratory nutrient analysis. It did not include in-vivo human feeding trials or clinical assessments of growth markers in children.

Storage and Packaging: The study assessed the immediate physical and sensory properties of the extruded flour. Long-term shelf-life studies (beyond 3 months) or specialized packaging material testing were outside the current scope.

Economic Analysis: While the justification mentions farmer income, this study did not perform a full-scale econometrics or cost-benefit analysis of the entire value chain.

1.10 Operational Definition of Terms

For the purpose of this study, the following terms are defined as follows:

Food and nutrition security: The condition in which school-aged children have physical access to a maize-cricket porridge that is not only calorie-sufficient but also provides the essential micro and macro-nutrients required for healthy development.

Nutrient optimization: The process of mathematically determining the most efficient ratio of cricket powder to maize flour to contribute to at least 20% of the Recommended Dietary Allowance (RDA) for protein, iron, and zinc in children aged 5–12.

Bioavailability: The proportion of nutrients (specifically protein, iron, and zinc) from the extruded porridge that is released from the food matrix during digestion and becomes available for absorption, measured in this study via *in-vitro* digestion methods.

Extrusion cooking: A high-temperature, short-time (HTST) food processing technique where the maize-cricket blend is subjected to high pressure and shear to induce starch gelatinization, protein denaturation, and the reduction of anti-nutritional factors.

Hidden hunger: A form of malnutrition characterized by micronutrient deficiencies (specifically Iron and Zinc) despite adequate calorie intake, which this study aims to mitigate through insect-based fortification.

Composite Blended flour: A binary blend of cereal (maize) and animal-protein (cricket powder) designed to achieve protein complementation, where the amino acids missing in one ingredient are provided by the other.

Subsistence-reared crickets: Crickets produced by small-scale farmers primarily for household consumption, characterized by low-input systems that this research seeks to standardize for industrial utilization.

Instant porridge flour: An extruded product that has undergone pre-gelatinization, allowing it to reach a consumable viscosity with minimal cooking time or simply the addition of hot water

Substitution: The act of blending a defined proportion of cricket powder with maize flour to obtain a maize-cricket blended product.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of the Nutrition Landscape for School Going Children in Kenya

While Kenya has made progress in reducing child malnutrition, the nutrition gap remains a significant public health issue. In Kenya, this demographic faces a dual burden—the persistence of undernutrition, such as stunting and micronutrient deficiencies, alongside a rising prevalence of overweight and obesity, particularly in urban settings (Kutwah et al., 2026).

Food and nutrition security—defined by the consistent availability, access, utilization, and stability of nutrient-dense food—is severely compromised for many school-aged children in Kenya due to a complex interplay of systemic factors. Primary among these are socioeconomic constraints, where household poverty remains a dominant driver of food insecurity; families frequently lack the financial resources to procure diverse, nutrient-rich diets, forcing a reliance on monotonous, staple-heavy meals that are often deficient in essential vitamins and minerals (Antwi et al., 2022). This situation is intensified by the challenges of urbanization, particularly within informal settlements where children face significant barriers such as limited access to clean water, poor environmental sanitation, and the impact of high food prices on household purchasing power (Macharia et al., 2018).

Furthermore, environmental and structural factors, including climate-driven drought, unpredictable weather patterns, and inadequate transportation infrastructure, continue to hinder both local food production and market access, disproportionately impacting rural populations (Antwi et al., 2022; Olielo, 2013). Finally, the instability of School Feeding Programs (SFPs) creates a precarious safety net; because many programs rely heavily on intermittent external donor funding, disruptions—such as school closures or budget shortfalls—leave children from the most vulnerable households without a critical and often primary source of their daily nutrition (Matengo, 2016; Watkins et al., 2024; Wineman et al., 2022)

The nutritional landscape in Kenya is marked by significant trends that underscore both recent progress and enduring challenges. Regarding chronic malnutrition, national figures for children under five have shown substantial improvement, with stunting prevalence declining from 35% in 2008 to 18% by 2022; however, high levels of stunting persist in specific vulnerable regions, highlighting ongoing regional disparities (Toweet et al., 2026). Household dietary diversity is a critical determinant of these outcomes, as it is directly correlated with food security; research demonstrates that children in food-insecure households are three times more likely to consume a diet with low diversity compared to their counterparts in food-secure households (Saaka & Osman, 2013).

Furthermore, acute malnutrition remains a persistent threat, with critical levels of wasting observed periodically—particularly in arid and semi-arid lands (ASAL)—where climate-related shocks and food price fluctuations frequently destabilize access to nutritious food (Kweyu et al., 2026). While robust monitoring systems exist for children under five, empirical evidence for school-aged children remains more fragmented, indicating a critical need for targeted data collection to better understand and address the specific nutritional burdens facing this demographic (Watkins et al., 2024).

2.1.1 The Nutrition Crisis: Persistent PEM and Hidden Hunger

In Kenya, school-aged children are increasingly recognized as facing a double burden of malnutrition, a complex phenomenon where chronic energy deficits coexist with widespread micronutrient deficiencies. While national nutritional programs often prioritize the first 1,000 days of life, recent research highlights that school-aged children represent a highly vulnerable demographic with significant, yet often overlooked, nutritional needs (Antwi et al., 2022). Protein-Energy Malnutrition (PEM) remains pervasive among this group; studies in public primary schools have reported stunting rates ranging between 20% and 25%, with underweight prevalence nearing 15% (KNBS, 2022; Ochola & Masibo, 2014). These physical growth deficits, which often serve as a "legacy" of early childhood nutritional deprivation, are directly linked

to impaired cognitive development and reduced academic performance, creating a long-term cycle of developmental disadvantage (UNICEF, 2021).

Simultaneously, hidden hunger—manifested as critical micronutrient deficiencies—remains rampant, even among children who may appear adequately nourished in terms of weight and height. Data from the Kenya National Micronutrient Survey and subsequent adolescent health assessments reveal severe gaps across key nutrients: iron deficiency anaemia, often exacerbated by helminth infections, affects between 25% and 56% of school-aged children (KNBS, 2022; MOH, 2019). Furthermore, deficiency rates for zinc and Vitamin A frequently exceed 30%, which significantly compromises immune function and increases susceptibility to common infections (MOH, 2011, 2019). Finally, deficiencies in essential B-vitamins, such as B12 and folate, are commonly documented, primarily driven by a reliance on monotonous, cereal-based diets like *ugali* that lack sufficient animal-source proteins (UNICEF, 2021).

The nutrition gap for school-going children in Kenya is systemic, rooted in poverty and exacerbated by climate and urban challenges. Future interventions must move beyond individual-level focus to address household food security, the sustainability of school feeding programs, and the specific nutritional shifts occurring in both rural and urban youth populations.

2.2 Maize as a Staple Food and its Nutritional Limitations

Maize is the major staple food in Kenya and its availability is significantly associated with food security in the country (Kariuki et al., 2020). Maize contributes about 3% and 12% of the Country's Gross Domestic Product (GDP) and agricultural GDP respectively (KNBS, 2020). Further evidence indicates that maize accounts for 26% of the caloric food intake (Ranum et al., 2014). Maize in Kenya is majorly grown in Trans Nzoia, Uasin Gishu, Nakuru as well as parts of Western and Nyanza region (Abodi et al., 2021). Maize, which is a staple food in many parts of the world including Kenya, has several nutritional limitations that can impact health when it forms a large part of the diet. Maize contains about 8-11% protein content which is considerably lower than other cereals. Further maize is deficient of two essential amino acids i.e. lysine and tryptophan (Ifie et al., 2026).

Thus, evidence suggests that over reliance of maize as a protein source may lead to malnutrition among children. Further maize lacks essential micronutrients such as iron, zinc and vitamin A (Ifie et al., 2026). Additionally, maize has significant levels of phytic acid which binds many of the micronutrients hence rendering them non-bioavailable (Kaplan et al., 2019). While maize remains a crucial staple food in Kenya, addressing its nutritional limitations is essential for improving public health outcomes. A multi-faceted approach involving food science technologies, agricultural, nutritional, and educational interventions can help mitigate the negative impacts of over-reliance on maize while respecting its cultural and economic importance.

2.3 Nutrient Composition of Crickets

Crickets are good sources of proteins, fat, carbohydrates and micronutrients. However it is worth noting that the nutritional composition of edible crickets varies depending on the species of the crickets (Akullo et al., 2018; Sampat et al., 2017). Further nutrition composition within the individual cricket species can vary depending on the stage of growth, climatic condition, habitat, sex as well as the food regimen fed on the insects (Finke & Oonincx, 2014; Musundire et al., 2016). Further evidence indicates that processing method such as roasting, frying, drying, smoking, roasting, toasting among others may further influence the nutritional composition of the edible crickets (van Huis et al., 2013; Musundire et al., 2014).

A majority of the edible cricket species are able to supply adequate amounts of energy and proteins to the consumer diet at the same time providing adequate amounts of essential amino acids. Cricket oil is majorly composed of monounsaturated and polyunsaturated fatty acids. Further, edible crickets are able to supply adequate amounts of potassium, calcium, zinc, iron, manganese, copper, folic acid, pantothenic acid, riboflavin and biotin (Orinda, 2018; Rumpold & Schlüter, 2013). This evidence suggests that edible insects are suitable for use and incorporation in diets to enhance the good health and growth.

2.3.1 Protein Composition of Crickets

The protein content (on DM basis or as is basis) of edible crickets ranges between 18.6% to 71.1% (Dobermann et al., 2017). The protein content of crickets is similar to that of other edible insects as well as other species in the order orthoptera (Rumpold & Schlüter, 2013).The range observed in protein content could be attributed to differences in species, diet used as well as stage of development. Evidence suggests that protein content in edible crickets is considerably higher than the content in goat meat, chicken and pork (Magara et al., 2021). The digestibility of *Acheta domesticus* (house crickets) proteins is considerably high at 83.9% than that of plant proteins such as rice (66%), maize (73%) and wheat (81%). Notably the digestibility of cricket proteins is slightly lower than the digestibility of beef (98%) and eggs (95%) (Poelaert et al., 2018). A study by Rumpold & Schlüter, (2013a) underscores the high protein content of crickets, suggesting their potential to contribute significantly to human nutrition. While these findings are promising, further investigation is necessary to optimize cricket farming practices and explore diverse processing methods for maximizing protein bioavailability.

2.3.2 Amino Acids Composition of Crickets

Glutamic acid is the most abundant amino acid in *Acheta domesticus* and *Gryllus bimaculatus* while leucine is the major amino acid in *Gryllus sigillatus*. Valine is the major essential amino acid in crickets which ranges from 1.07 to 11.45 g/100 g on dry matter basis followed by leucine and lysine. Evidence suggests that the amino acid profile of edible crickets may vary depending on the diet, stage of development, habitat, sex and species (Bednarova et al., 2013). Evidence further shows that some cricket species possess high levels of lysine, tryptophan and threonine which are some of the limiting amino acid in cereals and legume proteins (Magara et al., 2021). The amino acid composition makes crickets a potentially valuable protein source, especially in regions where traditional animal proteins may be scarce or unsustainable.

2.3.3 Lipids Composition of Crickets

The lipid content in edible insects is between 4.30 to 33.44% on dry matter basis. Cricket lipid content varies depending on the developmental stage whereby crickets at nymph stage have higher lipid content as compared to the adults. *Acheta domesticus* and *Gryllus bimaculatus* are among the cricket species with the highest lipid content. Triacylglycerols account for about 80% of the total lipid content (Magara et al., 2021). Studies by Tzompa-sosa et al., (2021) and Sampat et al., (2017) have revealed that cricket lipids are rich in unsaturated fatty acids, particularly polyunsaturated fatty acids (PUFAs), which are beneficial for human health. The major monounsaturated fatty acid (MUFA) in crickets is oleic acid (18:1, n9), while the major PUFA is linoleic acid (18:2, n-6). The main unsaturated fatty acids in edible crickets are stearic (18:0) and palmitic (16:0) acids, similarly to other edible insects (Magara et al., 2021; Smets et al., 2019). Additionally, house cricket oil was reported to contain the long chain omega-3 fatty acids, EPA (20:5, n-3) and DHA (22:6, n-3) (Tzompa-sosa et al., 2021). Evidence indicates that the lipid profile can vary depending on cricket species, diet, and rearing conditions.

2.3.4 Minerals Composition of Crickets

The mineral content of crickets is considerably higher than that of convectional protein sources such as beef, pork and broiler chicken meat (Frango & Hautrive, 2012). A study by Latunde-Dada et al., (2016) reported that consuming *Gryllus bimaculatus* could potentially provide a substantial amount of the recommended daily intake of iron. Phosphorus, potassium and sodium are the most abundant minerals in crickets, which also contain considerable amounts of iron, calcium and zinc (Zafar et al., 2023). However, the mineral composition in crickets may vary due to differences in cricket feed, species as well as age of the crickets. Further, contamination with heavy metals during processing could influence the mineral composition of crickets (Magara et al., 2021).

2.3.5 Vitamins Composition of Crickets

Crickets are rich in B vitamins, especially riboflavin (B2), pantothenic acid (B5), and biotin (B7) (Finke, 2002a). They have vitamin B12 levels comparable to those in beef, and may be an important source of this vitamin for vegetarians (Finke, 2002a). Rumpold & Schlüter, (2013a) reviewed multiple studies and confirmed that crickets generally contain higher levels of riboflavin compared to beef and chicken. Their work also highlighted the presence of tocopherols (vitamin E) in crickets, albeit in variable amounts. Subsequently, Montowska et al. (2019) investigated cricket powder and found it to be a good source of vitamins B1, B2, B3, and B5. However, they noted that vitamin content can vary depending on the cricket species and their diet. This observation was further supported by Kou & Adámková, (2016), who emphasized that rearing conditions and feed composition significantly influence the vitamin profile of crickets. While these studies collectively demonstrate the vitamin-rich nature of crickets, they also underscore the need for standardized rearing practices to ensure consistent vitamin content in cricket-based foods.

2.3.6 Carbohydrate Composition of Crickets

While crickets are primarily recognized for their protein and lipid content, their carbohydrate fraction plays a critical role in both their nutritional value and their functional behavior during food processing. Literature indicates that the total carbohydrate content in crickets is relatively low, typically ranging from 8% to 20% on a dry matter basis (Rumpold & Schlüter, 2013a). This fraction is predominantly composed of chitin, a structural polysaccharide found in the insect exoskeleton consisting of N-acetyl-D-glucosamine units (Kouřimská & Adámková, 2016).

From a nutritional perspective, chitin functions similarly to dietary fiber, potentially providing prebiotic benefits and promoting gut health, although its digestibility in humans is subject to ongoing debate (Lisboa et al., 2025). Beyond chitin, crickets contain small amounts of glycogen—the primary energy storage form—and various oligosaccharides. In the context of extrusion, these carbohydrates are significant because chitin is insoluble and does not gelatinize; therefore, its inclusion in a maize-

starch matrix can disrupt the continuous phase, influencing the expansion ratio and the final textural properties of the extruded porridge (Džima et al., 2025).

2.4 Food Processing Technologies

2.4.1 Drying

Edible insects are gaining attention as a sustainable and nutritious food source, but their widespread adoption faces challenges related to consumer acceptance and food safety. Various processing technologies are being explored to address these issues while preserving the insects' nutritional value. Drying is a common method used to extend shelf life and improve palatability. Studies have shown that different drying methods can affect nutrient retention differently. For instance, freeze-drying has been found to better preserve protein quality and fatty acid composition in mealworms compared to oven-drying (Kröncke et al., 2018). However, some nutrient losses are inevitable; a study on house crickets reported that oven-drying at 60°C resulted in significant reductions in vitamin B12 content (Khatun et al., 2021).

2.4.2 Grinding and High-Pressure Processing

Grinding dried insects into powder is another popular processing technique that can improve texture and facilitate incorporation into various food products. This process can affect nutrient bioavailability. For example, grinding has been shown to increase the *in vitro* protein digestibility of some insect species (Barroso & Fabrikov, 2022). However, it may also lead to increased oxidation of fats, potentially reducing the quality of fatty acids. To mitigate this, antioxidants may be added during processing (Liang et al., 2024). Novel technologies such as high-pressure processing (HPP) are also being investigated for insect processing. HPP has shown promise in improving the microbiological safety of mealworm larvae while maintaining nutritional quality better than traditional thermal processing (Muhammad et al., 2023).

2.4.3 Fermentation

Fermentation is another processing method gaining interest in edible insect preparation. It can enhance flavor profiles, improve digestibility, and potentially increase the bioavailability of certain nutrients. A study on fermented silkworm pupae showed increased levels of free amino acids and improved antioxidant activity (Santiago-I et al., 2020). Fermentation improves flavor, rheological properties, texture, and acceptability of fermented insect products (Hasan & Sultan, 2014; Sogari et al., 2018). For instance, fermented grasshopper and wax moth showed were comparable in regards to acceptability with commercial fish sauce. The acceptability of the fermented insects' products was attributed to the increased lactic acid content, free amino acids and fatty acids content (Mouritsen et al., 2017). Therefore the utilization of fermentation technology in processing edible insects has the potential of increasing the functionality of insect components as well as diversify edible insects based products (Santiago-I et al., 2020).

2.4.4 Extrusion

Extrusion processing has emerged as a promising technology for transforming edible insects into palatable and marketable food products. This versatile technique involves forcing insect flour or paste through a die under high pressure and temperature, resulting in textured, shelf-stable products with improved sensory attributes. However, there are only a few studies which have tried to explore the processing of edible crickets' flour by using extrusion technology. Evidence indicates that research to produce meat analogs from cricket flour is still in progress (Lee et al., 2024). A study by (Igual & Martínez-monz, 2020b) showed that in order to ensure that extrudates of good quality are generated only about 7.5% of cricket powder should be incorporated.

A study by Ribeiro et al., (2021) that produced extrudates of corn flour and cricket powder at different temperatures of 165 and 175°C found that the extrudates were a suitable alternative to other products in the market since they provide an additional level of proteins. For instance, rice extruded snacks with incorporated 10-15% cricket powder were found to have high protein, fat, fiber and iron. Cricket enriched extruded products may be a suitable nutritional alternative to the convectional potato and cereal

based extrudates that are in the market which have high fat, salt and carbohydrate levels (Oniszczyk et al., 2023). Research has shown that careful control of extrusion parameters can help minimize these losses (Prabha et al., 2021). As the field of edible insect processing evolves, more studies are needed to optimize processing methods for maximum nutrient retention and consumer acceptability.

2.5 Effect of Extrusion on Nutritional and Functional Properties of Foods

2.5.1 Effect of Extrusion on Nutritional Properties of Edible Insects

2.5.1.1 Proteins

Extrusion processing has significant effects on the nutritional composition of edible insect products, with both positive and negative impacts depending on the specific nutrients and processing parameters. One of the most notable effects is on protein quality and digestibility. Several studies have shown that extrusion can improve the *in vitro* protein digestibility of insect flours. For instance, Azzollini et al., (2018) reported an increase in protein digestibility from 67% to 82% for mealworm larvae flour after extrusion. This improvement is often attributed to the denaturation of proteins and inactivation of enzyme inhibitors during the extrusion process. Similarly, Yi et al., (2013) observed enhanced protein digestibility in extruded silkworm pupae powder, which they associated with structural changes in the proteins that made them more accessible to digestive enzymes.

The high temperatures involved in extrusion can also lead to the Maillard reaction between proteins and carbohydrates, potentially reducing the bioavailability of certain amino acids, particularly lysine (Pastor-cavada et al., 2011). Evidence suggests that about 40% of lysine is lost during low feed moisture extrusion of biscuits (Noguchi et al., 1982). There is still limited information regarding levels of Maillard reaction in cricket based extruded products. They suggested using lower temperatures and higher moisture content to mitigate this effect. Additionally, the formation of Maillard reaction products may have both positive and negative health implications, with some studies suggesting potential antioxidant properties of these compounds, while others raise concerns about their impact on protein quality.

2.5.1.2 Lipids

Extrusion also affects the lipid composition of insect products. The mechanical shear and high temperatures can lead to lipid oxidation, potentially reducing the quality of fatty acids. Evidence suggests that extrusion results to a reduction in lipid content due to the formation of lipid protein complexes when the extrusion temperatures were increased from 100 to 200°C. Further evidence indicates that the high extrusion temperatures results to oxidation of unsaturated fatty acids to lipid hydroperoxides which consequently reduces the amounts of lipids in the final product (Tumuluru et al., 2013). Studies further shows that the combination of shear stress, pressure and high temperatures during extrusion results to expulsion of oil (Sandrin et al., 2018). Additionally the formation of complexes between lipids and amylose further affects the texture of the extruded products (Dalbhagat et al., 2019).

2.5.1.3 Micronutrients

Regarding micronutrients, the effects of extrusion can vary. Some minerals, such as iron and zinc, may become more bioavailable due to the breakdown of anti-nutritional factors like phytic acid during extrusion (Gulati et al., 2020). For instance evidence suggests that the bio accessibility of iron in extruded maize, sorghum, legumes and dry beans increased significantly (Vilakati & Taylor, 2016). Other studies have also reported a significant increase in bio accessibility of magnesium and phosphorus in extruded bean flour (Gulati & Rose, 2018). The effect of extrusion on mineral bioavailability could be due to effect of extrusion on mineral binding components such as phytic acid, dietary fibers, proteins and phenolic compounds (Gulati & Rose, 2018). Further extrusion causes dephosphorylation of phytic acid and free chelated metals (Gulati et al., 2020). There however still very limited information regarding the effect of extrusion on mineral content of cricket-based products.

Evidence indicates that the stability of vitamins during extrusion is dependent on temperature, screw speed, pressure, feed rate and screw configuration. Vitamin A and E are very sensitive to extrusion conditions and especially temperature while vitamins D and K are considerably stable (Riaz et al., 2009). Studies have suggested that increase in extruder screw speed may considerably reduce vitamin A losses. Further

evidence shows that extrusion has a significant reduction effect in vitamin E levels of wheat, corn and soy bean flour (Ciudad-mulero et al., 2018). Additionally sensitive vitamins, particularly water-soluble vitamins like vitamin C and some B vitamins, can be significantly reduced during extrusion (Gulati et al., 2020).

2.5.2 Effects of Extrusion on Functional Properties of Foods

2.5.2.1 Pasting Properties

Pasting properties are important predictors of the behavior of flours during and after cooking. For instance, differences in peak viscosity is an indication of varying degrees of starch gelatinization and difference in amylose contents of cereal blends (Abah et al., 2020). Extrusion was documented to have significant effect on pasting properties of flours. For instance, extruded finger millet flour had considerably lower pasting properties as compared to the non-extruded flour. Increase in barrel temperature and screw speed had a negative impact on peak and final viscosity. On the other hand, increase in feed moisture resulted to an increase in viscosity profiles which was associated with plasticization effect of the moisture which resulted to residual un-gelatinized starch (Eliasson, 2010).

Further extrusion effect such as increase in barrel temperatures was documented to result to a decline in peak viscosity, break down, final viscosity and pasting temperatures in extruded maize flour (Yang et al., 2016). Evidence indicates that barrel temperature results to a destruction of starch granules at molecular, granular and crystalline level which further impacts on the pasting properties of the extrudates (Li et al., 2014). Ideally the cold viscosities of extruded products normally increase due to pre gelatinization effect and decreases later on due to dextrinization and rupture of the starch granules as the degrees of cooking increases (Ahmad & Pradyuman, 2016). Studies have shown that substitution of flour with other ingredients results to significant decline in pasting properties. This is hypothesized that replacing of the base material results to a decline in starch content and thus decline in pasting properties (Ahmad & Pradyuman, 2016). Further evidence indicates that pasting properties can be affected by amylose content, lip amounts and the distribution of the amylopectin branched chain (Zhang et al., 2016).

2.5.2.2 Water Holding Capacity

Water holding capacity is a critical attribute of determining protein functions such as swelling and gelation in food processing. Poor water holding capacity has been associated with liquid loss during processing which may cause textural changes in the final product (Lam et al., 2018). Extrusion resulted to a significant change in water holding capacities of maize, sorghum and chicken flour. For instance high barrel temperature of 150°C with high feed moisture resulted to a significant increase in WHC while low barrel temperature of 120 with high feed moisture resulted to a significant decline in WHC (Wang & Nickerson, 2019).

Evidence suggests that the extrusion temperatures results to breakdown of the complex protein structure into smaller sub units which have more water binding sites as compared to the complex protein quarterly structure (Alonso et al., 2000). Further a study by (Camire et al., 1990) suggested that the poorly ordered molecular phase with hydroxyl group in the disrupted starch granule could bind water. Evidence thus indicates that gelatinization and disruption of starch granule during the extrusion process would enhance WHC upon rehydration (S. Wang & Nickerson, 2019).

2.5.2.3 Water Absorption Index

Extrusion has been found to have significant effect on the water absorption index of products. For instance feed moisture and screw speed has been shown to have a positive correlation with water absorption index (Sahu et al., 2022b). Evidence suggests that extrusion results to a decrease in melt viscosity of starch at higher moisture content which results to free movement of the molecules in the melt and high heat penetration causes an increased gelatinization of starch (Rweyemamu & Mrema, 2015). On the other hand, barrel temperature has been shown to have a negative correlation with the water absorption index of the extrudates. Similarly rice soy extruded products have exhibited similar trend in water absorption index (Suksomboon et al., 2011). Evidence suggests that degradation of starch due to the high barrel temperature results to the reduction in water absorption index. Increase in water absorption index with increase in screw speed could be attributed to increased shearing action which results to increased gelatinization (Sahu et al., 2022b).

2.5.2.4 Water Solubility Index

WSI is usually an indication of the solubility of biomolecules such as starch, proteins, water soluble fibers and sugars before and after processing in excess of water (Oliveira et al., 2015). Water solubility Index (WSI) is significantly influenced by extrusion. Evidence suggests that extrusion causes excessive shearing of the melt hence leading to destruction of macromolecules and reduced molecular mass of starch particles (Sahu et al., 2022b). High screw speed has been shown to maintain the moisture in vapour form which causes higher expansion and a rough surface extrudate. Further barrel temperature has been documented to degrade starch molecules which in turn results to an increase in water solubility index of the extruded products. Additionally, increase in feed moisture has been shown to cause a reduction in water solubility index of extruded products. Evidence suggests that the high feed moisture causes a reduction in tangential expansion due to melt plasticization and consequently a decline in water solubility index (Kothakota et al., 2013).

2.5.2.5 Expansion Ratio

Extrusion processing significantly influences the expansion ratio of insect-based products, which is a key factor in determining their texture and consumer acceptability. The expansion ratio is typically inversely related to bulk density and is affected by various extrusion parameters. Evidence have shown that corn based products fortified with edible crickets have a much lower expansion ration after extrusion (Tellez-Morales et al., 2022). This phenomenon has been attributed to the high temperature and protein during extrusion which affects the distribution of moisture in the matrix which further affects the extensional properties of the melt hence reducing the expansion ratio (Martínez-monz & Igual, 2020). Extrusion has also been found to have a significant effect on the expansion ratio of cereal based products.

Evidence indicates that the expansion ration of maize based extruded products was significantly affected by barrel temperature, screw speed and feed moisture content (Sahu et al., 2022b). Studies shows that the expansion ratio of the extruded products increased with increase in barrel temperature and screw speed. Similarly the extrusion ratio of extruded rice based products increased with increase in temperature and screw

speed (Kumar et al., 2010). Evidence have also shown that increase in feed moisture produced products with considerably lower expansion ratio. This reduction in expansion ratio could be attributed to reduced elasticity of dough at high moisture and reduced gelatinization which consequently affects the formation of stable bubbles (Sahu et al., 2022b).

2.5.2.6 Bulk Density

Extrusion processing has a significant impact on the bulk density of products, which is a crucial parameter affecting their texture, expansion, and overall sensory appeal. Generally, extrusion tends to decrease bulk density by promoting expansion and creating a porous structure in the final product. Evidence suggests that feed moisture has a significant positive effect on the bulk density of maize based extrudates (Sahu et al., 2022b). Potentially the availability of moisture during the extrusion process may have resulted to a change in molecular configuration of amylopectin thus reducing their elasticity which further causes a reduction in puffing or expansion capacity (Ding et al., 2006). Evidence further indicates that increase in screw speed causes a reduction in bulk density of maize based extrudates. Further bulk density of maize based extrudates have been found to decrease with increase in barrel temperatures. Similarly the bulk density of soy protein extrudates have been found to decrease with increase in barrel temperature (Seker, 2005).

2.5.2.7 Hardness

The hardness of products is associated with the expansion and cell structure of the product (Singh et al., 2018). Extrusion processing significantly influences the hardness of products. Factors such as temperature, moisture content, screw speed, and die configuration affect the product's textural properties. Hardness of extrudates have been found to increase with increase in feed moisture content. Evidence suggests that at higher feed moisture the elasticity of dough decreases as a result of plasticization of melt hence consequently leading to a more compact or less porous structure (Sahu et al., 2022). Similar trend has been found in wheat and rice based extrudates (Ding et al., 2006; Seth & Badwaik, 2015). Further evidence shows that increase in barrel temperature and screw speed results to a decrease in hardness of maize based extruded

products. For instance, this has been observed in chickpea flour based extruded products (Meng et al., 2010).

Understanding the relationships of extrusion parameters is crucial for tailoring extrusion parameters to achieve the desired textural characteristics in insect-based foods. Extrusion was reported to significantly affect the crispness of maize-based products. For instance, increase in barrel temperature was found to considerably result to an increase in crispness of the extrudates. Evidence suggests that an increase in barrel temperature may have resulted to moisture loss which further lead to decrease in melt viscosity and consequently formation of a more porous extrudate (Sahu et al., 2022). On the other hand, evidence suggests that crispness of extruded products decreases with an increase in feed moisture content. Similarly, soy based extruded products have exhibited a similar behavior (Azam et al., 2016). The reduction in crispness with increase in feed moisture content could be attributed to reduction in dough elasticity during melt plasticization which further results to compact and bulky extrudates.

2.6 Optimization of Extrusion Processing Parameters

Extrusion processing offers a versatile approach to transforming edible insects into various food products. To maximize product quality, nutritional value, and consumer acceptance, careful optimization of extrusion parameters is essential. Key factors influencing the extrusion process include temperature, moisture content, screw speed, and die configuration (Zambrano et al., 2022). Studies have investigated the impact of these extrusion parameters on product characteristics such as expansion, porosity, and texture (Fenta & Kumar, 2019; Pismag et al., 2024; Samuel & John, 2015). Additionally, the incorporation of functional ingredients or co-extruded matrices can enhance the nutritional profile and sensory attributes of insect-based products (van Huis, 2013).

2.7 Incorporation of Insects into Food Products

Micronutrient is a major public health problem in low- and middle-income countries. Some of the interventions that have been proposed includes fortification with

micronutrients. Then need for fortification has been due to the nutritional limitations of cereals which are the major staple foods in these low and middle income countries (Ranum et al., 2014). Evidence suggests that cereals lack, iron, zinc, calcium as well as proteins which thus predisposes vulnerable groups to macro and micronutrient deficiencies. Authors have suggested incorporation of edible insects into cereals to enrich them. The proposal of use of edible insects is due to use of edible insects is due to their considerably high protein content which ranges from 47% to 57%, considerably good fat content which ranges between 27 to 36% and significantly high mineral and vitamin content. Furthermore edible insects' proteins have been shown to meet the WHO amino acid content requirement (Rumpold & Schlüter, 2013). Evidence further suggests that edible insects' proteins are considerably more digestible as compared to plant proteins (United States Dairy Export Council, 2004).

Crickets have been used to enrich sausages, pastas and brownies (Replacement et al., 2022). Further crickets have been used to enrich wheat flours and consequently used in production of cricket wheat enriched breads and pasta (Bresciani et al., 2022). Evidence further indicates that crickets have been used to enrich porridge flour in Kenya (Aboge et al., 2021; Kipkoech, 2019). Edible insects have been used to enrich wheat. For instance wheat flour has been enriched with cinereous cockroach, adult crickets, black soldier fly, and yellow mealworm (Acosta-Estrada et al., 2021).

Evidence suggests that fortification of wheat flour with edible insects flour had no significant effect on the dough properties (Gonzalez et al., 2019). Evidence further suggests that bread made with wheat meal enriched with cockroach meal have high levels of fat including unsaturated fatty acids i.e. omega 3 and omega 6 fatty acids. Studies have also shown that bread enriched with 10% cockroach flour had considerably increased protein levels as well as good sensory characteristics when compared with white bread and whole wheat bread (Acosta-Estrada et al., 2021). Mealworm and silkworm flour larvae has also been used to replace 10% of pork in sausage processing which indicates the potential of edible insects as novel protein ingredients (Kim et al., 2016).

The incorporation of insects into food products has also gained a lot of attraction since the rearing of edible insects is very economical. Evidence suggests that edible insects can be grown in a short period of time and the rearing requires very little space, minimal feeding as well as minimal maintenance (Gravel & Doyen, 2020). Evidence further indicates that rearing of edible insects is very environmental friendly since the rearing requires less land, water and feed as compared to conventional livestock (A. van Huis et al., 2013). Further the rearing of edible insects does not emit ammonia which is a greenhouse gas that is emitted by livestock (Oonincx et al., 2010).

Evidence suggests that amounts of edible insects incorporated into convectional foods should be monitored and controlled so as to ensure that the textural and sensory attributes of the food products are not significantly altered (Replacement et al., 2022). Altering of these vital properties of food products may potentially make products enriched with edible insects less competitive in the market as convectional products. For instance a study by Ardoin et al., (2021) reported that increasing of cricket powder into crackers significantly changed their textural properties which consequently affected their consumer acceptance.

2.8 Sensory Evaluation of Insect-Fortified Maize Products

Sensory characteristics of edible insect's enriched products have a significant influence on consumer acceptance. Evidence suggests that knowledge on the nutritional quality of edible insects as well as sensation seeking seems to enhance the acceptance of edible insects enriched products (Biro et al., 2020). Further studies have shown that food neophobia associated with edible insects' consumption could be reduced when insect powder is incorporated in baked or maize based products (Alemu et al., 2017; Baiano, 2020). For instance, 5% cricket enriched porridge flour was acceptable among caregiver and school going children in Kenya. The same study concluded that crickets can be used to develop nutritious, acceptable, and potentially affordable food for school going and young children especially in low and middle income countries (J. Kinyuru et al., 2021).

Bread enriched with *Acheta domesticus* meal at 5, 10 and 15% had an increased liking of taste and appearance as compared to the white bread (Bawa et al., 2020). In regards to overall liking bread enriched with 10% *Acheta domesticus* meal had similar liking with white bread (Mafu et al., 2022). Studies have suggested that substitution of wheat with cricket meal at higher levels may significantly affect the sensory attributed of the enriched products primarily because the chitin content potentially impact on techno functional properties of the dough and consequently the baked products (Struck et al., 2018). This will further affect the sensory appeal of the baked products hence influencing consumer acceptance.

Substitution of wheat with locust meal up to 5% resulted to a considerable increase in liking of taste of the enriched bread. In regards to appearance substitution of wheat meal with locust meal resulted to a significant decrease in liking. (Lthwab & Alhomaïd, 2021). Bread enriched with 5% and 10% *Tenebrio molitor* (yellow mealworm beetle) meal had a considerably higher liking for taste and appearance as compared to white bread. Similarly bread enriched with 10% *Alphitobus diasperinus* (lesser mealworms) had a significantly higher liking for taste and appearance as compared to white bread (Garcia-Segovia et al., 2020). Therefore scientists should ensure a balance in substitution of wheat as well as other cereal products in new product development to ensure that optimum organoleptic acceptance of edible insects enriched foods (Amoah et al., 2023)

2.9 Theoretical Review

2.9.1 Food and Nutrition Security Theory

The food and Nutrition Security Theory is a comprehensive framework that addresses the multifaceted nature of food security and its impact on nutritional outcomes. This theory is built upon the four pillars of food security as defined by the Food and Agriculture Organization (FAO) of the United Nations: availability, access, utilization, and stability (FAO, 2006). In recent years, the concept has evolved to explicitly include nutrition, leading to the term "food and nutrition security." This expansion recognizes that food security is a necessary but not sufficient condition for adequate nutrition (Pangaribowo et al., 2013). This theory also acknowledges the interconnectedness of

these pillars and their collective impact on individual and population health outcomes. For instance, even when food is available and accessible, poor utilization due to lack of dietary diversity or presence of anti-nutritional factors can lead to malnutrition (Gibson, 2011). In regards to the present study this theory provides a framework for understanding how the optimization of nutrients in maize using edible crickets and extrusion processing can contribute to improved food and nutrition security in Kenya. By enhancing the nutritional quality of a staple food, the project addresses primarily the utilization pillar, but may also indirectly impact the other pillars through improved agricultural diversity and potentially increased economic value of the enhanced product.

2.9.2 Nutrition Optimization Theory

Nutritional Optimization Theory posits that the nutritional value of foods can be enhanced through careful combination of ingredients and processing methods to maximize nutrient content, bioavailability, and overall nutritional quality (Aynalem & Duraisamy, 2022; Popova & Mihaylova, 2019; Townsend et al., 2023) . This theory integrates principles from food science, nutrition, and biochemistry to guide the development of more nutritious food products. The theory proposes on anti-nutrient reduction through processing technologies. For example, Alonso et al., (2000) showed that extrusion cooking could significantly reduce anti-nutritional factors in legumes, improving protein digestibility. The theory also focusses on nutrient fortification with the aim of addressing malnutrition in populations. For instance, Allen & Benoist, (2006) provided comprehensive guidelines on food fortification with micronutrients. In the present study, the addition of cricket powder to maize can be viewed as a form of food-to-food fortification. In the present study the Nutrition Optimization Theory provides a framework for understanding how the addition of cricket powder to maize and the use of extrusion processing can optimize the nutrient profile of the final product.

2.9.3 Edible Insect Utilization Framework

Edible Insect Utilization Framework is an emerging conceptual structure that focuses on the potential of insects as a sustainable and nutritious food source. This framework

encompasses various aspects of entomophagy (the practice of eating insects), including nutritional benefits, cultural acceptance, environmental sustainability, and economic implications. Insects are often rich in protein, healthy fats, fiber, and various micronutrients. (Rumpold & Schlüter, 2013a) conducted a comprehensive review of the nutritional composition of edible insects, highlighting their potential to address malnutrition. For instance, many insect species contain high-quality proteins with all essential amino acids in adequate proportions. In the present study the Edible Insect Utilization Framework provides a comprehensive structure for understanding and addressing various aspects of incorporating crickets into maize-based foods such as nutritional enhancement (Ayieko, Ogola, Ayieko, et al., 2016).

2.9.4 Food Processing and Fortification Theory

This theory encompasses the principles and practices of food processing and fortification to improve the nutritional quality, safety, and availability of food products. It posits that through careful selection of processing techniques and strategic addition of nutrients, we can enhance the nutritional value, digestibility, and bioavailability of nutrients in food products. Various processing methods can alter the nutritional profile of foods. These include thermal processing, fermentation, extrusion, and others. Each method can have different effects on nutrient retention, bioavailability, and creation of beneficial or harmful compounds. (S. Singh et al., 2007a) reviewed the nutritional aspects of food extrusion, highlighting how this process can improve protein digestibility and reduce anti-nutritional factors in cereals and legumes. In context of the present study the Food Processing and Fortification Theory provides a framework for understanding how extrusion processing and the addition of cricket powder can enhance the nutritional profile of maize-cricket based products.

2.10 Literature Review Summary

This summary synthesizes the current body of knowledge regarding insect-based food systems and extrusion technology, highlighting the specific intersection of cricket-maize fortification for school-age nutrition. The literature review provides a comprehensive analysis of the transition from traditional entomophagy to modern,

technology-driven food fortification. It is structured into four thematic pillars: food security and malnutrition challenge, cricket nutrition, cereal fortification strategies, extrusion technology, and consumer sensory dynamics.

2.10.1 Nutritional Profile of Edible Crickets

The review establishes that crickets, particularly *Acheta domesticus*, are a superior source of high-biological-value protein, containing all essential amino acids (EAAs) with high digestibility scores. Current literature indicates that crickets are rich in polyunsaturated fatty acids (PUFAs) and bioavailable minerals like iron, zinc, and calcium. However, the review highlights a significant characterization deficit in existing research: most nutrient data are inconsistent due to variations in rearing substrates and environmental conditions, underscoring the need for standardized local data for the National Food Composition Tables (FCTs).

2.10.2 Maize-Based Diets and the Protein Gap

Maize (*Zea mays*) remains the primary caloric driver for school-aged children (5–12 years) in Kenya. The literature confirms that while maize provides energy, it is intrinsically deficient in lysine and tryptophan, leading to stunted growth and cognitive impairment in children. The review evaluates fortification as the most viable intervention, identifying cricket powder as a potential fortificant.

2.10.3 Extrusion Cooking: Mechanics and Matrix Interactions

The review explores extrusion cooking as a High-Temperature Short-Time (HTST) bioreactor. It synthesizes existing research on how extrusion improves the safety and functionality of complementary and supplementary foods through various ways. First, through starch gelatinization by creating instant solubility for quick porridge preparation. Second, through anti-nutrient reduction- the thermal degradation of phytates and tannins which otherwise inhibit mineral absorption. Thirdly, through protein denaturation which increases the accessibility of peptide bonds for digestive enzymes.

Crucially, the literature identifies a knowledge gap regarding how insect lipids and protein interact with the maize starch-protein matrix. High inclusion of insect material can disrupt the expansion ratio and melt viscosity, potentially affecting the final texture of the porridge.

2.10.4 Consumer Acceptance and Sensory Optimization

The final section addresses the invisible integration of insects. Studies on food neophobia suggest that processing insects into fine flours significantly increases acceptance. The review examines the role of sensory optimization—balancing flavor, aroma, and mouthfeel—to ensure that fortified porridges are not only nutritionally dense but also highly palatable for school going children, which is a critical factor for the success of school feeding programs.

2.10.5 Conclusion of the Review

The literature review concludes that while the individual components (crickets, maize, and extrusion) are understood in isolation, their synergistic interaction remains under-researched. This gap justifies the current study's focus on optimizing processing parameters to create a standardized, shelf-stable, and culturally acceptable solution to childhood malnutrition.

2.11 Research Gaps

Many of the reviewed studies have focused on enrichment of wheat meal with edible insects such as crickets. Thus, many studies have assessed the nutritional, sensory and physicochemical attributes of muffins, biscuits, crackers, bread among other cereal based products that have been enriched with edible insects. However very few studies have investigated the enrichment of maize with edible insects. The only close studies have investigated acceptance and sensory attributes of porridge enriched with crickets. In regards to processing technologies a majority of studies have assessed processes such as roasting, frying, drying and traditional practices such as salting. However, no studies have investigated the effect of extrusion on nutritional and physicochemical

properties of maize cricket-based porridge flours. Additionally, very limited studies have focused on *Scapsipedus icipe* which is a newly described cricket species.

2.12 Conceptual framework

This study is anchored on the edible insect utilization framework, which integrates three core theories to address the malnutrition gap in school-aged children (5–12 years). This integration is summarized below.

Table 2.1: Integration of Core Theories in the Edible Insect Utilization Framework

Theory	Research Application	Targeted Gap
Food & Nutrition Security	Value addition to subsistence harvests	Utilization & stability
Nutrient Optimization	Blending maize + cricket for RDAs	Protein-Energy Malnutrition
Processing & Fortification	Extrusion for improved digestibility	Hidden hunger (micronutrients)

Food and Nutrition Security Theory: Food and nutrition security exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs (FAO, 2009). While traditional food security often focuses on calorie availability, nutrition security emphasizes the quality of the diet—specifically the intake of protein and micronutrients. In the context of this study, crickets represent an available but under-utilized resource within subsistence farming systems. According to Pinstруп-andersen, (2009), nutrition security is only achieved when food is properly utilized by the body. This study applies this theory by transforming raw cricket biomass into a culturally acceptable, shelf-stable porridge flour, ensuring that the high-quality proteins are not only available but effectively utilized by vulnerable school-going children.

Nutrient Optimization Theory: This involves the strategic blending of different food sources to achieve a superior nutritional profile that neither food could provide alone (Townsend et al., 2023). This is particularly relevant for maize-based diets, which are

limiting in essential amino acids like lysine and tryptophan. By utilizing crickets—which are rich in these missing amino acids—this study employs protein complementation. The optimization goal is guided by the Recommended Dietary Allowances (RDAs) for children aged 5-12 years. As noted by (WHO/FAO/UNU, 2007), nutrient optimization for school-aged children is critical for preventing hidden hunger and supporting rapid physiological and cognitive development. This research uses mathematical modeling to identify the optimal conditions where maize-cricket ratios meet these specific developmental targets.

Food Processing and Fortification Theory: This theory posits that the nutritional and functional quality of a food product can be significantly enhanced through technological interventions (Fellows, 2022). Fortification is not merely the addition of nutrients; it is the science of ensuring that those nutrients remain stable, safe, and bioavailable throughout the product's life cycle. Extrusion cooking serves as the primary vehicle for this theory in the current study. According to (S. Singh et al., 2007a), the High-Temperature Short-Time (HTST) nature of extrusion denatures anti-nutrients (like phytates in maize) that otherwise inhibit mineral absorption. This processing theory suggests that by manipulating barrel temperature and shear, we can improve the in-vitro protein digestibility of the cricket-maize blend, making it a highly efficient delivery system for the Iron and Zinc required by the target population.

Based on these theories, the conceptual framework for this study describes the nutritional gap as the driving force and the Recommended Dietary Allowance (RDA) as the benchmark. As such it is built around the nutritional problem loop and the solution through utilization of edible insects as described in the following paragraphs.

The Nutritional Problem (Context): High prevalence of Protein-Energy Malnutrition (PEM) and Hidden Hunger (micronutrient deficiencies) in children aged 5–12, caused by maize-dominant diets low in lysine, tryptophan, Iron, and Zinc.

Independent Variables (Inputs): Cricket Species: High-quality protein source containing essential amino acids. Substitution Levels: (e.g., 10%, 15%, 20%) to meet specific RDA percentages. Extrusion Parameters: Temperature/Moisture to ensure starch gelatinization (easy digestibility).

Dependent Variables (Outcomes): Nutrient Density: Amount of protein, Iron and Zinc per 100g serving. Bioavailability: Improved protein digestibility via extrusion. Acceptability: Sensory scores for school-aged children.

Impact (Goal): Contribution toward the daily protein requirement (approx. 0.9g/kg of body weight) and reduction of stunting/anemia in the target population. The complete conceptual framework for this research is described in **Figure 2.1** below.

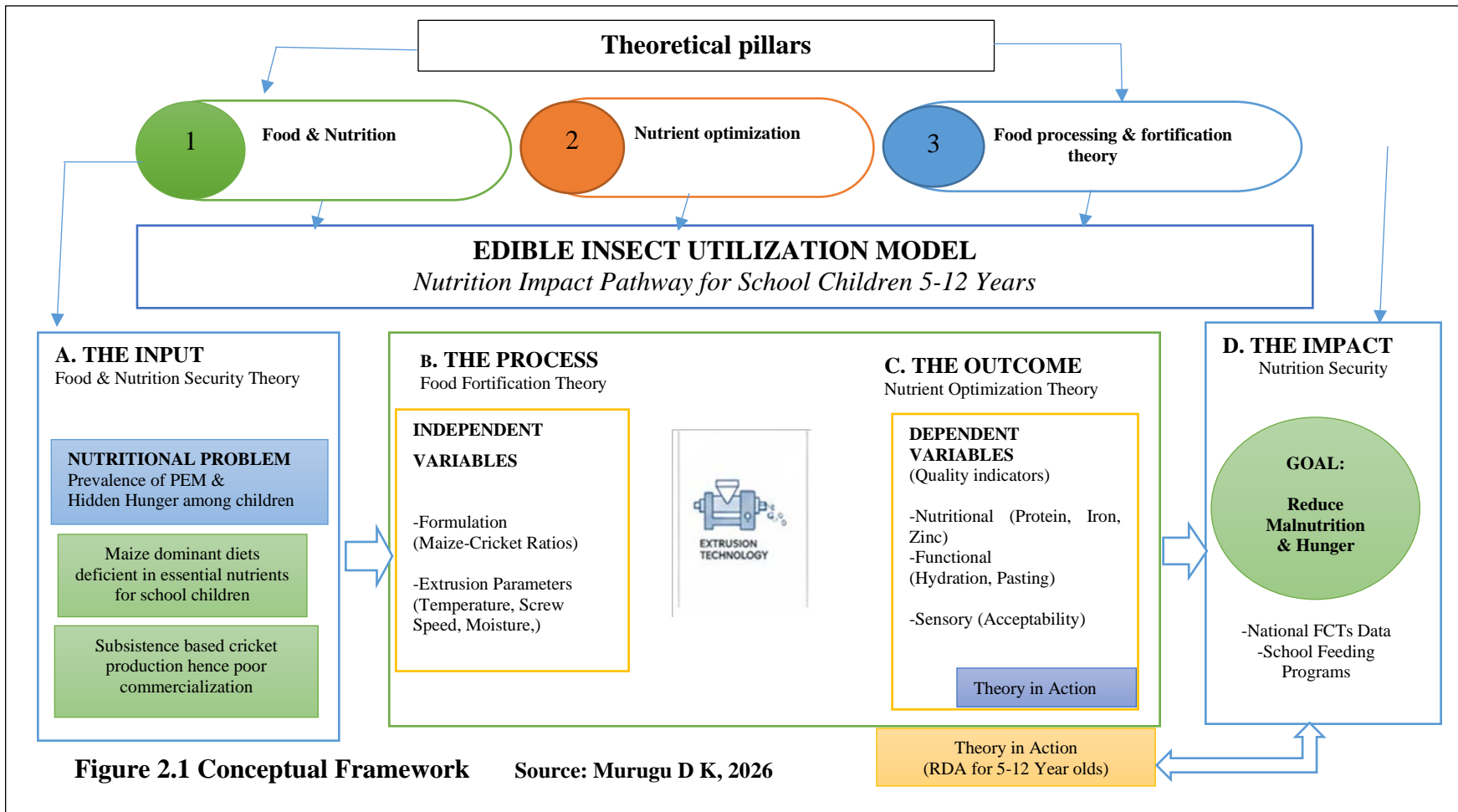


Figure 2.1: Conceptual Framework

CHAPTER THREE

NUTRIENT COMPOSITION OF CRICKET SPECIES *Scapsipedus icipe* and *Gryllus bimaculatus* REARED IN KENYA

3.1 Introduction

The consumption of edible insects is a longstanding practice integrated into the indigenous diets of diverse communities globally. Approximately 2,000 species of edible insects are traditionally consumed, valued not only for their unique sensory attributes but also for their significant nutritional density (Rumpold & Schlüter, 2013a). Edible insects are recognized as good sources of high-quality proteins, fats, minerals, and vitamins, capable of meeting a substantial portion of the daily nutrient requirements for human populations, particularly children (FAO, 2013c).

Recent years have seen a strategic departure from the traditional harvesting of insects from the wild toward the promotion of controlled rearing for food and feed. This shift is led by the Food and Agriculture Organization (FAO) and other global stakeholders focusing on food security. In sub-Saharan Africa (SSA), various species within the orders Orthoptera, Coleoptera, Isoptera, and Lepidoptera have been prioritized for commercial production. Species within the order Orthoptera are specifically noted for their high protein and lipid content. In Kenya, while cricket farming is the most established commercial insect enterprise and grasshopper rearing modalities are currently under development, the sector is constrained by a lack of robust data. Current literature suggests that information regarding the nutrient composition of commercially farmed insects remains limited and often inconclusive (Belluco et al., 2013; Rumpold & Schlüter, 2013a)

Several studies (FAO, 2013a; Nowak et al., 2016a; Payne et al., 2016b; A. Van Huis, 2016) have documented significant gaps in the nutrient composition data of edible insects, which hinders their full exploitation for nutrition and health security. Nowak (2016) highlights the conspicuous absence of insect-specific data in national food composition tables and global databases. Furthermore, much of the existing data fails to meet international standards for food composition; for instance, many studies report

values on a dry matter basis, whereas human consumption and dietary assessments are conducted on a fresh weight basis (Nowak et al., 2016a). Additionally, systematic reviews of commercially available insects have identified significant within-species variation in macro- and micronutrients, likely attributable to differences in feed composition and various ecological factors (Payne et al., 2016b).

On a global scale, insects of the order Orthoptera—most notably crickets—constitute one of the most widely cultivated and nutrient-dense groups (Kouřimská & Adámková, 2016). Beyond their nutritional profile, which is frequently comparable to conventional livestock in both quality and quantity (Kelemu et al., 2015), cricket farming serves as a vital socioeconomic driver. It generates significant income for women and youth, who manage over 60% of all medium- and large-scale enterprises in the sector (Van Huis et al., 2013). Furthermore, evidence suggests that crickets possess high-quality nutrients with superior digestibility and bioavailability relative to many traditional plant and animal-based food sources (Omotoso & Adesola, 2018).

In Kenya, there is increasing recognition of the role edible insects play in diversifying diets through the utilization of locally available sources. While the Kenya Food Composition Tables include data for edible insects, the entries are currently limited to grasshoppers and termites. Given the rapid promotion of commercial cricket farming in the country, it is imperative to provide comprehensive nutritional data for the species currently being scaled for production.

This study therefore seeks to provide a comprehensive analysis of the nutrient composition of the newly described cricket *Scapsipedus icipe* (Tanga et al., 2018) and the two-spotted cricket *Gryllus bimaculatus* (ICIPE, 2017) in Kenya. The research evaluates their profile in terms of protein, fat, amino acids, fatty acids, minerals, and vitamins. Furthermore, the nutrient components are discussed in relation to the Recommended Dietary Allowances (RDA) and compared to conventional food sources as documented in the Kenya Food Composition Tables (2018).

3.2 Materials and Methods

3.2.1 Sample Collection and Preparation

Samples of live adult crickets (*Scapsipedus icipe* and *Gryllus bimaculatus*) were obtained from selected smallholder farms located in the Nyanza region of Kenya. The selected farms were standardized according to the information gathered in **Appendix 1** and species verified by the International Centre for Insect Physiology and Ecology (ICIPE) (**Appendix 4**). Samples of each species were collected separately in 1kg Ziplock bags, frozen alive at -20°C in a Hisense chest freezer (model number: 1159Q61, China) and transported frozen in cooler boxes lined with ice packs to the ICIPE laboratories for analysis. The samples were blanched and blended into a paste using a domestic blender (Signature SG-201, China). The insect paste was subjected to various chemical analysis as described below.

3.2.2 Proximate Analysis

The moisture content was determined by oven drying method at 105 °C for 24 h (AOAC, 2009). Ash content was determined by ignition of samples at 550 °C in a muffle furnace until the weight remained constant (AOAC, 2005b). The crude fat content was determined by diethyl ether extraction in a fat extraction unit (SER 148/6; Velp Scientific, Usmate, Italy) following the Randall technique (AOAC, 2009). The crude protein content of the cricket powder was determined following the Kjeldahl method and the values multiplied by a conversion factor of 6.25 (AOAC, 2009). Crude fibre was determined by loss of ignition on weight of residue after hydrolysis with acid and alkali solutions (AOAC, 2005b).

3.2.3 Determination of Amino Acid Composition

The cricket powder (100 mg) was transferred into a 5 mL micro-reaction vial into which 2 mL of 6N HCl was added and closed after careful introduction of nitrogen gas. The sample was hydrolyzed for 24 h at 110 °C. After the hydrolysis, the mixtures were evaporated to dryness under vacuum. The hydrolysates were reconstituted in 1 mL 0.01% formic acid/acetonitrile (95: 5), vortexed for 30 s, sonicated for 30 min, and

then centrifuged at 14,000 rpm and the supernatant analyzed by LC-MS. The same procedure was performed to determine basic amino acid by substituting 6N HCl with 6N NaOH. The chromatographic separation was achieved on an Agilent system 1100 series (MA, USA) using ZORBAX SB-C18, 4.6 × 250 mm, 3.5 µm column, operated at 40°C. Mobile phases used were made up of water (A) and 0.01% formic acid in acetonitrile (B).

The following gradient was used: 0–8 min, 10% B; 8–14 min, 10–100% B; 14–19 min, 100% B; 19–21 min, 100–10% B; 21–25 min, 10% B. The flow rate was held constant at 0.5 ml min⁻¹ and the injection volume was 3 µL. The LC was interfaced to a quadruple mass spectrometer. The mass spectrometer was operated on ESI-positive mode at a mass range of m/z 50–600 at 70eV cone voltage. Serial dilutions of the authentic standard containing 18 amino acids (1–105 µg/µl, Sigma–Aldrich, St. Louis, MO, USA) was also similarly analysed by LC-MS to generate linear calibration curves (peak area vs. concentration) used for external quantification. Amino acid analysis was repeated three times using different batch of samples.

3.2.4 Determination of *In-Vitro* Protein Digestibility

Protein digestibility in the insect samples was analysed using a modified Mertz et al.,(1984) in- vitro digestion assay. Initially, the total crude protein content of each sample was quantified using the micro-Kjeldahl nitrogen determination method.

For the digestibility assay, 0.2 g of the homogenized sample was accurately weighed into 50 mL centrifuge tubes. A volume of 20 mL of buffered pepsin solution (0.1 M HCl, pH 2.0) was added to each tube, while a reagent blank was prepared concurrently without the sample. The tubes were incubated in a water bath at 37 °C for 2 hours, with manual agitation provided every 20 minutes to ensure uniform enzymatic activity.

Following incubation, the samples were centrifuged at 6,000 rpm for 15 minutes at 4 °C to separate the undigested residue from the supernatant. The supernatant was discarded, and the residue was washed by adding 10 mL of buffer solution, followed by a second cycle of agitation and centrifugation. The final residue was collected through filtration using Whatman No. 4 filter paper.

The filter paper containing the residue was carefully rolled, transferred into a Kjeldahl flask, and dried in an oven at 100 °C for 15 minutes. To determine the remaining undigested nitrogen, 10 mL of concentrated sulfuric acid (H₂SO₄), 1.0 g of potassium sulfate (K₂SO₄), and 1.0 mL of 10% copper sulfate (CuSO₄) solution were added to the flask. Digestion, distillation, and titration were subsequently performed following standard micro-Kjeldahl protocols. Protein digestibility was calculated as the difference between the total nitrogen in the initial sample and the nitrogen remaining in the undigested residue, expressed as a percentage.

$$\text{Protein digestibility (\%)} = (A - B)/A$$

Where

A = % protein content in the sample before pepsin digestion

B = % protein in the sample after pepsin digestion

3.2.5 Coupled Gas Chromatography–Mass Spectrometry (GC-MS) Analysis of Fatty Acids

Gas chromatography-mass spectrometry (GC-MS) was used to analyze the fatty acid composition with methyl esterification being done by a method described earlier by Cheseto and others (Cheseto et al., 2020a). A portion of the insect oil sample (0.1 g) was mixed with sodium methoxide in methanol (0.5 mL) of the concentration 15 mg/mL. The mixture was vortexed and then sonicated for 10 sec and 5 min, respectively. The reaction mixture was placed in an incubator maintained at 60°C for 1 hr before the addition of deionized water (100 µL) and vortexing for 1 minute.

A GC-grade hexane (1 mL) was used to extract the resultant methyl esters before a 5 min centrifugation at 14,000 rpm effected. Anhydrous sodium sulphate was then used to dry the supernatant before its transfer to vials. An auto sampler 7683 (Agilent Technologies, Inc., Beijing, China) was used to inject methyl esters (1 µL), in the splitless mode, into a GC-MS (7890A gas chromatograph; Agilent Technologies, Inc., Santa Clara, CA, USA) fitted with a 5975 C mass selective detector (Agilent Technologies, Inc., Santa Clara, CA, USA). The GC's inlet temperature was maintained at 270°C, while that of the transfer line was set at 280°C.

The column oven's temperature was preset to rise from 35°C to 285°C, with the former temperature being held for 5 minutes followed by a 10°C increase for every minute until the temperature reached 280°C, where it was maintained for 20.4 min. A low bleed capillary column (HP5) of miniature 30 m × 0.25 mm i.d., 0.25 μm (J&W, Folson, CA, USA) was used together with helium as a carrier gas, flowing at the rate of 1.25 mL/min. The mass selective detector was maintained at quadrupole (180°C) and ion source (230°C) temperatures. Electron impact (EI) mass spectra was obtained at the acceleration energy of 70 eV with fragment ions being analyzed over 40–550 m/z mass range in the full scan mode, having set a 3.3-minute delay time for the filament.

Fatty acids were identified via their methyl esters using comparisons of their fragmentation patterns and retention times to those of known fatty acid methyl ester standards where available and tentatively from their reference spectra published by library–MS databases: National Institute of Standards and Technology (NIST) 05, 08, and 11. Standard methyl octadecenoate (≥ 95 % purity, Sigma-Aldrich, St. Louis, MO) of known concentrations (0.2, 5, 25, 50, 75, 100 and 125 ng/μL) was subsequently analyzed under the same GC-MS conditions to obtain a linear calibration curve ($y = 7E + 06x - 4E + 07$ ($R^2 = 0.9757$)) that was used for external quantification of the fatty acid methyl esters. The quantities were presented in mg/100g of oil as well as in %.

3.2.6 Determination of Mineral Composition

The cricket powder was ashed and digested in 6N HCl and the content of the various minerals (Iron, Zinc, Calcium, magnesium, sodium, potassium, manganese, copper and cobalt) determined using atomic absorption spectrometry (AAS) (Shimadzu, AA-6300, Tokyo, Japan) in accordance with the standardized protocols set forth by the Association of Official Analytical Chemists (AOAC, 2005a), specifically methods 935.14 through 992.24. This analytical framework utilizes atomic spectroscopy to quantify inorganic elements by measuring the characteristic light absorbance of dissociated metallic atoms. Briefly, the analytical procedure commenced with the complete mineralization of the organic matrix through dry ashing. Precisely weighed, homogenized samples were placed in porcelain crucibles and subjected to thermal

oxidation in a muffle furnace at 550 °C for approximately six hours, or until a carbon-free white ash was achieved. This step is critical to eliminate organic interferences that could impede the atomization process. The resulting ash was subsequently solubilized using a dilute hydrochloric acid (HCl) solution (20% v/v), filtered, and diluted to a constant volume with deionized water.

For quantification, the mineral extract was analyzed using Atomic Absorption Spectrophotometry (AAS). The prepared sample was aspirated into an air-acetylene flame, where it was dissociated into free ground-state atoms. A hollow cathode lamp, specific to the elemental wavelength of the target mineral (e.g., 248.3 nm for iron or 213.9 nm for zinc), emitted radiation through the flame. The resulting absorbance was measured and compared against a multi-point standard calibration curve established using high-purity certified reference materials. To mitigate potential chemical interference—such as the formation of non-volatile phosphates—a releasing agent, typically lanthanum chloride (LaCl₃), was incorporated into both the samples and the standards. All mineral concentrations were expressed in milligrams per 100 grams (mg/100g) on a dry-matter basis, with each determination performed in triplicate to ensure analytical precision and reliability.

3.2.7 Determination of Vitamins Composition

The vitamin content of cricket samples was determined for selected fat-soluble (A, E, pro D) and water-soluble (B1, B2, B3, B6, B9) vitamins. Analysis of vitamins utilized methods described by Cheseto et al. and Jermacz et al. for analysis of fat soluble and water soluble vitamins respectively (Cheseto et al., 2020b; Jermacz et al., 2008). In summary, fat-soluble vitamins, were analysed as follows. Each cricket sample (300mg), was transferred into a 10mL glass vial containing a mixture of hexane, methanol and distilled deionized water (2:1:2, 5mL), vortexed for 30 s, sonicated for 30min and centrifuged at 14,000 rpm for 5min. The supernatant was dried over anhydrous Na₂SO₄, evaporated to dryness under a gentle stream of N₂(g) before derivatizing any residual fatty acids to fatty acid methyl esters to limit the matrix interference following the protocol described elsewhere (ThermoFisherScientific, 2017). The sample was then analyzed (1.0 µL) by GC-MS on a 7890A gas

chromatograph linked to a 5,975C mass selective detector (Agilent Technologies Inc., Santa Clara, CA, USA).

The GC was fitted with a (5%-phenyl)- ethylpolysiloxane (HP5MS) low bleed capillary column (30m × 0.25mm i.d., 0.25µm; J&W, Folsom, CA, USA). Helium at a flow rate of 1.25mL min⁻¹ served as the carrier gas. The oven temperature was programmed from 35°C to 285°C, with the initial temperature maintained for 5min, with a rise at 10°C min⁻¹ to 280°C, and then held at this temperature for 20.4min. The mass selective detector was maintained at ion source temperature of 230°C and a quadrupole temperature of 180°C. Electron impact (EI) mass spectra were obtained at the acceleration energy of 70 eV. Fragment ions were analyzed over 40–550 m/z mass range in the full scan mode. The filament delay time was set at 3.3min.

Serial dilutions of the authentic standard α -tocopherol ($\geq 95.5\%$ purity) (0.1–100 ng/µL, Sigma- Aldrich, St. Louis, MO) was analyzed by GC-MS in full scan mode to generate a linear calibration curve (peak area vs. concentration) which gave coefficient of determinations $R^2 = 0.9999$. The regression equation was used for the external quantification of the different selected fat- soluble vitamins (Retinol, γ -tocopherol, α -tocopherol, and Pro Vitamin D). These compounds were identified by comparison of mass spectral data and retention times with those of authentic standards and reference spectra published by library–MS databases: National Institute of Standards and Technology (NIST) 05, 08, and 11. The samples were analyzed in triplicate, with each replicate collected from a different batch of respective samples.

Determination of water–soluble vitamins was carried out according to previously described method (Ramos-Elorduy, Pino, & Ladron, 1997; ThermoFisherScientific, 2017) Briefly, 100mg of each cricket sample was transferred in to a 50mL falcon tube containing 25mL distilled deionized water (25mL), vortexed for 20 s, sonicated for 15min and the mixture filtered through 0.2µm filters into Ultra Performance Liquid Chromatography (UPLC) vials and analyzed by Shimadzu UPLC-DAD. The chromatographic analysis was performed on (LC-30AC with Nexera column oven

CTO-30A, Shimadzu, Tokyo, Japan) fitted with a Phenomenex C18 Column Synergi 100mm × 3.00mm, 2.6µm polar (Phenomenex, Torrance, CA, USA) at 30°C.

The mobile phase consisted of two phases, A: 25mM phosphate buffer. B: 7:3 v/v Acetonitrile-Mobile phase A. Total run time was 12min with a flow rate of 0.4 mL/min. Stock solutions of 1.0 mg/ml were prepared by dissolving the individual water-soluble vitamin standards in distilled water except for Vitamin B2 in (5mM potassium hydroxide) and Vitamin B9 in (20mM potassium hydrogen carbonate). Serial dilutions of the stock solution (2–15µg/mL) for the 5-watersoluble vitamins were also analyzed by UPLC-DAD giving R² of 0.996 or greater. These regression equations were used for the external quantification of the different water-soluble vitamins. All determinations were carried out in triplicates from different batch of respective samples.

3.2.8 Data Analysis

Data were checked for normality using the Shapiro-Wilk test. To determine the differences in nutritional value of the two cricket species, unpaired t-test was used for normally distributed data with equal variances while Welch's t-test was used to analyse data that did not fulfill the two assumptions. All the statistical analyses were conducted using R software version 3.6.0 (30).

3.3 Results and Discussion

3.3.1 Proximate Composition of *Scapsipedus icipe* and *Gryllus bimaculatus*

The crude protein content of the two cricket species i.e. *Scapsipedus icipe* (*newly described crickets*) and *Gryllus bimaculatus* (*field crickets*) was 56.8% and 56.9% respectively (**Table 3.1**) which was not significantly different ($P = 0.9092$). The protein content of the crickets was comparable to 58.3% crude protein obtained in field cricket as reported by Moreki and others (Moreki et al., 2012).

Both species record protein content within the range of 52-77% as described by Ramos-Elorduy. (Ramos-Elorduy, Moreno, et al., 1997) for insects in the order

Orthoptera. The crude protein recorded in this study varied notably with the range (64.38 %- 70.75%) reported by Rumpold and Schlüter. (Rumpold & Schlüter, 2013a). However, the crude protein values in the present study is relatively lower compared to that reported for *Acheta domesticus* Linnaeus (73.63%) (Yi et al., 2013). The variation can be attributed to inter-species differences as well as the type of substrates fed to cricket during rearing (Ramos-Elorduy et al., 2002).

The crude fat recorded for *G. bimaculatus* was significantly ($P = 0.0005$) higher (33.51 %) compared to that of *S. icipe* (31.74 %). These results are consistent to those reported for *A. domesticus* (32.6 %) Ramos-Bueno et al., (2016) but contrary to those documented in other study for the same species (18.55% - 22.80%) (Rumpold & Schlüter, 2013). Based on the crude fat content, it implies that the consumption of about 200 g of crickets would significantly contribute to the daily requirement of energy from fat for human nutrition, which ranges between 10-30% (FAO, WHO, 2001).

The protein and fat content of the cricket species studied was comparable to that of common animal foods and higher than most plant sources (**Figure 3.1**). These results imply that 100 g of either cricket species consumed per day would provide at least twice as much protein as any of the common plant sources. Studies carried out in South Korea found that protein and fat content of five insect species including *G. bimaculatus* surpassed that of conventional livestock sources Ghosh et al., (2017), which is slightly different from the current results. Therefore, consumption of *S. icipe* and *G. bimaculatus* could provide the much-needed fat and protein in communities where access to conventional animal sources are limited (Kelemu et al., 2015).

The values of crude ash reported in this study (**Table 3.1**) were slightly higher (5.25% for *S. icipe*; 5.41% for *G. bimaculatus*) than those reported for *A. domesticus* (3.57%) (Finke, 2002b). This aligns with crude ash results (3.57% - 5.10%) reported for adult crickets reported by Rumpold & Schlüter, (Rumpold & Schlüter, 2013). The crude fiber content of *S. icipe* (5.71%) and *G. bimaculatus* (8.39%) are comparable to the values (5.95 and 8.7%) reported by Finke, (2007) and Moreki, (2012) for crickets, respectively. Previous studies have demonstrated that the amount of crude fiber in an

insect is a direct reflection of the chitin on the basis of the chemical structure (Finke, 2002b, 2007). In literature it is reported people of the African origin have high activity of chitinase enzyme, thus this opens new opportunities for the promotion and commercialization of edible insects chitin (FAO, 2013b).

Recently, chitin and chitosan have attracted considerable attention due to their biological activities (antifungal, antibacterial, antitumor, immunoadjuvant, antithrombogenic, anti-cholesteremic agent) and bio-adhesivity (Venter et al., 2006). Thus, chitin is widely used as absorption promoters and hydrating agents, as well as for film production and wound healing (Khorr, 2002). The immunity-enhancing effects, promotion of beneficial bacterial growth and inhibition of pathogenic microorganisms have been reported, thus demonstrating clear health benefits after consumption (Galbraith, 2008; C. G. Lee et al., 2008; D. Liu et al., 2010; Muzzarelli, 2010; Xia et al., 2011). The application of chitin/chitosan for extension of shelf life of various foods from agriculture, poultry, and seafood origin by inhibiting microbial growth have been documented (No et al., 2007).

Table 3.1: Proximate Composition of Crickets, *Scapsipedus icipe* and *Gryllus bimaculatus*

Cricket Species	Crude Protein [%]	Crude Fat [%]	Crude Ash [%]	Crude Fibre [%]	Energy (Kcal/100g)
<i>Scapsipedus icipe</i>	56.80 ± 0.40 ^a	31.74 ± 0.25 ^a	5.25 ± 0.02 ^a	5.71 ± 1.39 ^a	512.66
<i>Gryllus bimaculatus</i>	56.90 ± 1.33 ^a	33.51 ± 0.16 ^b	5.41 ± 0.06 ^b	8.39 ± 2.28 ^a	529.2
P- value	0.9092	0.0005	0.0123	0.1564	

*Means with different superscript letters in each column are significantly different at p < 0.05. Carbohydrate was not detected**

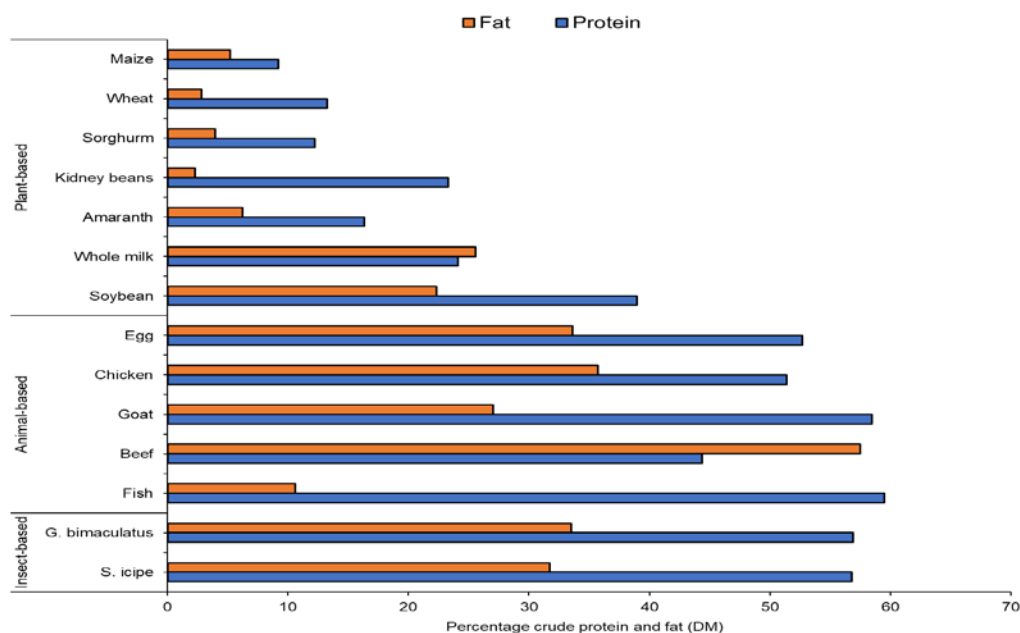


Figure 3.1: Comparative analysis of Percentage Crude Protein and Fat Content [On Dry Matter Basis – DM] of Crickets (*Scapsipodus icipe* and *Gryllus bimaculatus*), and Selected Plants and Animal Sources

Data for plant and animal sources was extracted from the Kenya Food Composition Tables (FAO/Government of Kenya, (2018)).

3.3.2 Protein Digestibility

In general, edible insects in the order Orthoptera have been reported to contain significantly higher amounts of crude proteins compared to other insects (Bukkens, 1997; Rumpold, B.A., Schluter, 2013). However, quantifying bioavailable insect protein has been of great concern given that crude protein analysis using Kjeldahl method often includes nitrogen embedded in the exoskeleton of these insects which largely comprises the polysaccharide chitin, a phenomenon that tends to overestimate digestible protein of edible insects (Bukkens, 1997; Jonas-Levi & Martinez, 2017; A. Van Huis, 2016). *In vitro* protein digestibility has been shown as a reliable predictor of protein bioavailability *in vivo* based on Protein Efficiency Ratio (PER) and Net Protein Ratio (NPR) (HSU et al., 1977; Hur et al., 2011).

In this study, there was significant difference in digestibility of protein from both species (**Figure 3.2**). The values for *S. icipe* (87.8%) and *G. bimaculatus* (79.5%) are within the range reported for other insects (76 - 96%) by (Ramos-Elorduy et al (1997). Other studies have also reported significantly higher protein digestibility values for the cricket species *Gryllus assimilis* (Fabricius) (73%) when compared to that of grasshopper, moth caterpillar and termite. The protein digestibility corrected for amino acid score of the newly described cricket species in Kenya (*S. icipe*) with 87.77%, is similar to that of egg (97%) and beef (98%) (Kouřimská & Adámková, 2016). Insect protein digestibility has been considered higher than most plant proteins in previous studies (Finke, 2004).

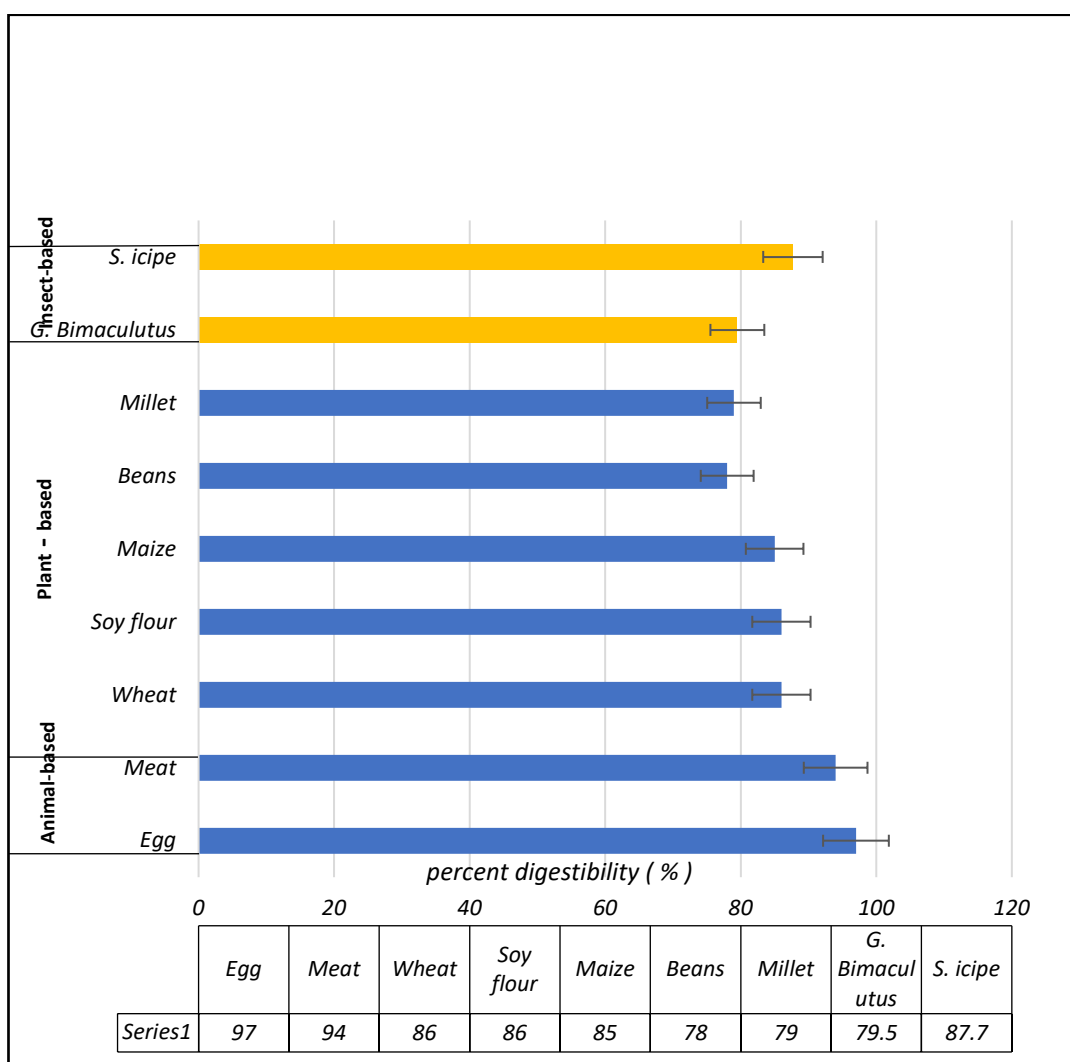


Figure 3.2: Comparative Analyses of in Vitro Protein Digestibility of Crickets (*Scapsipedus icipe* and *Gryllus bimaculatus*) with Plant and Animal Food Sources.

Data for plant and *animal* sources was extracted from FAO/WHO/UNU (WHO, 2007).

3.3.3 Amino Acid Composition

Both *Scapsipedus icipe* and *Gryllus bimaculatus* were found to contain seven essential amino acids (EAAs), including the critical limiting amino acids lysine and methionine (**Table 3.2**). Among the EAAs identified (histidine, lysine, valine, methionine, phenylalanine, leucine, and isoleucine), concentrations of five were found to be statistically distinct between the two species: histidine ($p = 0.0036$), leucine ($p = 0.0242$), phenylalanine ($p = 0.0131$), methionine ($p = 0.0103$), and valine ($p = 0.0018$).

Additionally, six non-essential amino acids were identified in both species (arginine, glutamine, proline, glutamic acid, tyrosine and hydroxyproline). In both *S. icipe* and *G. bimaculatus*, leucine was the most abundant amino acid, while glutamine was the least prevalent.

Significant inter-species differences were observed for several specific amino acids. *Gryllus bimaculatus* exhibited significantly higher concentrations of glutamic acid ($p < 0.0001$), valine ($p = 0.0018$), methionine ($p = 0.0103$), leucine ($p = 0.0242$), hydroxyproline ($p = 0.0049$), and phenylalanine ($p = 0.0131$). Conversely, *Scapsipedus icipe* recorded higher values for histidine ($p = 0.0036$) and proline ($p = 0.0004$). No significant differences were detected between the species regarding arginine ($P=0.0584$), lysine ($P=0.2742$), tyrosine ($P= 0.7285$), or isoleucine ($P=0.9412$) content.

The levels of methionine (19.6), leucine (66.7), and phenylalanine (30.2) in this study were comparable to those reported for reared *A. domesticus* by Rumpold & Schlüter. (Rumpold & Schlüter, 2013a). However, the values for histidine, arginine, lysine, glutamic acid, proline, valine, tyrosine, and isoleucine were lower than the corresponding values (22.7, 57.3, 51.1, 104.4, 54.2, 48.4, 44.0, and 36.4, respectively) reported in that study. Similarly, when compared to the field cricket data provided by Wang (2005) (Wang et al., 2005), the methionine (19.3) and phenylalanine (28.6) contents were consistent with current results. Nevertheless, the values for histidine (19.4), lysine (47.9), glutamic acid (90.7), proline (45.0), valine (48.4), and tyrosine (39.4) were notably higher than those observed in the present study, while isoleucine (30.9) and leucine (55.2) were lower. The high levels of isoleucine and leucine recorded for *icipe* and *G. bimaculatus* are similar to that reported for other edible insects (Chakravorty et al., 2016).

The methionine content in *S. icipe* and *G. bimaculatus* were comparable to that reported for eggs, which is well-known as an excellent source of methionine (**Figure 3.3**). Methionine and lysine are the most limiting amino acid in legume and legume products such as bean, peas, lentils, chickpeas and soybean as well as cereals (Tomé & Bos, 2007). Methionine is a classical sulphur amino acid, a limiting amino acid in

plant proteins of legume origin and aids availability of cysteine which is a metabolic product of methionine catabolism. The values of methionine, leucine and phenylalanine recorded for *G. bimaculatus* are similar to that reported for *A. domesticus* by Ramos-Elorduy et al., (1997). Similarly, methionine and phenylalanine of the field cricket *Gryllus testaceus* Walker are comparable to the results observed in the present study, although, histidine, lysine, glutamic acid, proline, valine, tyrosine were higher except for much lower values for isoleucine and leucine (Rumpold & Schlüter, 2013b).

Lysine deficient diets are common in African countries, where maize is a staple food (Figure 3.3), thus supplementing these diets with edible cricket protein would be a sustainable step towards dietary diversification Ghosh et al., (2017) and ensuring nutritional security. However, the protein quality of the edible insects can further be improved with the removal of chitin which binds some amino acids (Rumpold, B.A., Schluter, 2013).

Histidine is an indispensable amino acid whose dietary deficiency has been shown to cause deleterious effects on hemoglobin concentrations in humans Kurpad et al., (2001) and Press, (1987) thus consumption of these cricket species could be a quick fix to such health complications. Amino acids such as Leucine, isoleucine, and valine, which are branched chain amino acids (BCAA) were recorded notably in higher amounts in both crickets than in the animal and plant-based sources. Several studies have documented the potential role of the BCAA in brain function and maintenance of muscle mass during weight loss (Fernstrom, 2018; Layman & Walker, 2018; Shimomura & Harris, 2006). Other studies have cited leucine and histidine as essential in growth of children suggesting that both cricket species can be applied to supplemental diets to back up their protein requirements (Chakravorty et al., 2011; Millward, 2012).

Leucine has a wide range of metabolic and regulatory influences in the body and has been shown to have a potential role in the treatment of obesity and metabolic syndrome due to its influence on insulin secretion and sensitivity as well as dietary macronutrient disposal (J. Yang et al., 2006; Y. Zhang et al., 2007). Therefore, leucine can play a

potential role in the prevention of type II diabetes (Millward, 2012; J. Yang et al., 2006). Further, leucine has been shown to play a critical role in the reversal of adverse influences of high fat diet thus facilitating healthy weight maintenance in humans (Espinoza et al., 2011; Truby et al., 2007; Y. Zhang et al., 2007).

According to a FAO/WHO report on daily protein and amino acid requirements in human nutrition, the amino acid contents of the cricket species provides the daily amino acid requirements for histidine (0.010 mg/g), isoleucine (0.020 mg/g), leucine (0.039 mg/g), lysine (0.030 mg/g), methionine (0.015 mg/g), phenylalanine (0.025 mg/g) and valine (0.026 mg/g) (FAO/WHO/UNU, 2007) (**Table 3.3**). Therefore, the two cricket species are an excellent source of proteins and therefore a potential alternative to conventional sources of protein such as beef (**Figure 3.3**). The protein quality of the edible insects can further be improved with the removal of chitin which binds some amino acids (Rumpold & Schlüter, 2013).

Both cricket species in the present study were observed to have at least twice the amount of the recommended lysine and methionine for children at different age groups as well as adolescents (Press, 1987). Lysine and arginine are important factors in the release of growth hormone in young children (Ricardo et al., 2015). Foods containing high quality protein have been linked to reduced risk of stunting in young children aged 2-13 years (Ghosh et al., 2012; Grillenberger et al., 2018). Hence, incorporating cricket-based protein in diets of young children and complementary or supplementary food products targeted at this most vulnerable segment would contribute to easy access of diversified and well-balanced diets.

A comparative analysis of amino acid values between the two cricket species in the current study and the common conventional plant and livestock sources of amino acids as documented in the Kenya Food Composition tables is presented in **Figure 3.3**. The figure shows that both species of crickets contain more than the recommended nutrient intake for growing children. The comparative data presented in **Table 3.3** further provides evidence of viability of the two edible crickets' species as key ingredients in boosting protein quality in children's diets such as porridge for school going children in order to meet the recommended nutrient intakes (RNIs).

Table 3.2: Amino acid Profile of *Scapsipedus icipe* and *Gryllus bimaculatus* (Mean \pm SE) in mg/g

Amino acid	Type	Cricket species		P-value
		<i>Scapsipedus icipe</i>	<i>Gryllus bimaculatus</i>	
Histidine	Essential	10.80 \pm 0.87 ^a	4.83 \pm 6.24 ^b	0.0036
Arginine	Non-essential	13.59 \pm 1.06 ^a	14.0 \pm 1.96 ^a	0.0584
Lysine	Essential	18.21 \pm 3.85 ^a	15.64 \pm 6.74 ^a	0.2742
Glutamine	Non-essential	0 ^a	1.75 \pm 3.73 ^b	0.0171
Glutamic acid	Non-essential	9.58 \pm 0.31 ^b	11.34 \pm 0.55 ^a	<0.0001
Proline	Non-essential	19.21 \pm 6.10 ^b	30.47 \pm 6.29 ^a	0.0004
Valine	Essential	29.14 \pm 7.84 ^b	41.38 \pm 8.15 ^a	0.0018
Methionine	Essential	16.12 \pm 3.87 ^b	20.67 \pm 3.62 ^a	0.0103
Tyrosine	Non-essential	23.78 \pm 5.81 ^a	24.49 \pm 2.97 ^a	0.7285
Isoleucine	Essential	43.41 \pm 10.57 ^a	43.86 \pm 17.44 ^a	0.9412
Leucine	Essential	66.24 \pm 12.53 ^b	78.56 \pm 10.85 ^a	0.0242
hydroxyproline	Non-essential	8.83 \pm 0.51 ^b	9.37 \pm 0.17 ^a	0.0049
Phenylalanine	Essential	25.37 \pm 8.00 ^b	32.75 \pm 3.26 ^a	0.0131

Means with different superscript letters in each column are significantly different at $p < 0.05$.

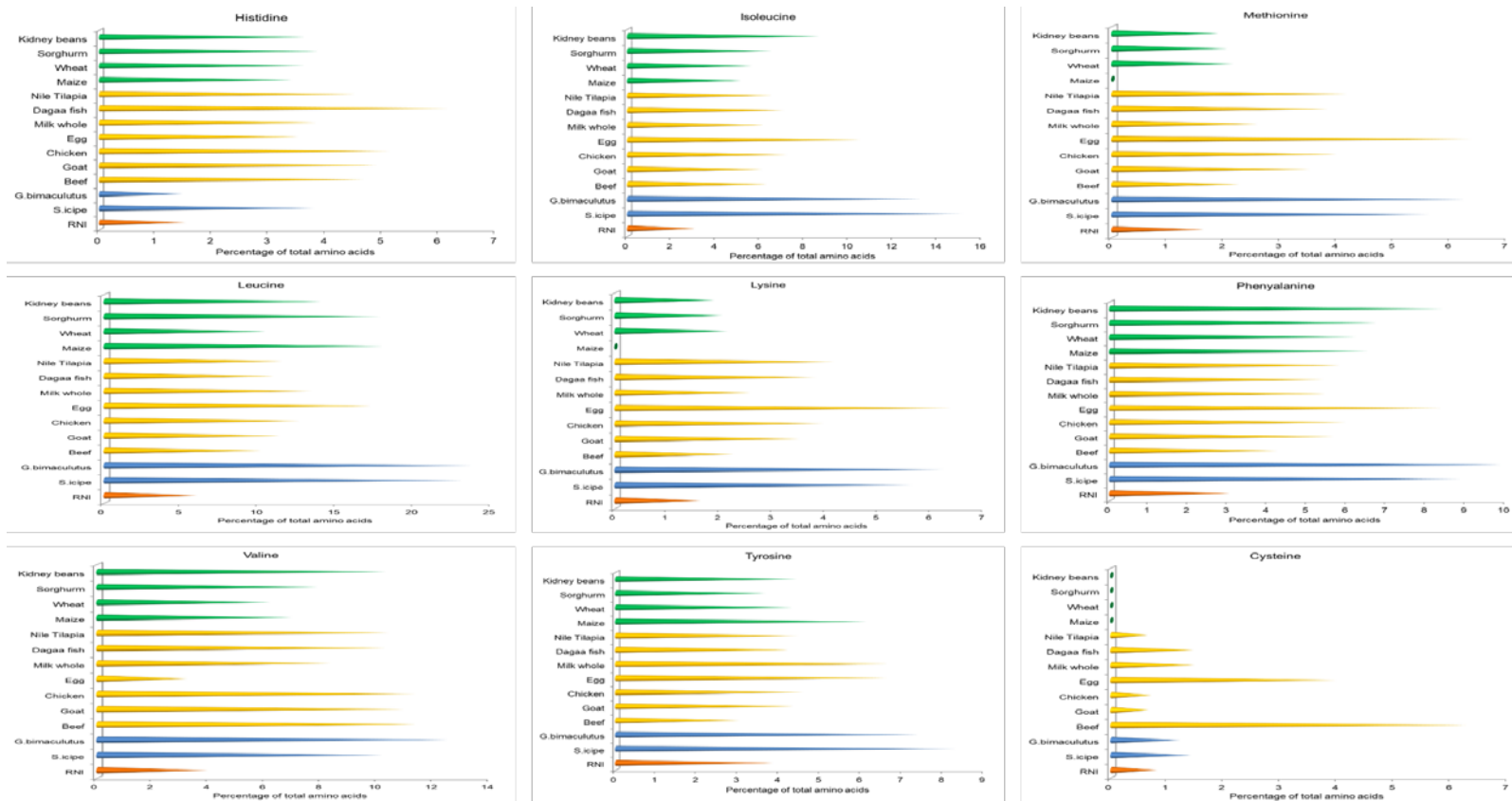


Figure 3.3: Comparison of Selected Essential Amino Acids Content of Crickets (*Scapsipedus icipe* and *Gryllus bimaculatus*) with Conventional Animal and Plant-Based Sources

Amino acid data for plant and animal sources was extracted from the Kenya Food Composition Tables, 2018 (FAO/Government of Kenya, 2018), while that of the recommended nutrient intake (RNI) was obtained from FAO/WHO/UNU (WHO, 2007).

Table 3.3: Comparative Distribution of Amino Acids in the Protein Fraction (% of Total Amino Acids) of Studied Insects against Recommended Amino Acid Values Based on FAO/WHO/UNU (2007) Consultation

		Percent of total amino acids in the given foods											
Category	Source	Histidine*	IsoLeucine*	Leucine*	Lysine*	Methionine*	Phenylalanine*	Valine*	Tyrosine**	Cysteine**	Arginine	Glutamic acid	Proline
	RNI per day	1.5	3	5.9	4.5	1.6	3	3.9	3.8	0.8			
Insect	<i>S. icipe</i>	3.75	15.06	22.98	6.32	5.59	8.80	10.11	8.25	1.39	4.71	3.32	6.66
	<i>G. bimaculatus</i>	1.45	13.17	23.58	4.70	6.21	9.83	12.42	7.35	1.20	4.20	3.40	9.15
Plant	Maize	3.38	5.06	17.88	5.21	0.00	6.48	6.88	6.09		8.38	26.56	14.08
	Wheat	3.61	5.55	10.31	10.31	2.13	6.17	6.13	4.29		6.91	40.82	9.32
	Sorghum	3.84	6.46	17.70	4.37	2.02	6.70	7.80	3.62		5.76	29.38	12.35
	Kidney beans	3.60	8.58	13.87	9.82	1.86	8.38	10.23	4.39		8.65	24.44	6.18
Animal	Beef	4.64	6.23	10.03	12.79	2.22	4.20	11.29	3.00	6.23	6.23	24.91	8.24
	Goat	4.87	6.02	11.20	12.06	3.47	5.62	10.86	4.31	0.64	11.63	19.58	9.75
	Chicken	5.10	5.17	12.53	16.74	3.94	5.90	11.30	4.55	0.69	9.73	0.92	5.64
	Egg	3.48	10.41	17.07	9.29	6.33	8.36	3.18	6.57	3.94	11.26	13.47	6.65
	Nile Tilapia	4.50	6.44	11.37	12.97	4.12	5.78	10.32	4.42	0.63	10.08	0.00	23.69
	Dagaa (Omena)	6.13	7.01	10.85	13.12	3.79	5.36	10.21	4.18	1.44	9.18	0.00	21.13
	Milk whole	3.81	6.10	13.32	10.99	2.54	5.41	8.27	6.60	1.45	4.64	0.00	25.18

Reference Nutrient Intake (RNI)

[*indicates essential amino acid and **indicates conditional essential amino acid]

3.3.4 Fatty Acids Composition of Crickets, *S. icipe* and *G. bimaculatus*

The fatty acid profiles of *S. icipe* and *G. bimaculatus* are presented below in **Table 3.4.** and **Figure 3.4.** The fatty acid groups in this study followed the order: SFA > MUFA > PUFA for *G. bimaculatus*, while that of *S. icipe* followed the order: SFA > PUFA > MUFA.

Overall in the saturated fatty acids (SFA) category, two fatty acids, Palmitic acid (23.9% – 31.2%) and stearic acids (14.7% – 17.3%), were predominantly higher compared to other SFAs in both insects. In fact, these two fatty acids contribute to more than three quarters of the total SFA values (*S. icipe* = 80.7%; *G. bimaculatus* = 79.7%) in both cricket species. Palmitic and stearic acids were also reported to be the predominant SFAs in cricket species elsewhere (Opitz & Müller, 2009; L. F. Yang et al., 2006). *Scapsipedus icipe* had similar values for palmitic acid as those reported elsewhere by Starčević and others (2017). However, palmitic values reported for *G. bimaculatus* were higher by about 1.3 folds than those reported by Starčević and others (Starčević et al., 2017). Stearic acid values reported in this study were consistently higher than values reported elsewhere by both Yang and others (Siriamornpun & Li, 2006) and by Starčević and others (Starčević et al., 2017).

Among the SFAs, butanoic (0.001%) and arachidic acids (0.004%) were detected in minute quantities in *S. icipe*, while caprylic and pentadecanoic acids were not detected in *G. bimaculatus*. Edible crickets in this study had a somewhat similar SFA content to that reported in the Kenya food composition table for beef (52.0%). On the contrary, these edible insects had considerably higher SFA values than dagaa fish (39.4%) and Nile tilapia (34.2%), but considerably lower SFA values than whole milk (67.4%) as reported also in the Kenya food composition table (Kenya, 2018).

The total monounsaturated fatty acid (MUFA) content in *S. icipe* was higher than in *G. bimaculatus* by 1.04 factors. Nonetheless, the predominant MUFA in both cricket species was oleic acid (*S. icipe* - 11.4%, *G. bimaculatus* - 10.9%). Oleic acid being the predominant MUFA was consistent with findings of other cricket species reported elsewhere (Siriamornpun & Li, 2006; Starčević et al., 2017; D. Wang et al., 2004). However, the values for these cricket species were lower compared to those of field

crickets (*Gryllus testaceus* Walker and *Gryllus assimilis* Fabricius) reported by others (Starčević et al., 2017; D. Wang et al., 2004), which could be attributed to feed and geographical differences. Oleic acid has been reported to have modulatory effects in health and disease. For instance, Sales-Campos and others suggested the potential role of oleic acid in enhancing immune function by modulating leucocytes, reducing inflammation, including its role in wound healing as well as in cancer prevention (Sales-Campos et al., 2013). Additionally, a review of intervention studies confirmed the role of oleic acid in reducing cardiovascular risk when added to milk as a substitute to counter the effects of saturated fatty acids thereby lowering cholesterol levels (Lopez-Huertas, 2010).

The second, third and fourth MUFAs followed the order: palmitoleic acid > gondoic acid > lauroleic acid for *S. icipe* and palmitoleic acid > gondoic acid > nervonic acid for *G. bimaculatus*. Similar to findings of this study, earlier studies for crickets and termites reported palmitoleic acid as the second most abundant MUFA (Starčević et al., 2017). Butenoic and myristoleic acids were not detected in *S. icipe*.

The total polyunsaturated fatty acid (PUFA) content in *S. icipe* was about 1.3 folds higher than that of *G. bimaculatus*. Nonetheless, linoleic acid was the predominant PUFA, contributing to more than two thirds of the total PUFAs in both cricket species. Linoleic acid as the predominant PUFA was in agreement with findings reported elsewhere for other cricket species (Starčević et al., 2017; Womeni et al., 2009; L. F. Yang et al., 2006). The linoleic acid value reported in this study were within the range of values reported elsewhere for crickets (L. F. Yang et al., 2006). Nonetheless, both *G. bimaculatus* and *S. icipe* had lower linoleic acid values compared to values reported for crickets (*Homorocoryphus nitidulus* Scopoli) (Womeni et al., 2009) and Jamaica field crickets (*G. assimilis*) fed on different oil blend diets (Starčević et al., 2017).

The presence of essential fatty acids - arachidonic, eicosatetraenoic, eicosapentaenoic and docosahexaenoic acids in the cricket species in this study could contribute to key roles in children's growth and development when incorporated in daily diets through conventional foods (Carlson & Colombo, 2017). All the differences observed in the MUFA and PUFA content among the edible insects could be attributed to diet

variations (Ghosh, Lee, Jung, et al., 2017). Additionally, the activity of enzymes like desaturase has been associated with the synthesis of long chain PUFAs among insect species that have the ability to synthesize them *in vivo* (J. N. Kinyuru et al., 2013; Lopez-Huertas, 2010; Sales-Campos et al., 2013), hence another possible explanation for the variations reported in unsaturated fatty acids. Both crickets in this study had more PUFA content than commonly consumed proteins like whole milk (3.56%) and beef (4.18%) but lower PUFA content compared to dagaa fish (36.22%) and Nile tilapia (31.97%) as reported in the Kenya food composition table (Kenya, 2018).

The ratios of PUFA to SFA and n-6 to n-3 were between 0.3–0.5 and 44.7–53.1 respectively for both cricket species. Both *G. bimaculatus* and *S. icipe* had higher PUFA/SFA ratios, which were higher than, a value derived for beef and whole milk from the Kenya food composition table (Kenya, 2018). However, the PUFA/SFA ratios were lower compared to values derived for Nile tilapia and dagaa fish (Kenya, 2018). A high ratio of omega 6 (n-6) to omega 3 (n-3) fatty acids has also been deemed undesirable in foods, as it has been linked to high risk of immunological disorders (Djuricic & Calder, 2021; Sprecher, 2000).

According to Gogus and Smith (Gogus & Smith, 2010), a joint report from FAO and WHO recommended a ratio of n-6 to n-3 of <5:1, while Canada recommended a range (4:1 to 10:1) for a balanced food. The cricket species studied had ratios of n-6 to n-3 that were within ranges reported elsewhere for edible insects (4:1 to 55:1), including crickets (Siriamornpun & Li, 2006; Starčević et al., 2017). This ratio is largely dependent on the insect's diet as demonstrated by Starčević and others (Starčević et al., 2017) and thus diet manipulated could lead to the production of edible insects that have maximum positive impact on human health. It is probable that the use of ingredients containing high omega 6 levels in feed formulations (whole maize, soy bean and grain amaranth) could have influenced the PUFA composition of cricket oil in the present study. Future studies can consider incorporation of ingredients with relatively low omega 6 content such as canola oil or linseed oil.

Nutritionally, the consumption of foods with high contents of SFA is undesirable as they have been linked to high incidences of cardiovascular diseases. On the contrary, consumption of unsaturated fatty acids (UFA) has been shown to reduce the prevalence of such illnesses (Simopoulos, 2004). This therefore implies that both edible crickets in this study are nutritionally commendable in terms of quality of fatty acids.

Table 3.4: Composition of Fatty Acids (% of Total Fatty Acids *, (mg/100g) *) of *Scapsipedus icipe* and *Gryllus bimaculatus*

Peak No.	tR (min)	Fatty Acid Methyl Ester	Fatty acid	Insect species		t value	P-value
				<i>S. icipe</i>	<i>G. bimaculatus</i>		
1 ^a	4.56	Methyl butanoate	Butanoic acid (C4:0)	0.001±0.0 ^a (0.2)	0.004±0.0 ^b (0.54)	-6.298	0.001
2 ^a	11.23	Methyl heptanoate	Enanthic acid (C7:0)	0.09±0.01 ^a (14.46)	0.21±0.03 ^b (31.72)	-6.641	0.001
3 ^a	13.67	Methyl octanoate	Caprylic acid (C8:0)	0.06±0.02 ^a (9.93)	Nd	7.250	0.001
4 ^a	15.80	Methyl decanoate	Capric acid (C10:0)	0.04±0.04 ^a (5.76)	0.02±0.01 ^a (3.34)	1.617	0.09
5 ^a	17.23	Methyl undecanoate	Undecanoic acid (C11:0)	0.26±0.02 ^a (40.81)	0.35±0.1 ^a (52.69)	-1.479	0.106
6 ^a	18.98	Methyl dodecanoate	Lauric acid (C12:0)	0.31±0.04 ^a (48.48)	0.35±0.02 ^a (51.94)	-1.341	0.125
7 ^a	20.07	Methyl tridecanoate	Tridecylic acid (C13:0)	0.22±0.06 ^a (33.83)	0.42±0.07 ^b (62.83)	-3.643	0.010
11 ^a	21.32	Methyl tetradecanoate	Myristic acid (C14:0)	5.43±0.85 ^b (841.53)	3.7±0.58 ^a (554.17)	2.926	0.021
12 ^a	22.37	Methyl pentadecanoate	Pentadecanoic acid (C15:0)	0.08±0.03 ^a (12.03)	Nd	4.643	0.004
15 ^a	23.66	Methyl hexadecanoate	Palmitic acid (C16:0)	23.89±0.63 ^a (3699.45)	31.18±0.7 ^b (4668.27)	-13.406	<0.001
16 ^a	24.05	Methyl heptadecanoate	Margaric acid (C17:0)	1.44±0.1 ^a (222.85)	1.4±0.27 ^a (210.5)	0.206	0.423
19 ^a	25.55	Methyl octadecanoate	Stearic acid (C18:0)	17.26±1.56 ^b (2670.53)	14.71±1.36 ^a (2200.85)	2.138	0.049
20 ^a	26.21	Methyl nonadecanoate	Nonadecanoic acid (C19:0)	0.73±0.13 ^a (113.23)	0.83±0.13 ^a (123.93)	-0.92	0.204
28 ^a	27.07	Methyl eicosanoate	Arachidic acid (C20:0)	0.004±0.0 ^a (0.64)	0.01±0.0 ^b (1.41)	-2.229	0.044
29 ^b	27.87	Methyl heneicosanoate	Heneicosylic acid (C21:0)	0.5±0.07 ^b (76.66)	0.32±0.08 ^a (47.37)	2.827	0.023
31 ^b	28.66	Methyl docosanoate	Behenic acid (C22:0)	0.37±0.03 ^b (757.61)	0.01±0.0 ^a (1.34)	20.073	<0.001
33 ^b	30.21	Methyl tetracosanoate	Lignoceric acid (C24:0)	0.28±0.02 ^a (43.98)	0.26±0.03 ^a (38.56)	1.239	0.141
			ΣSFA (%)	50.96	57.60		
8 ^b	20.10	Methyl (9Z)-decenoate	Caproleic acid (C10:1)	Nd	0.14±0.02 ^a (21)	-10.341	<0.001
9 ^b	21.01	Methyl (9Z)-dodecenoate	Lauroleic acid (C12:1 n-3)	0.16±0.02 ^a (24.56)	0.12±0.04 ^b (18.19)	1.443	0.111
10 ^a	21.15	Methyl (9Z)-tetradecenoate	Myristoleic acid (C14:1)	Nd	0.09±0.01 ^a (13.37)	-15.678	<0.001
13 ^b	23.24	Methyl (9Z)-hexadecenoate	Palmitoleic acid (C16:1)	11.14±0.97 ^b (1727.07)	9.22±0.63 ^a (1382.17)	2.869	0.022

18 ^a	25.24	Methyl (9Z)- Octadecenoate	Oleic acid (C18:1 n-9)	11.4±0.81 ^a (1767.2)	10.94±0.81 ^a (1639.54)	0.69	0.263
26 ^b	26.86	Methyl (11Z)- eicosenoate	Gondoic acid (C20:1 n-9)	1.56±0.25 ^b (241.3)	0.86±0.18 ^a (128.92)	3.968	0.008
27 ^b	26.99	Methyl (13Z)- eicosenoate	Paullinic acid (C20:1 n-7)	0.01±0.0 ^a (0.92)	0.01±0.0 ^a (1)	-1.314	0.129
32 ^b	30.03	Methyl (13Z)- tetracosenoate	Nervonic acid (C24:1 n-9)	0.05±0.01 ^a (7.71)	0.29±0.06 ^b (43.34)	-6.467	0.001
			∑MUFA (%)	24.33	23.24		
14 ^b	23.55	Methyl (7Z,10Z,13Z)- hexadecatrienoate	Hexadecatrienoic acid (HTA) (C16:3 n-3)	Nd	0.01±0.0 ^a (0.91)	-12.901	<0.001
17 ^a	25.21	Methyl (9Z,12Z)- octadecadienoate	Linoleic acid (C18:2 n-6)	23.56±0.25 ^a (3647.9)	23.34±0.51 ^a (3493.35)	0.673	0.268
21 ^a	26.34	Methyl(9Z,12Z,15Z)- octadecatrienoate	Linolenic acid (C18:3 n-3)	0.21±0.1 ^a (32.1)	0.32±0.04 ^a (48.6)	-1.823	0.071
22 ^b	26.35	Methyl (5Z,11Z,14Z)- eicosatrienoate	Sciadonic acid (C20:3 n-6)	0.86±0.09 ^a (133.18)	0.79±0.04 ^a (118.49)	1.192	0.149
23 ^b	26.40	Methyl (5Z,8Z,11Z,14Z)- eicosatetraenoate	Arachidonic acid (C20:4 n-6)	Nd	0.01±0.0 ^a (0.95)	-8.123	<0.001
24 ^b	26.45	Methyl (6Z,9Z,12Z,15Z)- octadecatetraenoate	Eicosatetraenoic acid (ETA) (C20:4 n-3)	Nd	0.01±0.0 ^a (1.12)	-12.422	<0.001
25 ^a	26.54	Methyl(5Z,8Z,11Z,14Z,17Z)- eicosapentaenoate	Eicosapentaenoic acid (EPA) (C20:5 n-3)	0.08±0.0 ^a (12.17)	0.07±0.0 ^a (10.97)	1.524	0.101
30 ^a	28.12	Methyl (4Z,7Z,10Z,13Z,16Z,19Z)- docosahexaenoate	Docosahexaenoic acid (DHA) (C22:6 n-3)	0.01±0.0 ^a (1.7)	0.01±0.0 ^a (1.87)	-0.534	0.31
			∑PUFA (%)	24.71	19.16		
			∑PUFA: ∑SFA	0.48	0.33		
			∑n-6/∑n-3	53.09	44.70		

Peak No. = Peak Number; ^a = fatty acid identity confirmed with authentic standard; ^b = fatty acid tentatively identified; tR (min) = Retention time (minutes); * = Mean ± standard deviations of triplicate determinations. In the same row, means (±standard deviations) with the same superscript letters are not significantly different at P ≥ 0.05. *Values in parenthesis are fatty acid values (mg/100g oil sample). SFA= saturated fatty acids; MUFA= monounsaturated fatty acids; PUFA= polyunsaturated fatty acids; ∑n-6= sum of linoleic, sciadonic and arachidonic acids; ∑n-3= sum of lauroleic, linolenic, ETA, EPA and DHA acids.

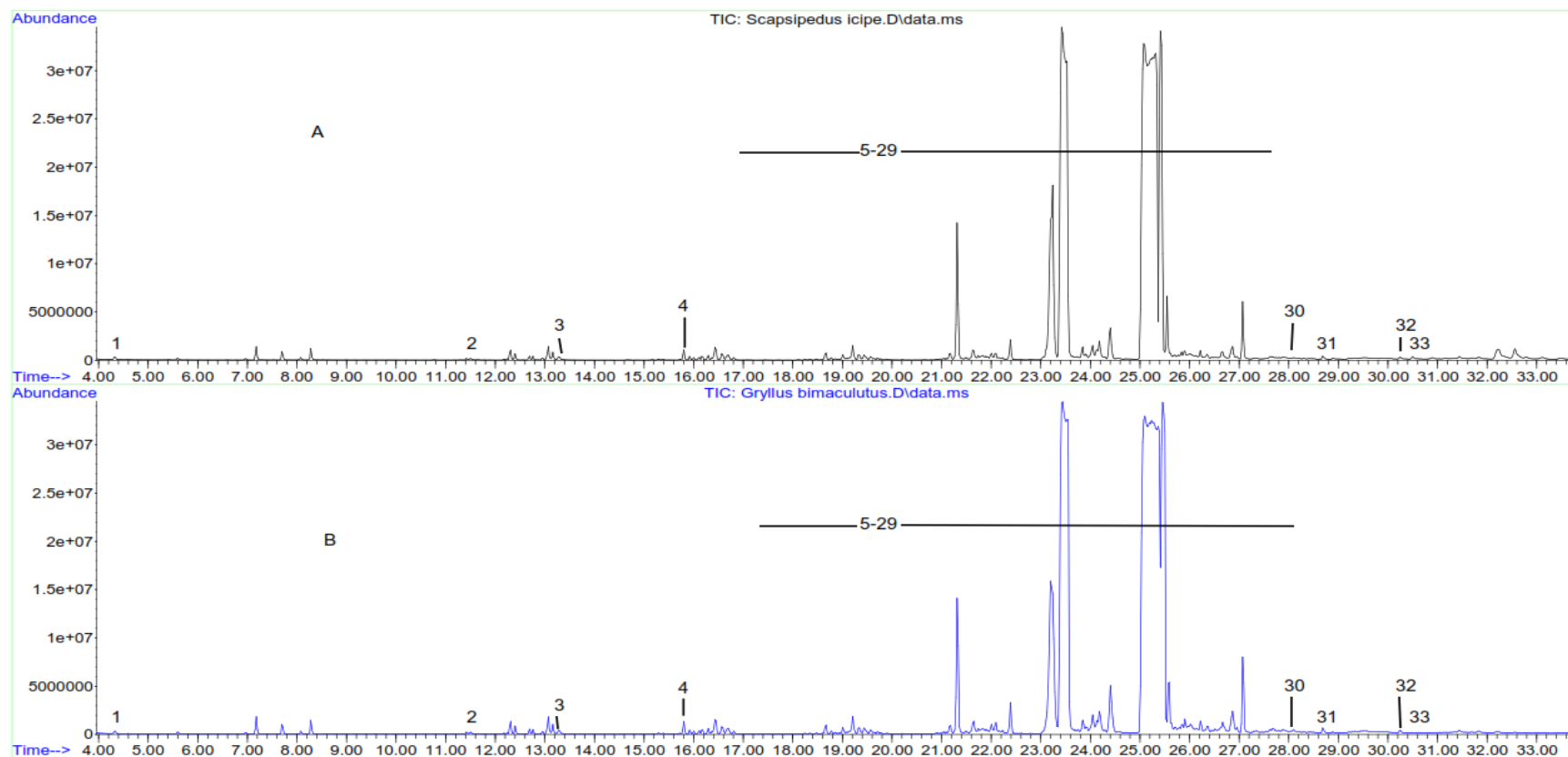


Figure 3.4: Representative Overlaid Total Ion Chromatogram of the Fatty Acid Profile

A = *Scapsipedus icipe* and B = *Gryllus bimaculatus*. Numbers 1-33 fatty acid identified as shown in Table 3.4

3.3.5 Mineral Composition

The importance of edible insects as a source of minerals has been documented in several studies (Christensen et al., 2006; Rumpold, B.A., Schluter, 2013; Zielińska et al., 2015). Based on the current study, the iron content of the two edible crickets ranged between 10.70 – 12.33 mg/100g, which is similar to that reported for *A. domesticus* (11.23mg/100g) (Barker et al., 1998). Thus, the consumption of 100g of *S. icipe* or *G. bimaculatus* will potentially provide at least 54% and 100% of the recommended dietary allowance (RDA) of iron for women of reproductive age and children below 5 years of age, respectively (**Table 3.5**).

Globally, iron deficiency is the commonest nutritional disorder affecting both children and women of reproductive age (WHO, 2025). For example, the anaemia prevalence statistics for developing countries show that four in every ten pregnant women and 40% of school going children are affected (Sukwuttichai, 2026; WHO, 2025). Anaemia which causes 20% of maternal deaths, also leads to irreversible health consequences including pre-term babies, poor physical and cognitive development and increased risk of morbidity in children (WHO, 2025). It is thus, evident that integrating edible crickets into the regular diets of women and children might have the potential to address the anaemia problem (Mwangi et al., 2018). Studies have also shown that acceptability of common staples that are fortified with edible insect meals is high and should be encouraged particularly for children (Homann et al., 2017; Rodrigues & Adegbeye, 2025; Zondo et al., 2026)

Zinc is another mineral of public health importance and the values obtained for *S. icipe* or *G. bimaculatus* in the present study are comparable to that of *A. domesticus* (18.64mg/100g) (Barker et al., 1998) but higher than that reported for *A. domesticus* (13mg/100g) (Rumpold & Schlüter, 2013b) and *Gryllodes Sigillatus* (13.9mg/g) (Zielińska et al., 2015). Consumption of 100g of *S. icipe* or *G. bimaculatus* per day would potentially contribute enough nutrient to meet 100% of the recommended daily allowance for zinc (2 – 11 mg/100g) for all age groups. As shown in **Figure 3.5**, the two cricket species are clearly superior in zinc content than common animal and plant

foods. Thus, they may play a great role in alleviating this most common deficiency, which is associated with stunting and hypertension (Mousavi et al., 2020).

Calcium content was higher in *G. bimaculatus* (72.70mg/100g) than in *S. icipe* (66.07mg/100g). Values obtained in this study are comparable to those recorded by Payne and others (Payne et al., 2016a) for *A. domesticus*. However, the calcium contents in this study are lower than 130mg/100g reported by Rumpold & Schlüter (Rumpold & Schlüter, 2013a) for the edible cricket *A. domesticus*. This wide variation observed between the various studies can be attributed to the choice of diet fed to the crickets (Ramos-Elorduy et al., 2002). It is anticipated that 100g of any of the edible cricket species in the current study would be able to provide at least 16.5 - 18% of RDA for children (**Table 3.5**). Thus, edible crickets could contribute significantly to alleviate calcium deficiencies if incorporated in the diet regularly.

Magnesium content was higher in *S. icipe* (35.57 mg/100g) than in *G. bimaculatus* (29.13 mg/100g) (**Table 3.5**). These values are close to 33.7mg/100g and higher than 22.6mg/100g previously reported for adult house cricket (*A. domesticus*) (Collavo et al., 2005; Finke, 2002b). Therefore, intake of 100g of *S. icipe* or *G. bimaculatus* could meet over 50% of RDA of magnesium requirements for young children. The role played by magnesium in the body as a cofactor of enzymes involved in metabolism, synthesis of protein, RNA and DNA and the maintenance of electrical potential of nervous tissues and cell membranes has been well documented (FAO & WHO, 2001).

The potassium content of *S. icipe* or *G. bimaculatus* was 66.32 mg/100g and 39.54 mg/100g respectively (**Table 3.5**), which is higher than the values reported in other studies (37.4 mg/100g) (Akhtar & Isman, 2017). The potassium content of *S. icipe* was close to that reported (74.6 mg/100g) for the giant African cricket (Adeyeye & Awokunmi, 2010). However, in another study notably a higher potassium content (1126 mg/100g) was reported in cricket *A. domesticus*, as compared to values obtained in this study (Rumpold & Schlüter, 2013a). The variation in potassium content could be attributed to differences in diets and age of the crickets (Banjo et al., 2006).

Sodium levels were significantly higher in *S. icipe* (395 mg/100g) than in *G. bimaculatus* (166 mg/100g), ($P < 0.0001$). The sodium content of *G. bimaculatus* was lower compared to that reported for adult *A. domesticus* (134 mg/100g) (Finke, 2002b), while that of *S. icipe* was comparable to that documented for the same cricket (430 mg/100g) species (Bernard et al., 1997).

The manganese content of *S. icipe* (9.57 mg/100g) and *G. bimaculatus* (10.85 mg/100g) were not significantly different. Comparative studies show that the consumption of approximately 100g of these crickets of the two cricket species in the current study would provide adequate amount of the RDA of manganese required for children, adolescents, adults, and even lactating mothers. However, the values obtained in this study are considerably higher than those reported for other adult crickets which ranged between 2.37 mg/100g - 3.73 mg/100g (Rumpold & Schlüter, 2013). Similarly, the manganese content of the two cricket species in this study was higher than the 1.15 mg/100g reported in cricket species (Finke, 2002b).

Cobalt which is one of the trace minerals and whose main role is being a component of vitamin B₁₂ (cyanocobalamin) (Farell, 2010) was recorded in *S. icipe* and *G. bimaculatus*. The value of cobalt in both crickets was closely comparable with *S. icipe* reporting 5.09 mg/100g while *G. bimaculatus* reported 4.36 mg/100g. These results of this current study are consistent with those reported in the Snout beetle (4.76 mg/100g), though higher than in other insects such as termite (Adeyeye & Olaleye, 2016). In addition, no significant variation of copper content was observed between *S. icipe* or *G. bimaculatus* but the values recorded are higher than what has been reported for adult *A. domesticus* (0.62 - 0.85 mg/100g) (Barker et al., 1998; Finke, 2002b).

Figure 3.5 presents a detailed comparative analysis of *S. icipe* and *G. bimaculatus* mineral content with conventional animal and plant mineral sources as documented in the Kenya Food Composition Tables (2018). Generally, both cricket species have higher amounts of Iron, Zinc and Potassium than conventional food sources of animal (eggs, chicken, goat, beef) and plant (maize, sorghum, kidney beans, wheat) origin. This implies that cricket species in this study could potentially be a good source of minerals of public health importance such as Iron and Zinc. The figure also shows

that both cricket species are generally low in calcium and magnesium compared to the selected food sources. In terms of sodium, both cricket species compare well with animal source foods with eggs showing highest levels of sodium. Generally, plant food sources (maize, sorghum, kidney beans and wheat) presented in this figure are very low in sodium compared to both cricket species.

Table 3.5: Mineral Composition of Edible Cricket Species (*Scapsipedus icipe* and *Gryllus bimaculatus*) in Milligrams/100 grams on Dry Weight Basis

Cricket species	Ca	K	Mg	Na	Fe	Zn	Mn	Cu	Co
<i>Scapsipedus icipe</i>	66.07± 1.63 ^a	66.32± 0.33 ^b	35.57± 1.95 ^b	395.44±4 1.63 ^b	10.70± 0.60 ^a	19.19± 0.64 ^a	9.57±1 7.22 ^a	7.93±0 .73 ^a	5.09±2 .64 ^a
<i>Gryllus bimaculatus</i>	72.70± 1.74 ^b	39.54± 0.92 ^a	29.13± 0.55 ^a	166.50±0 .01 ^a	12.33± 5.36 ^a	23.74± 1.30 ^b	10.85± 18.25 ^a	8.27 ± 1.5 ^a	4.36±1 .62 ^a
P-Value	0.0014	<0.000 1	0.0007	<0.0001	0.5676	0.0008	0.3462	0.6987	0.6547
	RDAs in mg/day**								
Children	400- 700	3000- 3800	54-100	1000- 1200	5.9	0.8-3.3	1.2-1.5	0.34- 0.44	-
Adolescents (male/female)	1300	4500- 4700	220/23 0	1500	12.5/20 .7	5.1/4.3	1.9-2.2/ 1.6	0.7- .089	-
Adults(male/ female)	1000- 1300	3510*	220/26 0	1200- 1500	9.1/19. 6	4.5/3.0	2.3/1.6	0.9/0.9	-
Lactating	1000	5100	310	1500	10	12-14	2.6	1.3	-

Means with different superscript letters in each column are significantly different at $p < 0.05$; *Guideline on potassium intake for adults and children (Organization, 2012); **All Recommended Dietary Allowance (RDA) values were derived from FAO/WHO expert consultation on Human vitamin and mineral requirements (FAO & WHO, 2001).

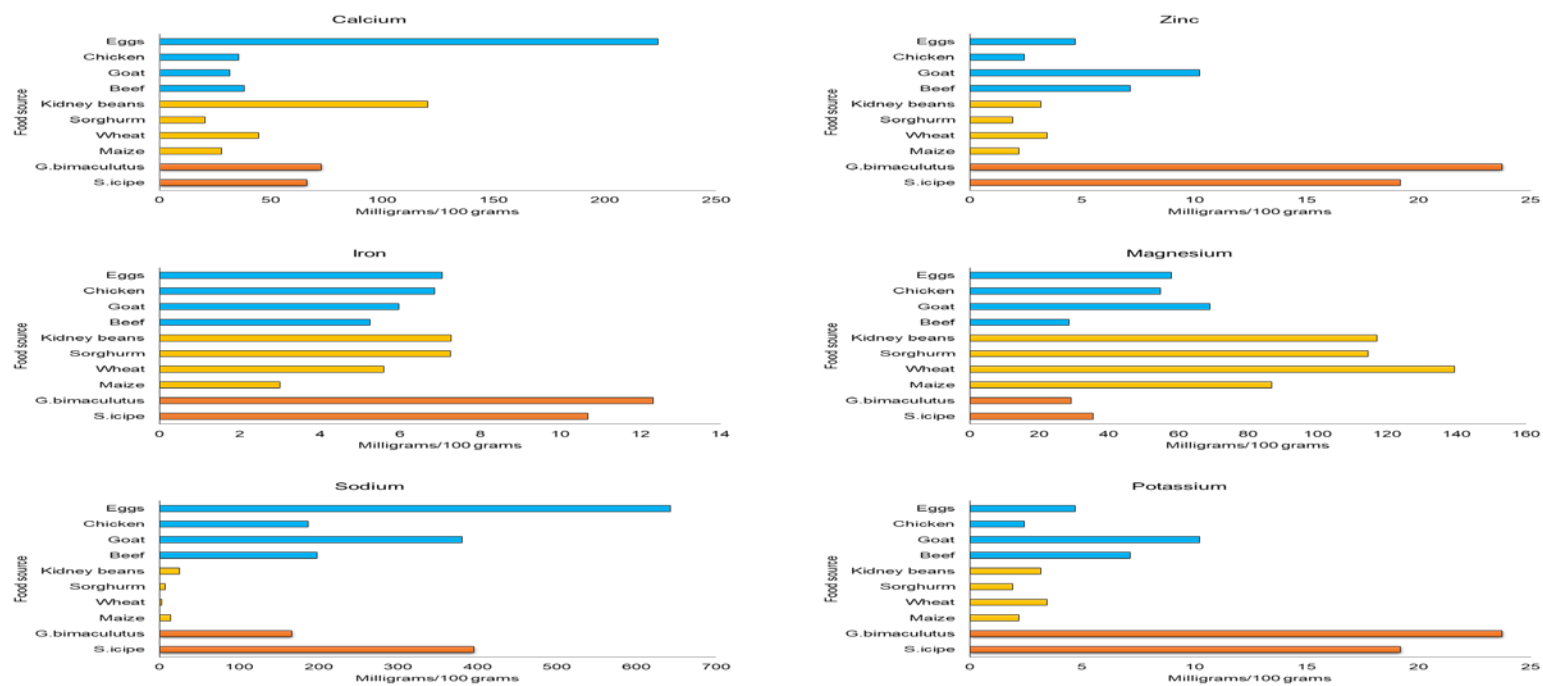


Figure 3.5: Comparison of Mineral Content of Crickets (*Scapsipedus icipe* and *Gryllus bimaculatus*), Animal and Plant-Based Sources

Mineral content data for plant and animal food sources was extracted from Kenya Food Composition Tables (FAO/GOK, 2018a).

3.3.6 Vitamins

There is insufficient data published on vitamin composition of edible insects and particularly on crickets such as house cricket (*A. domestica*) (Chen et al., 2009). In this study, the vitamin A (retinol) content of *S. icipe* (42 mcg/100g) and *G. bimaculatus* (32 mcg/100g) varied considerably (**Table 3.6**). These values of Vitamin A are relatively higher than what has been reported from adult domestic house cricket *A. domestica* (24.33 mcg/100g) (Rumpold & Schlüter, 2013b), (Banjo et al., 2006). Therefore, consumption of 100g of the newly discovered cricket species (*S. icipe*) will potentially provide up to 22% RDA of Vitamin A (retinol) among young children (Table 3.5). Children in sub-Sahara Africa and other low-income countries are particularly at risk of Vitamin A deficiency (VAD), thus insects can be a promising and sustainable source of Vitamin A (FAO & WHO, 2001).

The content of γ -tocopherol (P=0.7823), alpha-tocopherol (P = 0.1536), and pro-vitamin D (Vitamin D3 (cholecalciferol)) observed in *S. icipe* and *G. bimaculatus* did not vary significantly. The values reported in this study for γ - and α -tocopherol were considerably higher than the vitamin E content (0.072 mg/g) reported in reared crickets such as *A. domestica* (Rumpold, B.A., Schluter, 2013). The high level of discrepancy in results of tocopherol concentrations in edible insects could be attributed to the type of feeding substrate used (Kou & Adámková, 2016).

The Pro Vitamin D (Vitamin D3, cholecalciferol) concentration of the edible crickets was 0.43 mg/g and 0.22 mg/g for *S. icipe* and *G. bimaculatus* respectively. However, there was no significant difference (p=0.2611) in Pro Vitamin D concentration between the two cricket species. The Pro Vitamin D concentration recorded for *S. icipe* and *G. bimaculatus* (0.43 mg/g and 0.22 mg/g) is much higher than 0.0064 mg/g reported for *A. domestica* (Finke, 2002b). This implies that the consumption of 100 g a day of *S. icipe* and *G. bimaculatus* could potentially meet the Pro Vitamin D RDA for children, adolescents, adults, and lactating mothers. Pro Vitamin D is an easily absorbed precursor in the synthesis of Vitamin D and plays a critical role in supporting bone, muscle and immune health (Burns-whitmore et al., 2024; Charoenngam & Holick, 2020). Therefore, the two cricket species can be a viable alternative source of

Vitamin D for growing children especially when incorporated into flour based complementary and supplementary foods in ground or milled form (Nolle et al., 2024).

However, the concentration of thiamine (vitamin B₁) in *G. bimaculatus* (4.23 mg/kg) was significantly higher when compared to that of *S. icipe* (0.85 mg/kg). The vitamin B₁ content recorded for *G. bimaculatus* is comparable to that reported for *A. domesticus* (3.6 mg/kg) (Jonas-Levi & Martinez, 2017). On the contrary the vitamin B₁ of the two cricket species studied were considerably lower than 15.2 mg/kg reported for *A. domesticus* reared in Kenya (Ayieko, Ogola, & Ayieko, 2016). Contrarily, the Thiamine concentrations in *S. icipe* and *G. bimaculatus* are higher comparatively to that reported for other cricket species (0.4 mg/kg) (Finke, 2002b). These differences observed could be associated to species difference and variation in rearing diet formulation (Payne et al., 2015).

For vitamin B₂ (Riboflavin), no significant differences were observed ($p=0.0728$) between *S. icipe* (5.4mg/kg) and *G. bimaculatus* (8.9mg/kg). However, our values are comparable to that reported for the long-horned grasshopper *Ruspolia differens* (12.8 mg/kg) (J. N. Kinyuru & G. M. Kenji, 2010) and crickets (19.1 mg/kg) (Aree & Puwastien, 2010). The vitamin B₂ content of the two cricket species reported in the present study is higher than what has been documented for other Orthopteran species (0.3 – 0.8 mg/kg) (Alamu et al., 2013) and other commonly eaten insects in South Western Nigeria (0.03 – 3.24 mg/100g). The variation in vitamin B₂ content between literature and the findings of this study could be attributed to differences in species, age and feeding regime (Payne et al., 2015).

Notably, niacin was not detected in *S. icipe* but the value recorded for *G. bimaculatus* (10.93 mg/kg) are lower compared to other studies on crickets with values ranging between 31.0 - 38.4 mg/kg (Finke, 2002b; Jonas-Levi & Martinez, 2017).

Table 3.6: Vitamin Composition of Edible Cricket Species (*Scapsipedus icipe* and *Gryllus bimaculatus*).

Cricket species	Retinol (IU)/ (mcg/100g)	γ - tocopherol (mg/g)	α - tocopherol (mg/g)	Provitamin D (mg/g)	Vitamin B ₁ (mg/kg)	Vitamin B ₂ (mg/kg)	Vitamin B ₃ (mg/kg)	Vitamin B ₆ (mg/kg)	Vitamin B ₉ (mg/kg)
<i>Scapsipedus icipe</i>	139.41 ± 19.19 ^b /(41.847 ± 5.757)	0.48 ± 0.13 ^a	8.79 ± 4.57 ^a	0.43 ± 0.20 ^a	0.85 ± 0.11 ^a	5.40 ± 1.17 ^a	nd	16.0 ± 4.90 ^a	4.12 ± 0.99 ^a
<i>Gryllus bimaculatus</i>	107.2 ± 26.47 ^a / (32.172 ± 7.941)	0.52 ± 0.27 ^a	12.55 ± 0.63 ^a	0.22 ± 0.27 ^a	4.23 ± 0.67 ^b	8.90 ± 5.35 ^a	10.93 ± 2.67 ^a	52.76 ± 8.67 ^b	5.14 ± 1.01 ^b
P- Value	0.0094	0.7823	0.1536	0.2611	<0.0001	0.0728	<0.0001	<0.0001	0.0458
				RDAs in mg/day**					
Children	633-833/ (190 – 250)			0.005	0.3-0.9	0.4-0.9	4- 12NEs*	0.3-1.0	80-400
Adolescents (Male/Female)	1100-1333/ (330-400)			0.005	1.2/1/1	1.3/1.0	16NEs	1.3/1.2	400
Adults (Male/Female)	1000/900IU 300/270mcg			0.005	1.2/1.1	1.3/1.1	16/14NEs	1.3/1.3	400
Lactating/pregnancy	1500 IU/ 450 mcg			0.005	1.5/1.4	1.6/1.4	17/18NEs	2.0/1.9	500/600

Means with different superscript letters in each column are significantly different at $p < 0.05$; Values in brackets represent retinol content in mcg/100g; **All Recommended Dietary Allowance (RDA) values were derived from FAO/WHO expert consultation on Human vitamin and mineral requirements (FAO & WHO, 2001). *NEs refer to Niacin Equivalents which measures total available niacin (1 mg NE = 1 mg Niacin)

The concentrations of vitamin B₆ (pyridoxine) among the two cricket species differed significantly ($p < 0.0001$) with *G. bimaculatus* recording the highest value (52.76 mg/kg) compared to *S. icipe* (16.06 mg/kg). The vitamin B₆ concentrations observed in both crickets are lower than values (74.7 mg/kg) reported for other edible crickets (Rumpold & Schlüter, 2013a).

The folic acid (Vitamin B₉) content of *S. icipe* (4.12 mg/kg) and *G. bimaculatus* (5.14 mg/kg) were comparable but much higher than values reported for other edible crickets (1.5 mg/kg) in literature (Finke, 2002b). Similarly, the folic acid content of the two cricket species is higher than what has been reported in *Tenebrio molitor* (1.37 mg/kg) (Nowak et al., 2016b). These levels of folic acid are remarkably higher than that in some common foods (Figure 3.5). These folic acid values of the two cricket species (*S. icipe* and *G. bimaculatus*) are significantly higher than those of conventional animal and plant-based food sources (**Figure 3.6**).

Folic acid is a vitamin of public health significance whose deficiency is being addressed through folic acid supplementation and food fortification, especially during pregnancy to reduce cases of birth defects and consequently morbidity and mortality rates among children (Crider et al., 2011). Similarly, the riboflavin levels in *S. icipe* and *G. bimaculatus* are significantly higher when compared to animal and plant-based food sources. Interestingly the two cricket species can potentially meet the recommended nutrient intake (RNI) of riboflavin, thiamine, folic acids, and niacin among males, females, children, pregnancy, and lactating.

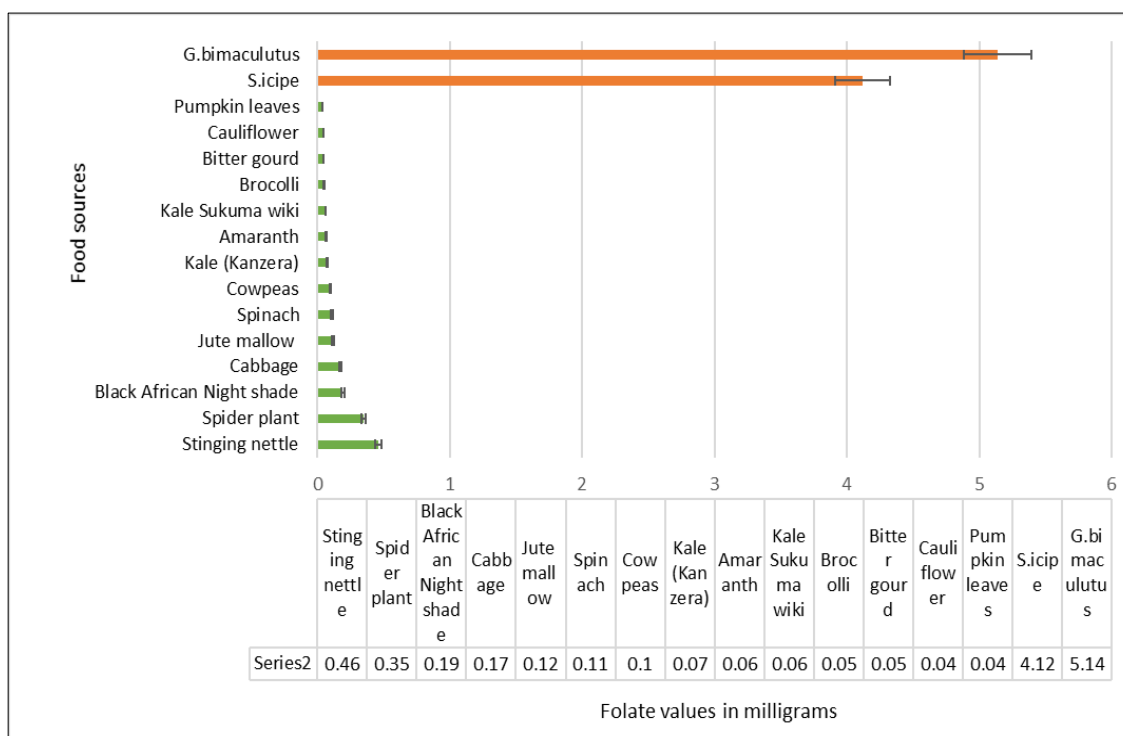
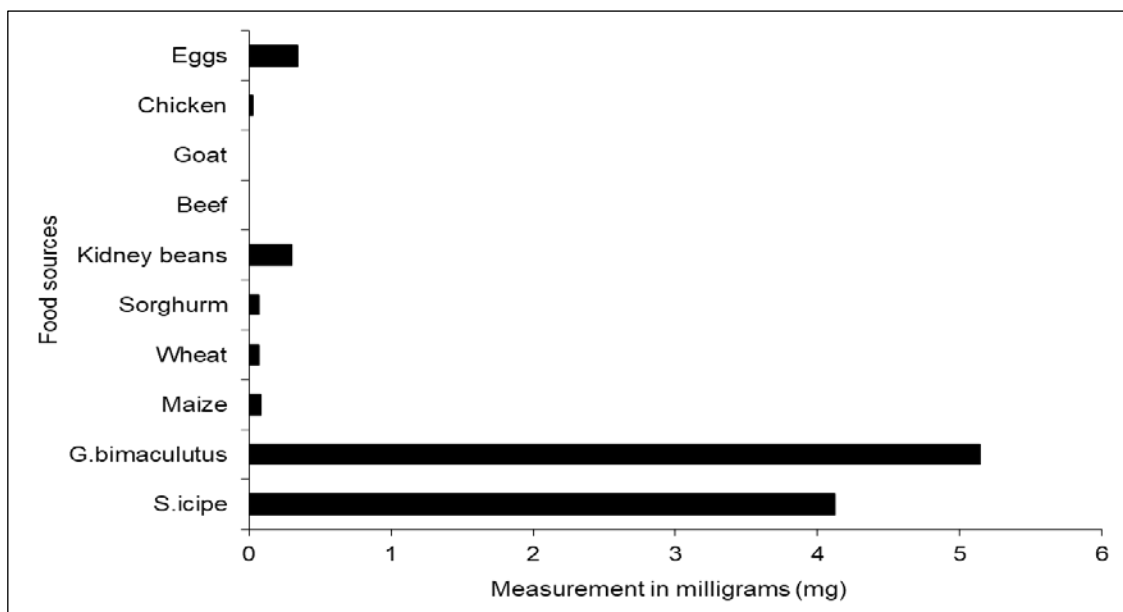


Figure 3.6: Folic Acid Content of *S. icipe* and *G. bimaculatus* Compared with Animal Source, Plant Source and Common Vegetables

Data for plant and animal food sources was extracted from the Kenya Food Composition Tables, (FAO/GOK, 2018)

3.4 Conclusions and Recommendation

The comparative proximate analysis of the two cricket species revealed that both are exceptionally dense in macronutrients, with protein content in both species being similar. In terms of protein consistency, both species proved to be excellent sources of protein, yielding 56.80% (*S. icipe*) and 56.90% (*G. bimaculatus*). The difference between them was not statistically significant ($P = 0.9092$), indicating that either species would serve equally well for protein fortification in the maize-cricket porridge.

Lipid and energy profiles: *G. bimaculatus* contained significantly higher crude fat (33.51%) compared to *S. icipe* (31.74%; $p = 0.0005$). This higher fat content contributed to a greater total energy value of 529.2 Kcal/100g for *G. bimaculatus*, making it a superior choice for addressing energy-density requirements in complementary feeding.

Mineral and fiber content: Statistical differences were also noted in the ash content ($p = 0.0123$), with *G. bimaculatus* showing a slightly higher mineral potential at 5.41%. While *G. bimaculatus* also recorded higher crude fiber (8.39%) than Species A (5.71%), this variation did not reach statistical significance ($p = 0.1564$).

While *G. bimaculatus* provided higher gross energy, *S. icipe* demonstrated significantly higher protein digestibility (87.8 %), offering a biological value comparable to bovine and avian proteins. This suggests that the selection of the cricket species for the maize-cricket porridge should be balanced between the raw caloric density of *G. bimaculatus* and the superior metabolic utilization of the protein found in *S. icipe*.

Based on these findings, the study concludes that both *S. icipe* and *G. bimaculatus* are viable nutritional vehicles compared to traditional staples. While *G. bimaculatus* offers a higher caloric and SFA-MUFA profile, *S. icipe* provides a more favorable PUFA balance and high protein digestibility. Crucially, the exceptionally high levels of Iron, Zinc, and Folic Acid—which exceed the requirements for children and women of reproductive age—validate the formulation of a maize-cricket porridge as a high-impact intervention for public health nutrition. These baseline nutritional advantages

are robust enough to withstand the extrusion process, providing a high-quality, nutrient-dense flour ready for sensory and functional optimization.

Ultimately, both species are nutritionally viable, with appreciable amounts of protein, fat and minerals. The two species are therefore recommended for the formulated maize-cricket porridge flour due to their significant contribution to daily caloric, protein and mineral requirements for school going children aged 5 -12 years. This nutrient density of both species optimizes the protein as well as caloric intake and micronutrient potential of the final product.

CHAPTER FOUR

PHYSICOCHEMICAL CHARACTERIZATION OF EDIBLE CRICKETS' (*Scapscipedus icipe* AND *Gryllus bimaculatus*) OILS AND THE ANTI- NUTRITIONAL PHYTOCHEMICAL PROFILE OF WHOLE GROUND CRICKET POWDER

4.1 Introduction

Edible insects have long been incorporated into human diets across different regions worldwide, contributing significantly to improved livelihoods (A. van Huis, 2013) and a multitude of health benefits (Brai et al., 2025). These insects are rich sources of nutrients, as well as phytochemicals (Durst & Johnson, 2010; A. van Huis et al., 2013; Kunatsa et al., 2020) As a result, there has been a parallel surge in the commercialization of edible insects on a global scale (Rao et al., 2022; Rumpold & Schlüter, 2013b). Among these diverse edible insect options, crickets emerge as a particularly promising species, largely due to their high protein content and potential for large-scale production. Consequently, there has been a growing interest in exploring the applications of cricket oils at industrial level, including in the food industry (Zondo et al., 2026)

While crickets are increasingly valued for their high protein content, their lipid content, which includes beneficial antioxidants and omega-3 & 6 fatty acids, remains under-explored (Tzompa-Sosa et al., 2021). The lipid content in crickets varies significantly, ranging from 22% to 32%, with dietary composition, developmental stage, and sex all exerting influence (Ghosh, Lee, Jung, et al., 2017; Magara et al., 2021)); notably, female crickets tend to have higher oil content than males. (Igual et al., 2020b). Cricket oils have shown promise in lowering the risk of coronary heart disease (Oonincx & Finke, 2021) due to their high content of Omega-3 and Omega-6 fatty acids, which can also inhibit the production of inflammation-inducing prostaglandin hormones (Tzompa-Sosa et al., 2021). Furthermore, crickets are an excellent source of vitamin E, renowned for its anti-inflammatory properties (Murugu et al., 2021).

However, due to their high unsaturated fatty acid (comprising more than two-thirds of the total oil) content, cricket oils are susceptible to deterioration (Tzompa-Sosa et al., 2021). Fortunately, they are also rich in antioxidants, which can enhance the oil's quality (Ugur et al., 2020). The presence and effectiveness of these antioxidants may vary depending on the species, sex, life stage, and diet of the crickets (Magara et al., 2021). Moreover, crickets contain phytochemicals such as phenolic compounds and phytosterols, which exhibit potential health benefits (Jimenez-garcia et al., 2018; Opitz & Müller, 2009; Tzompa-Sosa et al., 2021). Nonetheless, crickets also contain anti-nutrients that can hinder protein digestibility and mineral availability although these challenges can be addressed through appropriate processing methods (Khattab & Arntfield, 2009; Meyer-Rochow et al., 2021; S´anchez-Estrada et al., 2024).

The increasing use of cricket oils in food applications is rapidly gaining attention and momentum, primarily due to their unique properties and promising potential in a wide array of culinary uses. These insect-derived oils have shown remarkable versatility, finding application in various food products such as salad dressings, mayonnaise, baked goods, and confectionery items (Aondoakaa, 2025; Lisboa et al., 2025). Their exceptional emulsifying properties, attributed to the presence of phospholipids, with lecithin being a key component, facilitate the stabilization of oil and water mixtures, thereby enhancing the texture and extending the shelf life of baked goods (Aondoakaa, 2025; Lisboa et al., 2025).

The commercialization of edible crickets *S. icipe* and *G. bimaculatus* as staple food ingredients is currently hindered by a lack of standardized quality benchmarks. While the protein content of cricket powder is well-documented, the physicochemical behavior of its lipid fraction remains poorly defined, leaving food processors without the necessary data to predict shelf-stability, particularly if the cricket powder is to be added to maize flour formulations for complementary and supplementary porridges. Simultaneously, the emphasis on the high-protein content of these crickets has largely overlooked the anti-nutritional phytochemical profile of the whole ground powder. The presence of bio-accumulated phytates, tannins, and oxalates poses a significant risk to nutrient bioavailability, potentially interfering with the absorption of essential divalent cation nutrients like calcium and iron.

Without a comprehensive characterization of these physicochemical constants—such as acid and peroxide values—and a rigorous quantification of anti-nutritional factors, the true dietary value of cricket-derived ingredients remains speculative. This research, therefore, addresses this critical knowledge gap by establishing the physical and chemical benchmarks for edible cricket oil while simultaneously evaluating the phytochemical barriers to digestion in the whole powder. Such a dual-track approach is essential for ensuring that insect-based food systems are not only sustainable but also functionally reliable and nutritionally optimized.

4.2 Materials and Methods

4.2.1 Sample Collection and Preparation

Crickets were obtained from subsistence and commercial farms in Nyanza Kenya. Sampled crickets were generally fed on a diet comprising homemade composite flour (whole maize, soy bean, and amaranth grain), agricultural side streams such as waste vegetable leaves (kales, sweet potato leaves, pumpkin leaves) and ripe banana peels. A 5 kg sample of each edible insect species (*G. bimaculatus* and *S. icipe*) was collected separately in standard non-woven bags (12 x 16 inches), frozen alive at -21°C in a chest freezer. The insect samples were then packed in cool boxes that contained ice packs and transported to the International Centre of Insect Physiology and Ecology (*icipe*) for taxonomic identification. All the raw insect samples were then weighed into composite samples of 500 g, thawed and blended using a domestic blender (Signature SG-201), packed in plastic Tupperware of miniature 20 cm × 14.5 cm × 8 cm (Kenpoly manufacturers, Nairobi, Kenya) and kept in a deep freezer (-21°C) until analyzed for oil quality and phytochemical composition.

4.2.2 Extraction of cricket oil

Cricket oil was extracted using Folch's method described elsewhere with some modification (Igiehon et al., 2021). 5 g of milled samples were extracted using mixture of 50 mL solvent solution: chloroform - methanol (2:1 v/v) containing butylated hydroxyl toluene (10 mg/L). The mixture was vortexed for 10 s, sonicated for 10 min and allowed to stand for 30 min, followed by centrifugation (1500 g, 23 °C, 5 minutes).

The supernatant was then collected into a separating funnel mixed with 20 mL of 0.9% NaCl solution, shaken vigorously and allowed to stand until the biphasic system appeared. The upper aqueous phase was discarded. The lower phase was separated through anhydrous sodium sulfate into a conical flask and later to pre-weighed conical flasks (Fig 1) and the solvent removed *in vacuo*. Percentage (%) total extracted oils were calculated using equation 1. Fat content was based on proximate values reported in a previous study (Murugu et al., 2021).

$$\frac{[(\text{weight of conical flask} + \text{oil}) - (\text{the weight of the conical flask})]}{(\text{initial weight of the sample})} * 100 \quad (1)$$

Fig 1: Oils extracted from *Scapsipedus icipe* (A) and *Gryllus bimaculatus* (B)

4.2.3 Determination of Physicochemical Properties of Cricket Oil

4.2.3.1 Determination of Solidification Temperature

The solidification temperature was determined by the constant cooling rate method based on the Advancing Standards Transforming Markets (ASTM) standard test method as described earlier (Kruka et al., 1995). Edible insect oil was poured into a test tube to a half full with a mercury-bulb glass thermometer resting at the bottom of the tube. The test tube was then placed on a gasket in a temperature cooling bath. After every temperature drop of 1°C, the test tube was lifted off the gasket, inspected for clouding and quickly returned into the cooling bath. Once fat solids were observed, the temperature reading on the thermometer was recorded as the solidification temperature of the oil. The solidification temperature experiment was carried out in triplicates using different batches of insect oil samples.

4.2.3.2 Determination of Refractive Index

The refractive index was determined using a refractometer (Abbe's refractometer) as described in method 921.08 by AOAC (AOAC, 2002). The insect oil samples (1 mL) were passed through a filter paper (whatman filter paper no. 1) to remove traces of moisture and any impurities. The refractometer's prism was cleaned, dried and its

temperature adjusted to $40.0 \pm 0.1^\circ\text{C}$. Two- drops of the insect oil sample was positioned on the lower prism before firmly closing it using the screw head. The sample was allowed to stand for 2 minutes undisturbed. The refractometer and the light were then adjusted to obtain a distinct reading, which was recorded as the refractive index of that insect oil. The refractive index experiment was carried out in triplicates using different batches of insect oil samples

4.2.3.3 Determination of Specific Gravity

The specific gravity (SG) was determined using a 25 mL specific gravity bottle as described in method 920.212 by AOAC (AOAC, 2002). The empty specific gravity bottle was standardized and weighed (W_1) before it was filled with insect oil to the mark and its weight recorded (W_2). Water was also filled into the standardized specific gravity bottle and its weight recorded (W_3). Three replicates (done on different insect oil batches) were done and specific gravity of the oils calculated using equation 2.

$$SG = \frac{(W_2 - W_1)}{(W_3 - W_1)} \quad (2)$$

4.2.3.4 Determination of Peroxide, Acid, and Saponification Values

The peroxide (PV), acid (AV), and saponification values (SV) were determined using standard AOAC methods (AOAC, 2002). In the determination of PV, a portion of insect oil aliquot (2.5 g) was weighed to a glass stoppered flask before the addition of glacial acetic acid: chloroform mixture (3:2 v/v) (25 mL) and saturated potassium iodide (1 mL). The mixture was gently stirred for 1 minute before placing it in the dark for 30 minutes. Water (30 mL) was then added into the flask and shaken. Two drops of starch solution were added before titrating against sodium thiosulphate of 0.01 mol/L concentration until a colour change from blue to colourless (end point) was observed. Preparation of the blank was done concurrently, and later PV (mEq O_2/Kg) calculated using equation 3.

$$((V_S - V_B) \times N \times 1000) / W \quad (3)$$

V_S = sodium thiosulphate (mL) titrated against the oil sample.

V_B = sodium thiosulphate (mL) titrated against the blank.

N = sodium thiosulphate concentration (mol/L).

W = oil sample weight (g).

For AV, 2 g of insect oil aliquot was weighed into a conical flask (250 mL) before the addition of 50 mL of neutralized ethyl alcohol. This mixture was boiled in a water bath maintained at 80 °C for 5 minutes before its titration against 0.1 mol/L potassium hydroxide with phenolphthalein as the indicator. The AV (mg KOH) of the oil was calculated using equation 4.

$$(A \times M \times 56.1)/W \quad (4)$$

A = potassium hydroxide (mL) used.

M = KOH concentration (mol/L).

W = oil sample weight (g).

For SV, 2 g of insect oil aliquot was weighed into an Erlenmeyer flask and addition of 25 mL alcoholic potassium hydroxide (0.5 mol/L) done. The mixture was then boiled under a reflux condenser for 30 minutes, cooled, before addition of phenolphthalein indicator and titrating against hydrochloric acid (0.5 mol/L). Preparation of a blank was done concurrently under the same conditions and later SV (mg KOH/g) calculated using equation 6.

$$((V_B - V_S) \times N \times 28.05)/W \quad (6)$$

V_B = hydrochloric acid (mL) titrated against the blank.

V_S = hydrochloric acid (mL) titrated against the oil sample.

N = hydrochloric acid concentration (mol/L).

28.05 = the equivalent molecular weight of potassium hydroxide (0.5 mol/L).

W = oil sample weight (g).

4.2.4 Determination of Anti-Nutritional Phytochemical Profile

4.2.4.1 Determination of Oxalic Acid Content

Oxalic acid content was analyzed by high performance liquid chromatography (HPLC) (SDD/m20A, Shimadzu corp, Japan) according to Libert and Franceschi's method (Libert & Franceschi, 1987) with modifications by Yu and others (Yu et al., 2002). Briefly, blended insect sample (0.5 g) was mixed with hydrochloric acid (10 mL; 0.5 mol/L) and heated for 10 min at 80°C. A 25 mL solution was made by adding distilled water to the heated homogenate before a 10 min centrifugation at 10,000 rpm (25°C) effected. A whatman filter, paper no. 1, was then used to filter the supernatant before passing it through a 0.45µm syringe micro-filter. A portion of the filtered aliquot (20 µL) was injected into an octadecylsilyl reverse phase C-18 column (250 x 4.6mm) HPLC fitted with a photodiode array detector set at 210 nm. Sulphuric acid (0.01 mol/L), maintained at room temperature (25°C), was used as the mobile phase. Quantification of oxalic acid was done by extrapolation from a linear calibration curve obtained from known oxalic acid standard concentrations (10-100 ppm).

4.2.4.2 Determination of Phytic Acid Content

Phytic acid content was analyzed by HPLC based on a method described earlier by Camire and Clydesdale (A. L. Camire & Clydesdale, 1982)) with slight modification according to the method reported by Park et al 2006 (Park et al., 2006). A 5 g blended insect sample was mixed with 3% sulphuric acid and phytic acid precipitated with iron (III) chloride. Separation of the phytic acid precipitate and the supernatant was affected by centrifugation at 2,500 rpm for 10 minutes, after which the supernatant was discarded. Distilled water (30 mL) was added, centrifugation repeated, and the supernatant discarded. The iron (III) chloride-phytate complex was converted to sodium phytate by adding 3 mL of sodium hydroxide (1.5 mol/L) and sonicating to disperse the precipitate completely. Distilled water was used to adjust the volume of the mixture to 30 mL before boiling it for 30 minutes to precipitate iron (III) hydroxide.

Cooled samples were centrifuged (2,500 rpm, 10 minutes) and the quantitative transfer of the supernatant to a volumetric flask (50 mL) done. Rinsing of the precipitate with distilled water (10 mL) was done before centrifugation (2,500 rpm, 10 minutes) and addition of the resultant supernatant into the earlier 50 mL volumetric flask and made to volume. A 0.45 μ m syringe micro-filter was then used to filter the sample before injecting a portion of the aliquot (20 μ L) into an octadecylsilyl C-18 column (250 x 4.6mm) HPLC attached to a refractive index detector. The mobile phase, potassium dihydrogen phosphate (0.025 mol/L), was preset to flow at the rate of 1 mL/minute. Quantification of phytic acid was done by extrapolation from a linear calibration curve obtained from standardized sodium phytate of the concentration range from 50-1000 ppm.

4.2.4.3 Determination of Tannin Content

Tannins were analyzed using the modified vanillin-hydrochloric acid method with catechin (5 mg/ml; Sigma-Aldrich Chemie, Steinheim, Germany) being used as the standard (Price & Butler, 1977). Briefly, 250 mg of blended insect sample was mixed with 4% hydrochloric acid in methanol (10 mL). The mixture was placed on a shaker (Labortechnik KS 250b, Germany) for 20 minutes before separating it with a centrifuge (Kokusan, Type H-2000C, Japan) (25°C; 4,500 rpm) for 10 minutes. Quantitatively transfer of the supernatant into a volumetric flask (25 mL) was done before repeating the tannin extraction process on the residue using 1% hydrochloric acid in methanol (5 mL).

The second supernatant was combined with the first supernatant and diluted to 25 mL. Seven concentrations (0-100 μ g/mL) of standard catechin were also prepared. One milliliter of the extract and standard aliquot were each transferred to a test tube that contained 5 mL freshly prepared vanillin-hydrochloric acid reagent (equal volumes of 8% hydrochloric acid in methanol and vanillin in methanol). This mixture was left undisturbed for 20 minutes after which, absorbance measured in a 1-cm glass cell at 500nm on a spectrophotometer (Zeiss PMQ II). Tannin content was calculated as percent catechin equivalent from a linear calibration curve obtained from standard catechin absorbance readings.

4.2.4.4 Determination of Total Polyphenols

Total polyphenols were analyzed using a method described earlier by Waterman and Mole (Waterman & Mole, 1994) with gallic acid as a standard. A 10 g blended insect sample was mixed with 50% aqueous methanol (20 mL) at 80°C for 1 h. The solution was then filtered, and volume made to 50 mL. A portion of the solution (1 mL) was transferred to a volumetric flask (50 mL) before adding 20 mL of water, Folin Denis reagent (2.5 mL) and 17% sodium carbonate (10 mL). The mixture was then homogenized, before being topped up to 50 mL using distilled water after which it was left undisturbed for 20 minutes. Its absorbance was then measured in a 1-cm glass cell at 765 nm on a Uv-visible spectrophotometer (SP65, Gallenkamp, UK). Total polyphenols were calculated as gallic acid equivalents (GE) from a linear calibration curve obtained from gallic acid absorbance readings.

4.2.5 Data Analysis

To determine the differences physical-chemical, fatty acids and phytochemical composition of the two cricket species, unpaired t-test was used for normally distributed data with equal variances while Welch's t-test was used to analyze data that did not fulfill the two assumptions. Data was analyzed using R software version 4.0.5(R Core Team, 2021).

4.3 Results and Discussion

4.3.1 Physicochemical Properties of Cricket Oils

4.3.1.1 Physical Properties of Cricket Oils

The physicochemical properties of oils from *G. bimaculatus* and *S. icipe* are described in **Table 4.1**. The oil's solidification temperature for both cricket species ranged between 2–7°C. The solidification temperature values presented in this study were lower than reported values of oils from termites (*Macrotermes subhylanus* Rambur) and grasshoppers (*R. differens*) by Kinyuru (2020) (J. N. Kinyuru, 2020). This low solidification temperature is an indication that the oils are fluids at room temperature (Ekpo et al., 2009). *G. bimaculatus* oil presented a wider range of solidification

temperature (2-7⁰C) compared to that of *S. icipe* (2-5⁰C) indicating presence of slightly higher concentration of saturated fatty acids.

Specific gravity values of oils reported in this study were 0.88 and 0.89 for *G. bimaculatus* and *S. icipe* respectively. The specific gravity of oils from the edible insects in this study was not significantly different ($P = 0.0774$) and was comparable to values reported elsewhere (Ekpo et al., 2009) but was less dense than values reported for edible caterpillar (*I. oyemensis*) (Akposan et al., 2015), termites (*M. subhylanus*) and grasshoppers (*R. differens*) (J. N. Kinyuru, 2020) and conventional edible oils (Akpuaka & Nwankwor, 2000). In the food industry, specific gravity (SG)—the ratio of an oil's density to that of pure water at a defined temperature (typically 20°C or 25°C) (Wahyudi et al., 2018)—is a critical physicochemical parameter (Negash et al., 2019). Because edible oils are less dense than water, their specific gravity values consistently fall below 1.0, typically ranging between 0.910 and 0.930 (Wahyudi et al., 2018). Specific gravity serves as a valuable proxy for the internal molecular structure and chemical state of the oil (Noureddini & Teoh, 1992) and is used to estimate:

Level of unsaturation - SG increases with a higher degree of unsaturation, as polyunsaturated fatty acids are more polar and possess greater intermolecular forces, leading to tighter molecular packing and higher density (Wahyudi et al., 2018). Chain length - carbon chain length also influences density; longer fatty acid chains generally result in higher molecular sizes and densities, whereas shorter chains may exhibit different relative specific gravities depending on their saturation (Wahyudi et al., 2018).

Oxidation and rancidity - as oils undergo oxidation and develop rancidity, the formation of secondary metabolites—such as aldehydes, ketones, and polymers—increases the mass of the triacylglycerol matrix, causing the specific gravity to rise (Negash et al., 2019). Purity and classification - beyond identifying chemical changes, SG is a primary screening tool for oil purity. Sudden deviations from established characteristic ranges are often indicative of adulteration (Negash et al., 2019; Wahyudi et al., 2018). Additionally, these values help classify oils based on their fatty acid

profiles, distinguishing between light and heavy varieties. Therefore, oils from both *G. bimauculatus* and *S. icipe* could be considered lighter than conventional oils.

The refractive index (RI) of an edible oil is a fundamental physical constant representing the ratio of the speed of light in a vacuum to its velocity within the oil medium (Mariod, 2017). For the majority of edible triacylglycerols, RI values typically range between 1.440 and 1.480 (Wahyudi et al., 2018). This parameter serves as a critical indicator of the internal molecular architecture, specifically reflecting the degree of unsaturation and the average fatty acid chain length.

A direct, linear correlation exists between the RI and the density of double bonds within the fatty acid chains. High RI values are characteristic of polyunsaturated oils, such as soybean oil; the free electrons associated with double bonds interact more intensely with electromagnetic radiation, reducing the phase velocity of light and increasing the angle of refraction (Noureddini & Teoh, 1992). Conversely, more saturated fats, such as coconut or palm oil, exhibit lower RI values. Furthermore, RI is positively correlated with carbon chain length, facilitating the differentiation of oils with distinct molecular weights that may appear macroscopically identical (Wahyudi et al., 2018).

In food science, RI is an essential screening tool for purity and adulteration (Negash et al., 2019). By comparing measured values against established standards, analysts can identify fraudulent blending. For example, extra virgin olive oil possesses a standard RI range of 1.467–1.470; values exceeding this threshold suggest adulteration with more unsaturated, lower-cost seed oils like sunflower oil (Wahyudi et al., 2018).

Additionally, RI is utilized to monitor oxidative stability and rancidity. During storage or thermal processing (e.g., frying), oils react with oxygen to form high-molecular-weight polymers and secondary oxidation products. These denser metabolites alter the optical properties of the matrix, causing a measurable rise in RI, which serves as a proxy for oil degradation and the potential presence of free radicals (Negash et al., 2019).

To ensure consistency in quality control, the refractive index of edible oils is typically standardized at 40°C, a temperature that ensures even highly saturated fats are measured in a uniform liquid state (Mariod, 2017) . Characteristic values across common oils reflect their distinct chemical compositions: coconut oil exhibits the lowest range (1.448–1.450), signifying a profile dominated by short-chain saturated fatty acids (Wahyudi et al., 2018). Palm oil occupies a slightly higher range (1.453–1.459), representing a balance of saturated and monounsaturated fats. In contrast, olive oil (1.467–1.471) and soybean oil (1.472–1.476) show significantly higher refraction; these values correspond to their high concentrations of oleic acid and polyunsaturated linoleic acid, respectively (Noureddini & Teoh, 1992; Mariod, 2017). Recent documentation of edible insect oils (**Table 4.2**) reveals that their refractive indices align closely with these established vegetable standards, suggesting that insect-derived fats possess functional and nutritional properties comparable to traditional edible oils as further detailed in the accompanying comparative data (Mariod, 2017).

In the present study, Refractive Index values for *G. bimaculatus* and *S. icipe* were 1.46 and 1.47 respectively. The differences reported for refractive index ($P = 0.1047$) were not statistically significant. The refractive index values for oil extracted from the cricket species in this study were similar to that of oil from edible caterpillar (*Imbrasia oyemensis* Rougeot) (Akpossan et al., 2015), and was in close agreement with refractive index values for groundnut and acacia oils (Falade et al., 2007). The high refractive index confirms the presence of unsaturated fatty acids or presence of long chain fatty acids (Eromosele & Paschal, 2003).

Table 4.1: Physical and Chemical Characteristics of *Gryllus bimaculatus* and *Scapsipedus icipe* Oil

Parameter	Insect species		t value	P-value
	<i>G. bimaculatus</i>	<i>S. icipe</i>		
Solidification temperature (°C)	2 – 7	2 – 5		
Refractive index	1.46 ± 0.02 ^a	1.47 ± 0.02 ^a	-2.598	0.1047
Specific gravity	0.88 ± 0.01 ^a	0.89 ± 0.06 ^a	2.36	0.0774
Acid value (mg KOH)	1.10 ± 0.01 ^a	2.19 ± 0.36 ^b	180.2	< 0.001
Peroxide value (mEq O ₂ /Kg)	1.92 ± 0.45 ^a	2.49 ± 0.95 ^a	9	
Saponification value (mg KOH/g)	246 ± 3.02 ^a	234 ± 9.51 ^a	-22.89	0.3581

In the same row, means (±standard deviations) with the same superscript letters are not significantly different at $P \geq 0.05$.

Table 4.2: Refractive Index Values for Selected Edible Insect Oils

Insect species	Refractive Index (40°C)	Primary nutritional profile	Key reference(s)
Black Soldier Fly (<i>H. illucens</i>)	1.452 – 1.460	High Saturated: rich in Lauric acid (C12:0), similar to coconut oil.	(Srisuksai et al., 2024; Wahyudi et al., 2018)
Cricket (<i>A. domesticus</i>)	1.460 – 1.467	High PUFA: dominant in Linoleic acid (Omega-6) and Oleic acid.	(Mariod, 2017; Otero et al., 2020)
Yellow Mealworm (<i>T. molitor</i>)	1.460 – 1.466	Balanced MUFA/PUFA: high Oleic and Linoleic content; low erucic acid.	(Bogusz et al., 2026; M. H. Lee et al., 2022)
Silkworm Pupa (<i>B. mori</i>)	1.462 – 1.470	High Alpha-Linolenic: significant Omega-3 content compared to other insects.	(Hăbeanu, 2023; Tassoni et al., 2022)
Grasshopper (<i>Ruspolia differens</i>)	1.463 – 1.468	High Polyunsaturated: rich in Essential Fatty Acids (EFAs) and Vitamin E.	(Ahmed et al., 2025; J. N. Kinyuru, G. M. Kenji, et al., 2010)

4.3.1.2 Chemical Properties of Cricket Oil

The chemical characterization and identification of edible oils are established through specific physicochemical indices. Peroxide value (PV), acid value (AV), and saponification value (SV) constitute the primary parameters for evaluating the freshness, stability, and molecular architecture of lipid matrices (Mariod, 2017). These metrics provide a quantitative assessment of oxidative state, hydrolytic stability, and mean molecular weight, respectively.

The peroxide value quantifies the concentration of peroxides and hydroperoxides generated during the nascent stages of lipid oxidation, typically expressed in milliequivalents of active oxygen per kilogram of oil (mEq/kg). As an indicator of primary oxidation, PV is the standard analytical method for determining oxidative rancidity. Given that hydroperoxides are the initial products of the reaction between unsaturated fats and atmospheric oxygen, elevated PV levels signify the onset of lipid degradation. In terms of quality grading, high-purity refined oils generally exhibit a PV of < 1 mEq/kg, whereas the threshold for virgin oils may extend to 15 mEq/kg (Negash et al., 2019)). Consequently, PV serves as a predictive marker for the induction period, determining the duration an oil remains palatable before the development of volatile off-flavors.

The acid value is defined as the mass of potassium hydroxide (KOH), in milligrams, required to neutralize the free fatty acids (FFAs) present in one gram of the lipid sample. While PV monitors oxidative damage, AV serves as a proxy for hydrolytic rancidity—the degradation caused by moisture and enzymatic lipolysis. This biochemical pathway facilitates the cleavage of the ester bonds in triacylglycerols, thereby releasing FFAs.

In industrial processing, the AV determines the degree of neutralization required to refine crude oils. Furthermore, it functions as a diagnostic tool for quality; elevated AV levels frequently correlate with suboptimal storage conditions, high moisture content in the source substrate (seed or insect biomass), or chronological age. From a culinary perspective, high acidity is undesirable as it significantly reduces the smoke point of the oil.

The saponification value represents the milligrams of KOH required to saponify one gram of fat under standardized conditions. SV is fundamentally inversely proportional to the mean molecular weight of the constituent fatty acids. High SV results indicate a prevalence of short-chain fatty acids (SCFAs), whereas lower values characterize long-chain fatty acids (LCFAs). Due to these species-specific molecular fingerprints, SV is a critical parameter in the detection of lipid adulteration and the verification of oil purity.

The physiological impact of these measurements is significant, as oxidized lipids (indicated by high PV/AV) generate free radicals associated with cellular damage and systemic inflammation (Negash et al., 2019). Comparative analyses of edible insect oils against Codex Alimentarius benchmarks reveal that insect-derived lipids frequently mirror the chemical profiles of conventional plant-based oils (**Table 4.3**).

Black Soldier Fly (*Hermetia illucens*) Oil: Exhibits high SVs analogous to coconut oil, a direct consequence of its high concentration of medium-chain fatty acids, specifically lauric acid (C12:0). This molecular similarity positions BSF oil as a viable sustainable precursor for the cosmetic and oleochemical industries. Mealworm Oils: Demonstrate lower SVs, behaving similarly to soybean and olive oils. These profiles indicate a dominance of long-chain fatty acids (C18 series), providing essential fatty acid profiles typically associated with premium seed oils.

Regarding stability, while insect oils generally maintain PV levels comparable to vegetable oils (suggesting adequate oxidative stability), their acid values are consistently higher. This suggests that while insect lipids are not inherently more susceptible to oxidative rancidity, they are highly prone to enzymatic hydrolysis during extraction. This necessitates more rigorous post-harvest processing controls—such as rapid blanching—compared to traditional industrial vegetable oil production (Mariod, 2020).

In the current study, the peroxide value (PV) for oil extracted from *G. bimaculatus* and *S. icipe* were 1.92 and 2.49 mEq O₂/Kg; while saponification values (SV) were 246 and 234 mg KOH/g respectively. The differences within the chemical parameters were however not statistically significant (PV: $P = 0.3581$; SV: $P = 0.1080$). Both *S. icipe*

and *G. bimaculatus* had 2.5-19.1 and 2-14.7 times higher PV respectively than the reported values for rhinoceros beetle larvae (*O. owariensis*) (Assielou et al., 2015), termites (*M. subhylanus*) and grasshoppers (*R. differens*) (J. N. Kinyuru, 2020).

On the other hand, these cricket species had lower PV compared to commercial oils like olive oil (8 mEq O₂/Kg) and palm oil (8 mEq O₂/Kg) (Azlan et al., 2010). In addition, the PV of the cricket species in this study was below the Codex general standards for good oils (10 mEq O₂/Kg) (Codex Alimentarius, 1992). The low PV found in the cricket species in this study could be attributed to the existence of antioxidants such as α -tocopherol that have been found in earlier studies of edible insects (J. N. Kinyuru, Kenji, et al., 2010; Murugu et al., 2021).

The AV of oil from *S. icipe* was significantly higher (2.19 mg KOH) ($P < 0.001$) by 2-folds than the reported value (1.10 mg KOH) of *G. bimaculatus* oil (**Table 4.1**). The AV of *G. bimaculatus* was similar to, while *S. icipe* had 1.35 times higher AV than that reported for palm weevils (*Rhynchophorus phoenicis* Fabricius) (Tiencheu et al., 2013). Even so, both edible insects had lower AV than that reported for rhinoceros beetle larvae (*O. owariensis*) (Assielou et al., 2015) and that for codex alimentarius standard for a virgin olive oil (4.0 mgKOH) (Codex Alimentarius, 1992). The low PV and AV therefore implies that these cricket species oils are less susceptible to oxidation during processing and storage (Ekop & Akpan, 2010; Musundire et al., 2014) and thus could be utilized in food processing industries.

In summary chemical properties of lipids: saponification (SV), peroxide (PV) and acid values (AV) are often determined to indicate the mean molecular weight of the lipids, their level of unsaturation and their stability during processing and storage (Guillén & Cabo, 2002; Laroche et al., 2019). Differences in such chemical properties have been shown to be largely dependent on the fatty acid profile, which in turn is dependent on: insect species, sex, developmental stage of the insect and their diet (J. N. Kinyuru et al., 2013; Lehtovaara et al., 2017; Ooninex et al., 2015).

Table 4.3: Comparative Analysis of Chemical Indices: Vegetable vs. Insect Oils

Oil Source	Peroxide Value (mEq/kg)	Acid Value (mg KOH/g)	Saponification Value (mg KOH/g)	Primary Fatty Acid Profile
Coconut Oil	≤15.0	≤0.6	248 – 265	High Saturated (Lauric)
Black Soldier Fly	2.0 – 5.0	1.5 – 25.0	–	High Saturated (Lauric)
Palm Oil	≤10.0	≤0.6	190 – 209	Saturated / Monounsaturated
Olive Oil (Virgin)	≤20.0	≤4.0	184 – 196	High Monounsaturated (Oleic)
Cricket Oil	3.0 – 8.0	2.0 – 5.0	185 – 210	High PUFA (Linoleic)
Mealworm Oil	1.5 – 4.5	1.0 – 3.5	185 – 205	Balanced MUFA / PUFA
Soybean Oil	≤10.0	≤0.6	189 – 195	High PUFA (Linoleic)

Source: Codex Alimentarius (2021); Oonincx et al, (2015)

4.3.2 Anti-Nutritional Phytochemical Properties of Ground Cricket Powder

The results of anti-nutritional phytochemical analysis revealed that the *G. bimaculatus* and *S. icipe* contain oxalates, phytates and polyphenols (Table 4.4). Oxalates ranged between 75.1 mg/100g and 97.0 mg/100g, with no statistical difference ($P = 0.076$) between the two species. The phytate concentration differed significantly ($P = 0.012$) with *G. bimaculatus* having higher concentration by 2.7 folds than *S. icipe*.

Table 4.4: Phytochemical Composition (mg/100g) of *Gryllus bimaculatus* and *Scapsipedus icipe*.

	Insect species		t value	P-value
	<i>G. bimaculatus</i>	<i>S. icipe</i>		
Oxalates	97.01 ± 9.14 ^a	75.13 ± 5.94 ^a	-1.993	0.076
Phytates	10.33 ± 6.00 ^b	3.85 ± 0.44 ^a	-3.23	0.012
Tannins ¹	1.56 ± 1.08 ^a	Nd*	-4.342	0.003
Total polyphenols ²	48.00 ± 4.49 ^a	65.00 ± 1.79 ^b	2.797	0.021

In the same row, means (±standard deviations) with the same superscript letters are not significantly different at $P \geq 0.05$. Nd*= Not detected; ¹Catechin equivalents; ²Gallic acid equivalents

The values reported in this study for oxalates were lower, while those of phytates were higher compared to those reported elsewhere for crickets (*Henicus whellani* Chopard) (Kunatsa et al., 2020). The oxalates and phytates concentration presented for the edible

crickets studied were higher than values reported earlier for four edible insects consumed in Nigeria: crickets (*Gymnogryllus lucens* Walker), yam beetles (*Heteroligus meles* Billberg), palm weevils (*R. phoenicis*) and grasshoppers (*Zonocerus variegatus* Linnaeus) (Ekop & And Akpan, 2010). With respect to recommended permissible levels (oxalates: 250 mg/100g; phytates: 250-500 mg/100g) (Ekop & And Akpan, 2010; Musundire et al., 2014), both crickets in this study have acceptable levels of these anti-nutrients.

Tannins had the least concentration among the phytochemicals with *S. icipe* having non-detectable levels. *G. bimaculatus* had higher tannin levels compared to values reported for crickets (*G. lucens*) in the study of Ekop and others (Ekop & And Akpan, 2010). In another study, Omotoso and Adesola (O. T. Omotoso & Adesola, 2018) found 0.54-1.13mg/100g tannin level in four edible insects while Chakravorty and others (Chakravorty et al., 2016) reported 496.67-615mg/100g tannins in two edible insects in India, which was higher than values obtained in this study.

Phytochemicals such as oxalates, phytates and tannins are considered anti-nutrients as they chelate minerals like calcium and magnesium consequently making them unavailable for absorption and utilization in the body (Udousoro et al., 2018). In addition, oxalates could lead to formation of calcium oxalate complexes in kidneys hence, kidney stones (Kunatsa et al., 2020). Although tannins are considered anti-nutrients, they have been shown to have both biological and pharmacological activity such as anti-oxidative, antibacterial, antiviral, anti-inflammatory, immune-modulatory and cardio-protective (Kumari & Jain, 2012).

The concentration of the total polyphenols in *G. bimaculatus* was significantly lower ($P = 0.021$) by 0.7 factors than that of *S. icipe* (Table 4.4). The cricket species in this study had about 0.01-0.06 times lower polyphenols compared to edible insects reported elsewhere including crickets (*H. whellani* and *A. domesticus*), mealworms (*T. molitor*), superworms (*Zophobas morio* Fabricius), and palm weevils (*Rhynchophorus ferrugineus* Olivier) (Botella-Martínez et al., 2020). However, the polyphenol concentrations reported here were about 5 times higher than the value reported earlier

for termites (*M. facilger*) (Kunatsa et al., 2020). Total polyphenols are used to indicate the antioxidant capacity of a food (Viuda-martos et al., 2011).

In the study of Liu and others (S. Liu et al., 2012), polyphenols were demonstrated to inhibit lipid oxidation in black chafer beetle (*Holotrichia parallela* Motschulsky) extracts. Therefore, the presence of polyphenols in *G. bimaculatus* and *S. icipe* oils could contribute to their preservation during their application as food ingredients. For instance a Chinese study documented the potential of insects in treating diseases that have been associated with oxidative stress such as immunodeficiency, cancer and heart disease (Hou et al., 2007; Oh et al., 2003). Elsewhere, Liu and others (Liu et al., 2012) demonstrated the ability of insects as nutraceuticals in alleviating oxidative induced diseases as well as being natural antioxidant additives in the food industry.

In general, variations in the anti-nutritional phytochemical composition of edible insects is reliant on: insect species, inclusion of a starvation step prior to harvesting, the part of the insect used to obtain the extract, the methods and solvents used in phytochemical measurement (Botella-Martínez et al., 2020; Di Mattia et al., 2019; Viuda-martos et al., 2011). Moreover, ways of value addition through processing of insects are not well documented (Imathiu, 2020), although traditional cooking methods such as boiling have been shown to notably reduce anti-nutrient level in some foods hence achieving their recommended intake quantities (Palermo & Fogliano, 2014; Sangketkit et al., 2001)

4.2.3.1 Comparative Analysis of Anti-Nutritional Factors

Comparative analysis of anti-nutritional factors (ANFs) (**Table 4.5**) and the maize-cricket synergy reveals potential viability for products targeted at school meals such as maize based porridge blends. A significant finding of this research is the remarkably low concentration of anti-nutritional factors in *S. icipe* and *G. bimaculatus* compared to traditional plant-based protein sources such as legumes. While whole maize—the primary vehicle for complementary porridges—is inherently high in phytates (ranging from 600 to 1,000 mg/100g), the addition of cricket powder does not exacerbate this anti-nutritional load.

When maize is fortified with common legumes such as soybeans or kidney beans, the total phytate and tannin content of the composite flour increases substantially, as these legumes can contain phytate levels exceeding 1,000–2,000 mg/100g (**Table 4.5**). In contrast, this study found that both cricket species contain less than 10 mg/100g of phytates and tannins. The nutritional implication of this phenomenon is that substituting or supplementing soy with cricket powder allows for high protein fortification without the anti-nutritional tax, typically associated with plant-based proteins. This ensures that the mineral density of the crickets (rich in iron and zinc) is not negated by its own chemical matrix.

The impact of legume-based fortification on whole maize formulations is nutritionally significant. Whole maize contains phytates predominantly in the germ and aleurone layers, which bind to divalent cations (Ca^{2+} , Fe^{2+} , Zn^{2+}) to form insoluble complexes that the human gut cannot absorb. However, because the cricket powder is exceptionally low in anti-nutritional factors, its inclusion effectively acts as a nutritional diluent for the maize phytates. By increasing the ratio of minerals to phytates in the final porridge blend, the overall molar ratio of [Phytate]: [Mineral] is improved, moving it closer to the World Health Organization (WHO) recommended thresholds for optimal absorption (Dahdouh et al., 2019) (WHO, 2018).

The use of extrusion further optimizes this synergy. While the inherent phytates in maize are quite heat-stable, the high-temperature, high-shear environment of the extruder can cause a partial hydrolysis of phytates into lower inositol phosphates, which have a reduced affinity for minerals. When the low-ANF cricket powder is extruded with whole maize, the process not only stabilizes the cricket lipids but also reduces the maize-derived inhibitory barriers. The result is a complementary food where the iron and calcium from the crickets are significantly more bioavailable than they would be in a traditional maize-bean blend.

Unlike traditional grain-legume composites where both ingredients contribute to a cumulative anti-nutritional load, the maize-cricket matrix isolates the ANF challenge solely to the maize fraction. This makes crickets a superior fortifier for school nutrition, where mineral absorption is as critical as protein density.

Table 4.5: Comparison between Maize, Beans and Crickets Anti-Nutrient Factor Density in (mg/100g)

Fortifier Source	Phytates	Tannins	Oxalates
Whole Maize	600 – 1,000	30 – 150	~200
Soybean	1,000 – 2,200	500 – 900	200 – 300
Kidney Bean	1,500 – 2,500	800 – 2,000	400 – 600
Cricket (<i>S. icipe</i>)	3.85	nd*	75
Cricket (<i>G. bimaculatus</i>)	10	1.56	97

*nd- not detected: *Data source: Kenya Food Composition Tables, 2018*

4.2.3.2 Mineral Bioavailability in Maize-Cricket versus Maize-Soy Blends: A Theoretical Projection:

Based on the results of this study, it is possible to demonstrate mathematically how the low anti-nutrient factor profile of edible cricket species, optimizes the mineral bioavailability of the entire maize-based food system. This estimation is done by calculating the Phytate: Iron molar ratio. The World Health Organization (WHO) suggests that for iron absorption to be "good" (approx. 15%), the [Phytate]: [Iron] molar ratio should ideally be <1.0, and certainly <10.0 for basic adequacy in cereal-based diets (WHO, 2018). The molar ratio is calculated using the following formula:

Molar Ratio= (mg of Iron/MW of Iron) (mg of Phytate/MW of Phytate) Where: The Molecular Weight (MW) of Phytate is 660 g/mol and Iron is 55.8 g/mol (Dahdouh et al., 2019).

Assuming a comparative scenario of fortifying whole maize in a standard 70:30 blend (70% Maize: 30% Fortifier) whereby the fortifier is either soy bean or cricket powder. In the maize-soy blend, both ingredients contribute significant phytates. The cumulative phytate load often pushes the ratio above 20.0, severely inhibiting iron and zinc absorption unless the blend is extensively fermented or chemically treated. On the other hand, in the maize-cricket blend, since *S. icipe* and *G. bimaculatus* contribute negligible phytates (< 10 mg/100g), the only phytate source is the maize itself. Because crickets are iron-dense (approx. 10–12 mg/100g), they simultaneously increase the denominator (Iron) while keeping the numerator (Phytate) low.

This data demonstrates the dilution and synergistic effect whereby crickets act as a bioavailability enhancer. The dilution effect is achieved by adding the low ANF cricket powder to maize thus effectively diluting the total phytate concentration of the final porridge. There is also the mineral loading effect whereby the crickets deliver highly bioavailable heme and non-heme iron, lowering the overall molar ratio significantly compared to soy or beans. Additionally, when extrusion process is applied, the high-shear environment of extrusion further cleaves a portion of the maize phytates into lower inositol phosphates (*IP3*, *IP4*), which do not inhibit mineral absorption as aggressively as *IP6*.

Therefore, negligible concentrations of phytates and tannins in *S. icipe* and *G. bimaculatus*—coupled with their high mineral density—render them superior to traditional legumes for the fortification of whole maize. When processed via extrusion, the resulting matrix not only secures the lipid fraction through amylose-lipid complexation but also ensures that the inherent phytate load of the maize does not inhibit the dietary bioavailability of essential cations, thereby maximizing the nutritional efficacy of complementary porridges. The implication of this scenario and comparative impact of ANF concentration in maize/legume versus maize cricket blend is summarized in **Table 4.6**.

Table 4.6: Maize Legume Blend versus Maize Cricket Blend: Impact of Anti-Nutritional Factors Concentration

Parameter	Maize-Legume Blend	Maize-Cricket Blend
Phytate Source	Dual (Maize + Legume)	Single (Maize only)
Lipid Stability	Prone to oxidation if unrefined	High (Amylose-lipid complexes)
Bioavailability	Low (High Phytate :Iron ratio)	High (Low Phytate :Iron ratio)
Processing	Needs anti nutrient factor	
Goal	reduction	Focuses on lipid stabilization

4.4 Conclusion

In conclusion, oils from the edible cricket species and the whole cricket powder in this study have the potential for exploitation in the food industry as depicted by their

physicochemical characteristics and the anti-nutritional phytochemical composition. These are summarized in the following paragraphs.

4.4.1 Synthesis of Lipid Benchmarks and Stability Profiles

The characterization of the lipid fractions of *S. icipe* and *G. bimaculatus* successfully established the foundational physical and chemical benchmarks required for their industrial application. The refractive indices and saponification values obtained align closely with established benchmarks for premium unsaturated vegetable oils, such as soybean and olive oil. Critically, the chemical indices—specifically the Peroxide Value (PV) and Acid Value (AV)—confirm that when subjected to appropriate pre-treatment, these oils maintain oxidative and hydrolytic stability within the thresholds established by the Codex Alimentarius. These results provide food processors with the empirical data needed to predict the shelf-stability of fortified porridges, ensuring that the addition of cricket-derived ingredients does not compromise the sensory or chemical integrity of the final product.

4.4.2 Characterization of the Anti-Nutritional Phytochemical Profile

Analysis of the anti-nutritional factors (ANFs) reveals that *S. icipe* and *G. bimaculatus* possess a remarkably safe anti-nutritional phytochemical profile, alleviating concerns regarding nutrient sequestration. Both phytates and tannins were found at negligible concentrations (< 10 mg/100g), while oxalate levels remained low (≤ 97 mg/100g). These values are significantly below the inhibitory thresholds typically found in plant-based protein sources like legumes or cereals. Consequently, the anti-nutritional phytochemical barrier to digestion is minimal, suggesting that the high-protein and mineral content of these crickets is highly bioavailable. This confirms that ground cricket powder is not only a dense nutrient source but one that does not inherently interfere with the absorption of essential divalent cations like calcium and iron in maize-based formulations.

4.4.3 Comparative Assessment of *S. icipe* and *G. bimaculatus*:

Direct comparative analysis indicates that while both species offer robust nutritional profiles, they exhibit distinct physiological advantages. *S. icipe* demonstrated a slightly higher degree of lipid unsaturation (higher PV and AV values), which, although nutritionally superior, necessitates more stringent antioxidant controls. Conversely, *G. bimaculatus* exhibited a less stable anti-nutrient phytochemical profile with marginally higher oxalate concentrations. Despite these variations, both species demonstrate sufficient functional similarity to be treated as interchangeable ingredients under a unified regulatory framework, provided that processing protocols are calibrated to their specific enzymatic and phytochemical loads.

4.4.4 Impacts of Extrusion on Physicochemical Lipid States

The application of extrusion cooking for the maize-cricket flour blend would present a favorable scenario for the physicochemical state of the oils. As a high-temperature, short-time (HTST) process, extrusion effectively achieves thermal denaturation of lipase enzymes, which is critical for preventing hydrolytic rancidity and maintaining low Acid Values during storage. While the intense mechanical shear and heat can potentially initiate primary oxidation, the short residence time typically minimizes significant rises in Peroxide Values. Furthermore, extrusion facilitates the formation of amylose-lipid complexes, which can actually enhance the stability of the cricket oils by encapsulating them within the starch matrix, thereby protecting unsaturated fatty acids from atmospheric oxygen.

4.4.5 Enhanced Shelf-Life through Extrusion and Matrix Stability

The integration of *S. icipe* and *G. bimaculatus* powder into a maize matrix via extrusion is likely to result in a superior shelf-life compared to raw or traditionally blended flours. This improved stability is attributed to two synergistic factors identified in this research:

- Enzymatic deactivation: The high-temperature, short-time (HTST) nature of extrusion effectively deactivates the endogenous lipases and lipoxygenases

present in the insect biomass. By eliminating the catalysts for hydrolytic and oxidative rancidity, the Acid Value (AV) remains stable over time, preventing the development of bitter off-flavors.

- Amylose-lipid complexation: During extrusion, the cricket oils (which this study confirms are functionally similar to liquid vegetable oils) interact with the gelatinized maize starch. This forms amylose-lipid complexes, a process where the fatty acid chains are physically shielded within the helical structure of the starch molecules.

This micro-encapsulation acts as a barrier against atmospheric oxygen, significantly slowing the rate of primary oxidation (PV). Given that the Peroxide Values were already low in the raw insect matrix, this added protection suggests that maize-cricket complementary porridges can achieve the extended shelf-stability required for distribution in tropical climates without the immediate need for synthetic antioxidants.

4.4.6 Addressing the Knowledge Gap

By establishing these physicochemical constants and quantifying the negligible anti-nutritional presence, this research effectively transitions the discourse on cricket-based ingredients from speculative potential to data-driven reality. The knowledge gap regarding lipid behavior and mineral bioavailability has been addressed, providing a technical roadmap for the formulation of fortified maize porridges. Food processors now possess species-specific benchmarks for *S. icipe* and *G. bimaculatus* that ensure functional reliability, showing that these insects mirror the performance of traditional vegetable oils while offering superior mineral accessibility due to their low anti-nutritional factor profiles.

4.4.7 Final Recommendations and Future Outlook

To optimize the dietary value of these insects, extrusion is recommended as a superior processing method, as it simultaneously stabilizes the lipid fraction and further reduces the already low concentrations of oxalates and tannins. Furthermore, these findings advocate for the integration of these benchmarks into regional regulatory standards, such as those of the East African Standards (EAS) or Kenya Bureau of Standards

(KEBS). Ultimately, the dual-track characterization of lipids and phytochemicals presented here ensures that insect-based food systems are not only sustainable in theory but functionally reliable and nutritionally optimized for the most vulnerable populations.

CHAPTER FIVE

EFFECT OF EXTRUSION PROCESSING ON SENSORY PROPERTIES OF A FORMULATED MAIZE – CRICKET PORRIDGE

5.1 Introduction

Globally, the idea of edible insects as a sustainable source of food is increasingly being accepted. The food systems thinking has increased emphasis on edible insects as a sustainable solution to challenges currently disconcerting the world including the exponential rise in global population, rise in cost of animal proteins, growing concerns on environmental degradation and the growing demand for proteins (Belluco et al., 2013; van Huis et al., 2013; van Berkum et al., 2018; Guiné et al., 2021).

Edible insects are good sources of proteins, mono-unsaturated fats, poly-unsaturated fats and essential minerals such as iron and zinc as well as having high feed conversion ratios as compared to other animals (Latunde-Dada, Yang, & Vera Aviles, 2016; Payne et al., 2016c). (Fernandez-Cassi et al., 2018; Murugu et al., 2021). However, entomophagy is significantly influenced by taste, appearance, safety and quality of the edible insects (Abdullahi et al., 2021; Wilkinson et al., 2018). For instance chitin, a non-digestible fibre found in crickets, can impart a bitter taste on the sensory attributes of final products enriched with the insect powder (Sipponen et al., 2018; Tao, 2016; Wolf, 2010).

Research indicates that the limited acceptance of crickets can be mitigated by incorporating cricket powder as an ingredient into porridge, pastry, bread, and biscuits which has proved to be a successful strategy of addressing food neophobia (Adamek et al., 2018; Wilkinson et al., 2018) (Tan et al., 2016) as well as offering a food-to-food fortification strategy to address undernutrition (Chadare et al., 2019; Kruger et al., 2020; Adegboye et al., 2021). Incorporation of edible insects as an ingredient in extruded products significantly improves the sensory characteristics of the products, including aroma, texture, taste, and shelf life (Tao, 2016).

However, few studies have documented the effects of integrating crickets on the properties of conventional foods, and specifically on the acceptability of new food products in Kenya (Alemu et al., 2017). Studies recommend further research on the acceptability of cricket-enriched foods (Adegboye, 2022; Ochieng et al., 2023; Zielińska et al., 2021). Extensive literature reviews on the acceptability of cricket-enriched foods have not been conclusive as the area remains fragmented prompting the need for further investigation (Dagevos, 2021; Kauppi et al., 2019). The newly described edible cricket *S. icipe* has the potential to significantly address malnutrition, but there remains a dearth of information to show its sensory acceptability as a food ingredient.

It has been suggested that the use of modern food technologies could enhance the consumption of edible insects through provision of foods that are safe and attractive (Jacob et al., 2013). Addition of crickets to plant based foods has been recommended as a means of improving the protein and micronutrient density of the latter (WHO et al., 2010). Extrusion is a popular food processing technology when dealing with raw materials containing proteins, starch, dietary fibre, which aids in developing healthy and highly nutritious products (Chan et al., 2019; Šárka et al., 2015). For instance, the extrusion process allows the production of low fat products and further induces the formation of resistant starch (Larrea et al., 2005a).

Additionally, the high- temperature and high- pressure combinations in the extrusion process have been postulated to breakdown chitin in cricket meal thus improving the texture and flavour of the final product. As such, extrusion may significantly influence the sensory attributes of food products. Thus, this study sought to evaluate the effects of extrusion on sensory attributes of a formulated *S. icipe* cricket enriched porridge. It also sought to assess the effect of various cricket powder substitution levels on sensory attributes of the formulated *S. icipe* cricket maize porridge in order to identify the cricket powder substitution level with the most acceptable sensory attributes when extruded. The present study findings will therefore demonstrate the suitability of utilizing edible crickets in food formulations and consequently pave way for product development aimed at shielding vulnerable populations from malnutrition.

5.2 Materials and Methods

5.2.1 Materials Preparation

Exactly 3 kg of edible adult crickets, *Scapsipedus icipe* Hugel & Tanga, were collected from farms in Nyanza region in Kenya. The crickets were then transported from the farms to the International Centre of Insect Physiology and Ecology (*icipe*), Nairobi, Kenya in ice pack lined cooler boxes. The samples were then washed with chilled distilled water (4°C), blanched at 90 °C for 1 min and dried in an oven (UF 110, Memmert, Schwabach, Germany) at 50 °C for 72 h. The dried crickets were then pulverized (FPM250 grinder, Kenwood, Havant, UK) to less than 250 µm particle size to yield a fine powder. On the other hand, sifted maize flour and granulated white sugar were sourced from a local retail shop in Nairobi, Kenya.

5.2.2 Porridge Flours Formulation

Cricket powder, maize flour and sugar were optimized using mixture design analysis in Minitab Statistical Software Version 20. Ingredient optimization was done to identify the best cricket substitution levels that would achieve the target protein requirement for children aged 5-12 years as a preliminary step to identification of appropriate concentrations of cricket meal in corn-cricket blends that were used in sensory evaluation. **Table 5.1** shows 7 runs of various ingredient ratios as optimized through extreme vertices model of the mixture design. Out of the 7 runs, and considering the optimal blend predicted by the model (**figure 5.1 and figure 5.2**), three maize flour-cricket meal formulations (substituting maize flour with 10%, 15% and 20% of cricket meal) were then prepared according to the recommendations by (Maiyo et al., 2022). The formulations were each apportioned into two batches. The first batch was taken for extrusion while the other portion was temporarily stored in zipped polyethylene bags awaiting porridge preparation.

Table 5.1: Mixture Design Extreme Vertices Model Optimizing Maize-Cricket Blend Ingredients

StdOrder	Optimization Order		Ingredient Ratios				Mixture Constraints	
	RunOrder	PtType	Maize	Cricket	Sugar	Total	Lower	Upper
Blend sample 1	1	1	0.75	0.20	0.05	1	0.70	0.75
Blend sample 2	2	1	0.70	0.20	0.10		0.15	0.20
Blend sample 3	3	0	0.73	0.18	0.08		0.05	0.10
Blend sample 4	4	-1	0.74	0.17	0.09			
Blend sample 5	5	-1	0.74	0.19	0.07			
Blend sample 6	6	-1	0.72	0.19	0.09			
Blend sample 7	7	1	0.75	0.15	0.10			

Std Order = Standard order; PtType = Point type

5.2.3 Extrusion

A twin-screw extruder (DP70-III Double Screw inflating food Machine, China) with a die diameter of 26mm, barrel length of 1.56m, feed rate of 30 Hz and cutter rate of 50 Hz was used. Extrusion was done at 140 °C, screw speed was set at 250 rpm while feed moisture was set between 15-25%. Extrusion parameters were based on recommendations documented by an earlier similar study (Mahungu et al., 1999). The extrudates were ground in a hammer mill (Model CMC-20, Chiang Rai, Thailand) and screened through a sieve of 150µm aperture size.

5.2.4 Porridge Preparation

The extruded and non-extruded 10%, 15% and 20% maize flour-cricket meal formulations were used in the porridge preparation. To mitigate bias, a preliminary preference ranking test was conducted to assess the impact of cricket meal on the traditional acceptability of maize meal. This step informed the decision to exclude the control (0% cricket meal substitution or pure maize meal flour) from the main sensory evaluation study, as the established organoleptic preferences for maize flour were significantly higher. Briefly, 200g of each of the formulated flours was mixed with 300 mL of cold distilled water in a glass jar and stirred gently for 3 min using a wooden spoon. The resultant mixture was then transferred into 500 mL of boiling water in aluminium cooking pot set on a hotplate and continuously stirred for 5 min until a

consistent viscous paste (porridge) was achieved. The porridge was then cooled to 38 °C and served into sterile cups and taken to a sensory room for analysis.

5.2.5 Sensory Analysis

Forty-six panelists of diverse ages and genders were recruited for sensory evaluation after providing informed consent (**Appendix 3**) to participate in the study. The potential panelists were, both verbally and in written form, asked if they had consumed edible insects and whether they manifested any associated allergic reactions. Those with reported hypersensitivities to insect and insect products were excluded from the study.

The panelists underwent basic training to acquaint them with rating different sensory attributes. The six porridges were presented to the semi-trained panel to rate taste, texture, thickness, appearance, colour, aroma, mouthfeel, aftertaste and overall liking against a 9-point hedonic scale with 9, 8, 7, 6, 5, 4, 3, 2, 1 denoting like extremely, like very much, like moderately, like slightly, neither like or dislike, dislike slightly, dislike moderately, dislike very much and dislike extremely, respectively (**Appendix 2**). The like scores were categorized as positives while the dislike scores were analyzed as negatives. Sensory data was collected digitally using Kobo Toolbox software and subsequently exported to an Excel file for analysis.

5.2.6 Data Analysis

Data obtained from sensory evaluation of porridge was analysed using SPSS software version 26 and SAS JMP version Pro 16. Analysis of variance (2-way ANOVA) was carried out to test the study hypothesis and *post-hoc* analysis was done using Tukey's HSD (Honestly Significant Difference) method at 95% confidence level. t-test was used to compare sensory scores of porridges from formulas that were extruded and non-extruded. Data output is presented as means with standard error and frequencies in form of tables and graphs.

5.3 Results and discussion

5.3.1 Maize-cricket formulation optimization

Regression model for optimizing protein content in mixtures of cricket, maize, and sugar is presented in **Table 5.2**. The overall model was statistically significant at $P=0.034$. This indicates that the proportions of these ingredients collectively influence protein levels. However, neither individual ingredients nor their pairwise interactions were found to significantly affect protein content.

Table 5.2: Analysis of Variance for the Protein Optimization Model

Source	DF	Seq SS	Adj SS	Adj. MS	F	P
Regression	5	6.86584	6.865844	1.373169	503.50	0.034
Linear	2	6.74800	0.100531	0.050265	18.43	0.163
Quadratic	3	0.11784	0.117844	0.039281	14.40	0.191
Maize*Cricket	1	0.09188	0.049324	0.049324	18.09	0.147
Maize*Sugar	1	0.01254	0.022401	0.022401	8.21	0.214
Cricket*Sugar	1	0.01343	0.013427	0.013427	4.92	0.270
Residual Error	1	0.00273	0.002727	0.002727		
Total	6	6.86857				

$S = 0.0522$, $PRESS = 1.15194$, $R-Sq = 99.96\%$, $R-Sq(adj) = 99.76\%$, $R-Sq(pred) = 83.23\%$

Contour plots illustrating the interactive effects of cricket, maize, and sugar on protein content in mixtures are presented in **Figure 5.1**. These results indicate a negative relationship between cricket flour proportion and protein levels. Conversely, sugar proportion did not significantly influence protein content. This observation could be attributed to the low levels of protein in maize flour and the remarkably high content of protein in cricket flour, thus qualifying cricket flour as a viable ingredient in food to food fortification of the widely used maize flour in porridges. This results corroborates the findings of a similar study optimizing protein in a porridge flour mixture containing rice flour, sorghum flour and bamboo shoots (Wanjala et al., 2020), in which the protein content increased with increasing amounts of bamboo shoots.

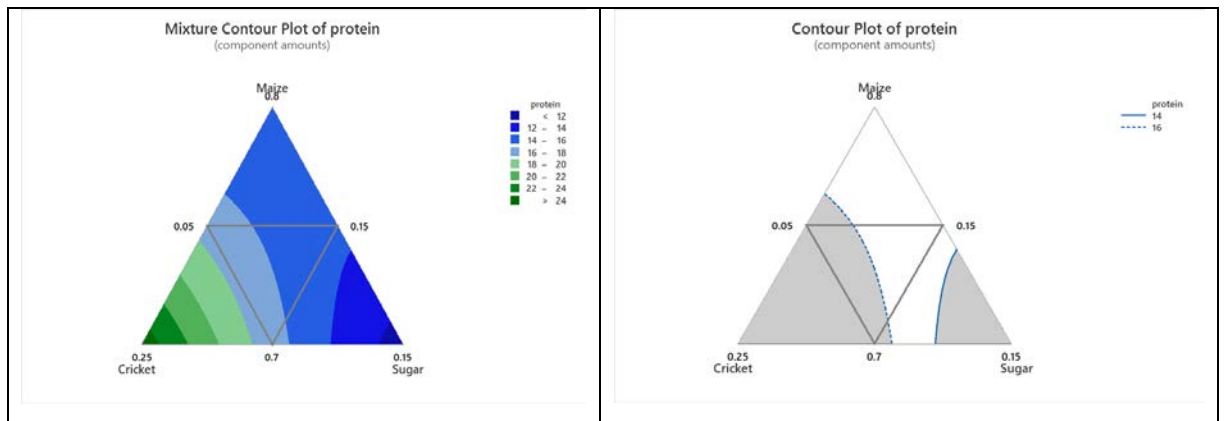


Figure 5.1: Contour Plots Showing Interactive Effects of Individual Ingredients on Protein Content

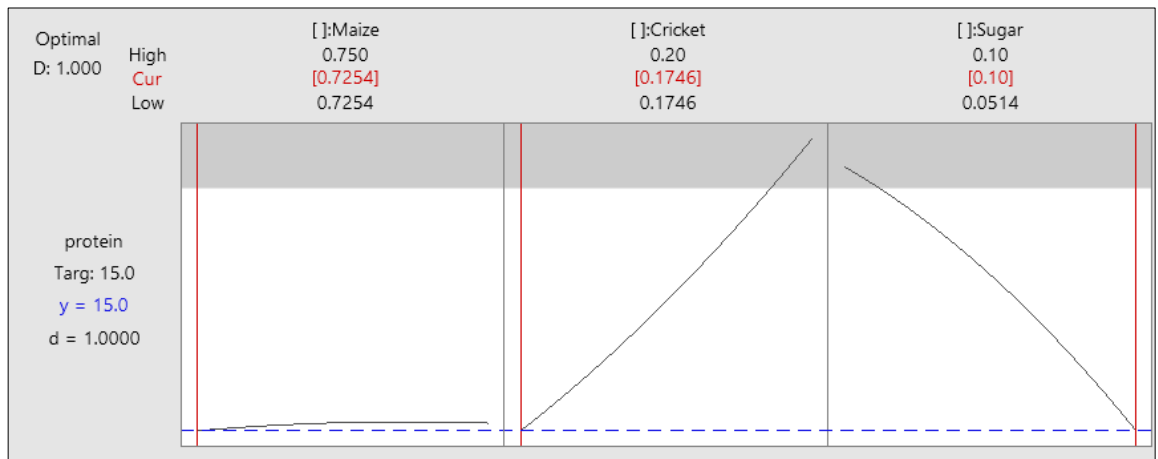


Figure 5.2: Optimization Plot Showing Optimum Mixture Composition for the Corn-Cricket Blends

Figure 5.2 presents proportions for each ingredient required in the mixture to obtain optimum protein content. It was observed that preparing a blend from combining 72.5% maize, 17.5% cricket and 0.10% sugar gives a mixture with optimum required protein content of 15%. The incorporation of cricket meal (*S. icipe*) into maize meal had a profound impact on the sensory attributes of the resulting porridge prepared with either extruded or non-extruded ingredients.

Ingredient optimization proved a remarkably useful step in determining ideal mixture concentrations for subsequent sensory analysis particularly for *S. icipe* cricket blends whose literature is very limited. The regression model for optimizing protein content in mixtures of cricket, maize, and sugar was found to be statistically significant (**Table 5.2**). This indicates that the proportions of these ingredients collectively influence protein levels. However, neither individual ingredients nor their pairwise interactions were found to significantly affect protein content.

5.3.2 Effect of Extrusion Cooking On the Rating of Sensory Attributes

The effects of extrusion cooking on the rating of the sensory attributes of the porridges are indicated in **Table 5.3**. Extrusion processing significantly ($P < 0.05$) influenced the appearance, texture, taste and mouthfeel of resultant porridges. Appearance, texture, taste and mouthfeel of porridges prepared from extruded flour ingredients were highly rated compared to non-extruded counterparts.

Overall, porridges prepared from extruded formulas were significantly preferred over non-extruded porridges in terms of visual and flavour attributes, with the exception of aroma. This enhanced preference for extruded porridges is likely attributed to the Maillard reactions and other non-enzymatic browning reactions triggered by extrusion temperature and feed moisture (Adams et al., 2019; Gbenyi et al., 2016). Additionally, extrusion is believed to impart a softer texture to the porridge (S. S. Patil et al., 2016), which may explain the higher preference for the texture of extruded cricket meal-based porridge products. This improved texture could also be a consequence of reduced chitin as a result of extrusion (Wolf, 2010).

The findings of this study suggest that extrusion processing induces physico-chemical reactions within the extruder barrel, leading to alterations in the physical properties of the products that make them more appealing to consumers reinforcing reports from previous research (Wanjala et al., 2020). Further, these findings echo another study that demonstrated that extruded cricket-enriched porridge exhibited significantly different texture and colour compared to non-extruded porridge, with panelists showing a higher preference for the former (Sanya et al., 2020).

Table 5.3: Effect of Extrusion Processing on Mean Scores of Sensory Attributes of Porridge from Maize Enriched with Cricket Meal

Processing	Appearance	Colour	Texture	Aroma	Thickness	Taste	Mouthfeel	Aftertaste	Overall
Extruded	6.10±0.16 ^a	6.08±0.15 ^a	6.70±0.16 ^a	5.25±0.17 ^a	6.10±0.17 ^a	5.91±0.17 ^a	5.91±0.15 ^a	5.42±0.17 ^a	6.09±0.16 ^a
Non-extruded	5.42±0.15 ^b	5.68±0.14 ^a	5.75±0.16 ^b	5.34±0.15 ^a	6.13±0.17 ^a	5.58±0.15 ^a	5.44±0.15 ^b	5.37±0.16 ^a	5.87±0.13 ^a
t-value	2.99	1.88	4.18	-0.38	-0.16	1.47	2.21	0.15	0.99
p-value	0.003	0.061	0.001	0.707	0.872	0.143	0.028	0.882	0.325
Difference	12.55%	7.04%	16.52%	1.71%	0.49%	5.91%	8.64%	0.93%	3.75%

Means with the same letter along the column are not significantly different at $p < 0.05$

5.3.3 Effect of Cricket Substitution on Sensory Scores of Extruded and Non-Extruded Porridges

The effects of cricket inclusion levels on the sensory scores of both the extruded and non-extruded porridges are presented in **Table 5.4**. The cricket meal substitution levels significantly ($p < 0.05$) influenced the scores of all sensory attributes except aroma for the non-extruded products and only colour and thickness for the extruded products. As a general trend, except for aroma, the scores for appearance, colour, texture thickness, taste, mouthfeel, aftertaste and overall acceptability significantly ($p < 0.05$) decreased with increasing cricket incorporation levels in the non-extruded products.

On the contrary, the extruded products featured rather unfluctuating scores for appearance, aroma, taste, mouthfeel with colour and aftertaste ratings decreasing with the cricket flour inclusion levels. Porridge formulated with 20% cricket powder-maize flour extrudate were highly rated for thickness than the non-extruded counterpart with the latter receiving low appearance, colour, texture, taste, mouthfeel, aftertaste and overall acceptability scores.

Table 5.4: The Effect of Substitution Level on the Mean Scores of Sensory Attributes of Maize Porridge Enriched with Cricket Meal

Processing	Substitution	Appearance	Colour	Texture	Aroma	Thickness	Taste	Mouthfeel	Aftertaste	Overall
Non-Extruded	10%	5.78±0.24 ^a	5.92±0.25 ^a	6.40±0.23 ^a	5.50±0.26 ^a	6.42±0.26 ^a	6.24±0.21 ^a	5.96±0.23 ^a	5.98±0.23 ^a	6.32±0.19 ^a
	15%	5.70±0.28 ^{bc}	5.85±0.25 ^a	5.64±0.31 ^b	5.32±0.24 ^a	6.04±0.31 ^a	5.70±0.24 ^a b	5.43±0.28 ^{ab}	5.66±0.26 ^a	5.98±0.22 ^a
	20%	4.73±0.27 ^b	5.24±0.23 ^b	5.13±0.29 ^b	5.18±0.26 ^a	5.89±0.32 ^b	4.73±0.28 b	4.87±0.28 ^b	4.38±0.2 ^b	5.24±0.24 ^b
Extruded	10%	6.49±0.22 ^a	6.38±0.26 ^a	7.07±0.22 ^a	5.40±0.27 ^a	6.27±0.23 ^a	6.00±0.24 ^a	6.20±0.24 ^a	5.80±0.26 ^a	6.27±0.27 ^a
	15%	5.93±0.29 ^a	6.05±0.26 ^a	5.98±0.34 ^{ab}	5.33±0.34 ^a	4.88±0.34 ^b	6.03±0.31 ^a	5.65±0.31 ^a	5.43±0.30 ^a	5.90±0.28 ^{ab}
	20%	5.80±0.30 ^a	5.76±0.26 ^{ab}	7.00±0.22 ^a	5.02±0.28 ^a	7.07±0.24 ^a	5.71±0.31 ^a	5.88±0.25 ^a	4.93±0.30 ^{ab}	6.00±0.26 ^a

Means with the same letter along the column are not significantly different at p<0.05

Increasing the substitution level of cricket flour in maize formulas from 10% to 20% resulted in a significant decrease in the liking of all sensory attributes except for texture and thickness of extruded formulas. Panelists highly preferred the appearance, colour, texture and mouthfeel of porridge prepared from an extruded formula with 10% cricket meal, while the non-extruded product with 10% cricket meal fared better in the taste, aftertaste and overall acceptability. These observations suggest that when enriching maize-based porridges with cricket meal, a substitution of 10% or less produces a resultant product that may be better liked by consumers.

The findings of this study agree with a study previously conducted in Kenya by Aboge et al. (2021) who found that participants' liking of maize porridge significantly declined with incremental level of cricket meal enrichment. Other studies have also found that foods enriched with low levels of cricket meal are more acceptable than foods enriched with high levels of cricket meal (Konyole et al., 2012; Pauter et al., 2018). The acceptability of porridge is a function of both sensory and functional attributes, which are affected by the substitution level of cricket meal in maize formulas (J. Kinyuru et al., 2021).

While extrusion processing generally enhanced the acceptability of porridge enriched with cricket flour, a higher substitution level led to a corresponding decline in preference scores due to the increasing concentration of sensory-impairing compounds in crickets. These compounds, including chitin, free amino acids, and lipids, become more pronounced with increasing substitution levels of cricket flour in maize meal, consequently negatively impacting visual and flavour sensory properties.

Chitin, a structural exoskeleton polysaccharide, interferes with the gelatinization process during porridge preparation, affecting thickness and texture. Thermal decomposition of free amino acids produces decomposition products that negatively impact taste, while lipids, through oxidized volatile compounds, negatively affect aroma. This finding is corroborated by a previous study that investigated the nutrient composition of *S. icipe*, revealing high levels of amino acids, particularly isoleucine and phenylalanine (Murugu et al., 2021). Such amino acids break down during

extrusion cooking, releasing thermal decomposition products such as toluene that likely impart a bitter taste which renders a product repugnant with their additive levels.

5.4 Conclusion

Edible cricket (*S. icipe*) flour integration into maize-based formulas for porridge preparation affected the sensory attributes of the final product. Maize-based formulas with 10% cricket, whether extruded or not, had higher sensory scores than other formulas. However, extruded formulas had significantly higher sensory scores than non-extruded formulas, except for aroma and thickness. Therefore, an extruded formula with 10% cricket is the most accepted enriched maize-based product to address the protein-energy malnutrition problem in formulation targeting school feeding programs. The study results further demonstrate the potential of extrusion processing in overcoming disgust and thus promoting entomophagy.

CHAPTER SIX

EFFECT OF EXTRUSION PROCESSING ON NUTRITIONAL AND FUNCTIONAL PROPERTIES OF A FORMULATED MAIZE – CRICKET PORRIDGE FLOUR USING EXISTING PROCESS CONDITIONS

6.1 Introduction

In recent years, food fortification and enrichment have gained significant traction, driven by increased consumer awareness regarding the nexus between nutrition and human health. Within the food industry, fortification is primarily employed to correct nutrient deficiencies—specifically protein, vitamins, and minerals—thereby enhancing both the nutritional density and the health-promoting properties of staple foods (Agrahar-Murugkar, 2020). Traditionally, cereal-based products have been nutritionally improved through the addition of legumes and oilseeds. However, emerging trends are shifting toward the incorporation of unconventional, nutrient-rich sources, such as edible insects, to address global food security challenges (Zielińska et al., 2021).

Edible insects, while nutrient-dense, possess a high moisture and nutrient content that facilitates microbial proliferation and rapid spoilage. Consequently, researchers have emphasized the necessity of thermal treatments prior to consumption to ensure microbial safety (Nyangena et al., 2020). Extrusion cooking, a high-temperature short-time (HTST) technology operating under intense shear and pressure, has emerged as a transformative solution. Beyond ensuring microbial lethality, extrusion induces the formation of resistant starches with physiological benefits similar to dietary fiber, while simultaneously enhancing protein digestibility and the bioavailability of essential minerals (Larrea et al., 2005b).

The application of extrusion to composite flours, particularly in the context of insect-enriched cereal products, significantly alters the material's functional properties. The mechanical shear and thermal energy lead to starch gelatinization and protein denaturation, which improve water absorption capacity, solubility, and pasting properties (Bravo-Núñez & Gómez, 2019). Furthermore, extrusion helps mitigate

sensory challenges associated with insect-based ingredients, such as off-flavors, thereby increasing consumer acceptability (Yi A et al., 2022). Previous studies have demonstrated that optimized extrusion parameters can yield a 40–60% improvement in the functional properties of cricket-enriched maize flour compared to conventional mixing methods (Atukuri et al., 2019; Camacho-Hernández et al., 2014; Mohammed et al., 2024) Despite these benefits, the development of a novel food system requires a systematic, phased approach.

Because no standardized extrusion profile currently exists for a maize-cricket composite, a complex interaction between new ingredients and mechanical parameters is expected. To navigate this, the present chapter adopts a preliminary investigative framework. The research strategy involves holding extrusion processing conditions constant—utilizing established parameters optimized for traditional extruded maize-based products—to serve as an experimental baseline. By maintaining these existing process conditions, the study isolates the effect of the *S. icipe* cricket-to-maize substitution ratio on the nutritional and functional characteristics of the extrudate.

The primary objective of this chapter is to screen various formulations to determine which blend yields the optimal combination of nutrient density (specifically for school-going children) and functional performance (water absorption, solubility, and viscosity). This foundational screening phase was essential for identifying the optimal formulation when subjected to extrusion processing. This specific blend was then carried forward to the next chapter. That research focused on optimizing extrusion conditions, including screw speed, barrel temperature, and feed moisture. These parameters were tailored to the unique rheology of the maize-cricket blends.

Ultimately, this study aimed to investigate the impact of extrusion and cricket substitution levels on the nutritional composition and functional properties of cricket-enriched maize porridge flour. This preliminary evaluation ensured that future process optimization was built upon a formulation that was both nutritionally viable and functionally compatible with industrial technology. Furthermore, these findings were aimed at providing a vital baseline for the utilization of other cricket species, such as

Gryllus bimaculatus and *Acheta domesticus*, in the production of enriched food products.

6.2 Materials and Methods

6.2.1 Sample Collection and Preparation

Adult crickets (*S. icipe*) were collected and transported to the International Centre of Insect Physiology and Ecology (*icipe*) as described in section 3.3.1. They were then washed with chilled distilled water (-4°C), before blanching for 1 min and drying in an oven maintained at 50°C for 72h. The dried crickets were then milled into cricket flour and passed through a 250 µm mesh sieve to yield a fine powder. Maize flour (Jogoo brand, from Unga limited) and granulated sugar were sourced from a local shop at Kasarani, Nairobi.

6.2.2 Formulation Optimization

Ingredient optimization was done using MINITAB® Statistical Software Version 20 where three formulations with three levels of maize meal substitution with cricket meal were identified. Three formulations intended to provide a final product that contributed significantly to daily protein requirements for children aged 5 to 13 years old were developed. The full rationale for choice of this target group is described in chapter 3- research methodology. A control formulation comprising only maize flour was also developed and was used for preliminary sensory preference studies as reported in the previous chapter. The composition of the four formulations is as shown in Table 6.1.

Table 6.1: Cricket Enriched Maize Flours Formulations

Substitution level	Maize flour (%)	Cricket powder (%)	Sugar (%)
0%	95	0	5
10%	85	10	5
15%	80	15	5
20%	75	20	5

6.2.3 Extrusion

Extrusion was done at Peak Value Industries Limited in Mukono Uganda. The extruder (DP70-III Double Screw inflating food Machine, China) used was a twin screw extruder with a die diameter of 26mm, barrel length of 1.56m, feed rate of 30 Hz and cutter rate of 50 Hz. Extrusion was conducted at a barrel temperature of 140°C and a screw speed of 50 rpm, with feed moisture maintained between 15% and 25%. These parameters align with established protocols for corn-based flours fortified with plant-based proteins, such as the corn-soy blends traditionally modeled by (Harper, 1981) and further refined in modern industrial applications (Riaz, 2020).

The selection of these specific conditions was necessitated by the current paucity of data regarding optimized extrusion processing for maize-cricket blends, particularly concerning the unique rheological behavior of insect chitin and lipids (Gadzama, 2025). Consequently, these existing parameters served as a baseline proxy—supported by successful cereal-legume moisture ranges documented by (Danbaba et al., 2019) and (Joseph et al., 2025)—to develop formulations for initial sensory evaluation. This preliminary phase was essential to establish an acceptable product profile, providing a foundational benchmark for the subsequent chapter, which details the systematic optimization of a dedicated maize-cricket extrusion process using the theoretical frameworks suggested by (Moscicki, 2011).

6.2.4 Proximate Analysis

Proximate components were determined using Association of Official Analytical Chemists (AOAC) methods. Moisture content was determined by oven drying method at 105°C for 2 h (Method No. 930.15) (AOAC, 2009) and converted to dry matter (DM) using the equation: % Dry matter (DM) = 100% – Moisture content (%). Ash content was determined by ignition of samples at 550°C in a muffle furnace (Method No. 930.05) (AOAC, 2009). The crude fat content was determined by diethyl ether extraction in a fat extraction unit (SER 148/6; Velp Scientific, Usmate, Italy) following the Randall technique (Method No. 2003.05) (AOAC, 2009). Crude protein was determined following the Kjeldahl method and values multiplied by a conversion factor of 6.25 (Method No. 2001.11) (AOAC, 2009). Crude fibre was determined by

loss of ignition on weight of residue after hydrolysis with acid and alkali solutions (Method number 978.10) (AOAC, 2005b).

6.2.5 Functional Properties Analysis

Water absorption index (WAI), water solubility index (WSI), bulk density (BD) and water holding capacity (WHC) were determined as described by (Igual et al., 2020a). The pasting properties of the two porridge flours were studied using a Rapid Visco-Analyser (RVA 4500) (Newport Scientific Pty. Ltd. Warriewood, Australia) with the aid of a thermocline for windows version 3.0 (1998). The RVA was connected to a computer where the pasting properties and curves were recorded directly. Test runs were conducted following a standard profile cycle as described elsewhere (Sayanjali et al., 2017). Both extruded and non-extruded samples were prepared and runs conducted using the RVA to determine pasting properties of both types of samples. Pasting properties are described in terms of 7 parameters namely: Peak 1 Viscosity, Peak 1 Temperature, Trough Viscosity, T, Trough Temperature, Peak 2 Viscosity, Peak 2 Temperature, and Final Viscosity.

6.2.6 Data Analysis

Data obtained from laboratory analysis of porridge flour was analysed using MINITAB® Statistical Software Version 20. T-test was used to compare effect of processing on functional and nutritional properties of formulas that were extruded and non-extruded at 95% confidence level. Pearson's correlation was done to establish the strength of relationship among functional properties and grouping them in clusters based on the strength. Output is presented as means with standard error in form of tables and graph.

6.3 Results and Discussion

6.3.1 Effect of Extrusion on Nutritional Properties of *S. icipe* Enriched Maize Porridge Flour

The overall effect of extrusion processing on proximate composition of *S. icipe* enriched maize porridge flour is shown in **Table 6.2**. Extrusion processing

significantly affected fiber, fat and protein digestibility of *S. icipe* enriched maize porridge flour. The extrusion process significantly reduced fiber from 3.28% in non-extruded formulas to 0.95%, reduced fat from 2.46% to 0.81% and significantly increased protein digestibility (PD) from 43.78% to 54.50%. However, although not significant, extrusion also increased protein from 14.93% in non-extruded formulas to 16.52%, total carbohydrates (CHO) from 69.80% to 72.50% while total minerals reduced from 0.71% to 0.59%.

Table 6.2: Overall Effect of Extrusion Processing on Proximate Composition and Protein Digestibility of *S. icipe* Enriched Maize Porridge Flour

Parameter	DM	Ash	Fiber	Fat	Protein	CHO	PD
Non-extruded	91.17±0.30 ^a	0.71±0.09 ^a	3.28±0.52 ^a	2.46±0.42 ^a	14.93±1.28 ^a	69.80±2.16 ^a	43.78±2.34 ^b
Extruded	91.38±0.35 ^a	0.59±0.08 ^a	0.95±0.14 ^b	0.81±0.10 ^b	16.52±0.30 ^b	72.50±0.64 ^a	54.50±1.71 ^a
t-value	-0.45	-1.07	-4.31	-3.78	1.21	1.21	3.70
p-value	0.657	0.295	<0.0003	<0.0010	<0.240	<0.246	0.0012

Means with the same letter along the column are not significantly different. DM=Dry Matter, CHO=Carbohydrate, PD=Protein Digestibility.

6.3.1.1 Impact of Extrusion on Nutritional and Protein Digestibility Profiles

The data provided compares the nutritional profile and protein digestibility of a maize-cricket formulation before and after extrusion processing using existing process conditions. The results indicate that applying existing extrusion process conditions to the maize-cricket formulation significantly enhances the nutritional quality of the flour, particularly in areas critical for child development.

6.3.1.1 Enhancement of Protein Digestibility

The most significant finding for the target demographic—school-going children—is the increase in protein digestibility from 43.78±2.34% to 54.50±1.71% ($p=0.0012$). The high-temperature and mechanical shear of extrusion likely induced the denaturation of cricket and maize proteins, unfolding their tertiary structures and making peptide bonds more accessible to digestive enzymes. For children suffering from or at risk of Protein-Energy Malnutrition (PEM), the total protein content is less important than the bioavailable protein. This 10.7% increase suggests that the extruded

porridge provides more usable essential amino acids per gram consumed compared to the raw blend.

6.3.1.2 Reduction of Crude Fiber and Fat

Extrusion resulted in a significant reduction in both fiber (3.28% to 0.95%; $p < 0.0003$) and fat (2.46% to 0.81%; $p < 0.0010$). Regarding fiber breakdown, the intense shearing forces likely broke down insoluble fiber (cellulose and hemicellulose) into smaller, potentially soluble fragments. While fiber is generally healthy, high-fiber diets in young children can lead to early satiety and bulky stools, which may hinder the total caloric intake required for growth. A moderate reduction here may actually improve the energy density and intake volume of the porridge. Regarding lipid stability, the reduction in fat is often attributed to the formation of amylose-lipid complexes during extrusion or mechanical oil loss. This is a positive outcome for shelf-stability, as it minimizes the risk of lipid oxidation (rancidity), ensuring the porridge remains palatable and safe for longer periods in school feeding programs.

6.3.1.3 Preservation of Core Macronutrients

The stability of dry matter, ash (minerals), and total Protein ($p > 0.05$) demonstrates that the high temperature short time (HTST) nature of the process is gentle enough to preserve the foundational nutrients of the cricket-enriched flour. As such, the slight numerical increase in carbohydrates (CHO) (69.80% to 72.50%) is likely a relative increase due to the significant loss of the fat and fiber fractions. Additionally, the preservation of ash is particularly encouraging, as it suggests that the essential minerals provided by the cricket powder (such as Iron and Zinc) are not lost during the high-pressure processing.

6.3.2 Effect of Extrusion Processing and *S. icipe* Substitution Levels in Maize Porridge Flour on Proximate Composition

The effect of extrusion processing and *S. icipe* substitution levels in maize porridge flour on proximate composition is indicated in **Table 6.3**. The word substitution is used in this chapter to mean the act of replacing maize flour in a formulation of 100%

maize flour with cricket powder in proportions of 10%, 15% and 20%. Ash content did not significantly change on extrusion across each substitution level, however, extruded formulas recorded lower values as compared to the non-extruded flours. Fiber content significantly reduced at 15% and 20% substitution levels only from 2.76% to 0.94% and 6.10% to 1.53% respectively but the reduction was not significant at levels below 15%. Also, significant reduction in crude fat between extruded and non-extruded was noted through all the substitution levels except at zero per cent level. Protein content significantly increased at 0% and 10% substitution levels, remained constant at 15% and significantly reduced at 20%. Total carbohydrates and protein digestibility content recorded a significant increase at each level of *S. icipe* substitution.

Table 6.3: Effect of Extrusion Processing and *S. icipe* Substitution Levels in Maize Porridge Flour on Proximate Composition

Level	Parameter	DM	Ash	Fiber	Fat	Protein	CHO	PD
0%	Raw	90.00±0.50 ^b	0.25±0.02 ^a	1.62±0.39 ^a	0.53±0.06 ^a	8.84±0.18 ^b	78.75±0.59 ^a	32.02±1.88 ^b
	Extruded	92.96±0.14 ^a	0.23±0.01 ^a	0.30±0.02 ^a	0.41±0.02 ^a	16.60±0.28 ^a	75.42±0.28 ^b	45.76±1.65 ^a
	t-value	13.77	-2.95	-0.43	-2.84	9.84	101.30	16.14
	p-value	0.0052	0.098	0.711	0.105	0.012	<0.0001	0.004
10%	Raw	92.31±0.51 ^a	0.90±0.05 ^a	2.63±0.32 ^a	1.96±0.12 ^a	13.85±0.00 ^b	72.97±0.70 ^b	49.47±0.00 ^b
	Extruded	90.71±0.49 ^a	0.59±0.08 ^a	1.02±0.12 ^a	0.64±0.08 ^b	15.13±0.17 ^a	73.33±0.61 ^a	59.72±1.41 ^a
	t-value	5.76	-1.97	1.28	8.20	20.52	78.75	82.22
	p-value	0.289	0.187	0.328	0.015	0.002	0.0002	0.0001
15%	Raw	91.12±0.36 ^a	0.77±0.04 ^a	2.76±0.18 ^a	2.99±0.11 ^a	16.55±0.10 ^a	68.04±0.64 ^b	48.93±4.14 ^b
	Extruded	90.32±0.15 ^a	0.65±0.03 ^a	0.94±0.03 ^b	0.86±0.04 ^b	16.86±0.24 ^a	71.01±0.37 ^a	54.24±0.37 ^a
	t-value	10.50	-2.25	28.07	24.43	22.27	83.12	10.65
	p-value	0.809	0.154	0.001	0.002	0.200	0.0001	0.009
20%	Raw	91.26±0.14 ^a	0.91±0.14 ^a	6.10±0.21 ^a	4.35±0.10 ^a	20.46±0.55 ^a	59.44±0.80 ^b	44.70±0.82 ^b
	Extruded	91.54±0.60 ^a	0.88±0.09 ^a	1.53±0.12 ^b	1.31±0.05 ^b	17.47±0.56 ^b	70.35±0.56 ^a	58.29±0.32 ^a
	t-value	10.36	-1.53	6.12	25.30	47.75	52.19	49.56
	p-value	0.092	0.266	0.026	0.002	0.0004	0.0004	0.0004

Means with the same letter along the column are not significantly different. DM=Dry Matter, CHO=Carbohydrate, PD=Protein Digestibility.

6.3.2.1 Impact of Extrusion and Substitution Levels on Proximate Composition

The data compares the effects of extrusion across four cricket substitution levels (0%, 10%, 15%, and 20%) on the nutritional and functional profile of the cricket enriched maize flour.

6.3.2.1.1 Synergistic Effect of Substitution and Processing on Protein

The substitution of maize with cricket powder significantly elevates the baseline protein content of the flour. More importantly, the extrusion process acts as a

nutritional unlock by significantly increasing protein digestibility (PD) across all formulations. For school-going children, this means that the higher protein density provided by the 15% and 20% substitution levels is made more bioavailable through the thermal and mechanical denaturation of proteins during extrusion.

6.3.2.1.2 Impact on Lipids and Fiber for Digestibility

A consistent trend across all levels was the sharp reduction in fat and fiber following extrusion. The significant reduction ($p = 0.002$) is likely due to the formation of starch-lipid complexes or mechanical loss during high-shear processing. While this lowers total energy from fats, it greatly enhances the shelf-life of the porridge by reducing the risk of rancidity. The reduction in crude fiber—most notably at the 20% level where it dropped from 6.10 % to 1.53 %—is beneficial for young children. High fiber can cause early satiety and hinder the absorption of other nutrients; thus, this reduction improves the overall nutrient density and digestibility of the porridge.

6.3.2.1.3 Carbohydrate and Mineral Stability

The ash content, representing essential minerals, showed no significant degradation during extrusion ($p > 0.05$), indicating that the process is efficient at preserving the mineral boost provided by the crickets. Carbohydrates (CHO) showed relative increases post-extrusion at higher substitution levels, likely due to the proportional loss of fiber and fats.

6.3.2.1.4 Most Nutritionally Balanced Product

Based on a synthesis of the proximate composition and protein digestibility data, the 10% cricket substitution level emerges as the most nutritionally balanced formulation when combined with the extrusion effect. While higher substitution levels provide more total protein, the 10% level offers the best equilibrium between nutrient density, biological usability, and stability. The rationale for the 10% substitution level emerging the most nutritionally balanced formulation is explained below:

- Peak protein digestibility: After extrusion, the 10% level achieved the highest protein digestibility score of 59.72%. This is a critical metric for school-going

children, as it ensures that a higher percentage of the ingested protein is actually absorbed and utilized by the body.

- **Optimal protein increase:** This level effectively increased the raw protein content from 8.84% (control) to 13.85%. Following extrusion, the protein remained stable and highly bioavailable, meeting the increased nutritional demands of growing children without drastically altering the traditional maize base.
- **Balanced fiber content:** At the 10% level, the extruded fiber content was reduced to 1.02%. This is ideal for child nutrition; it is low enough to prevent early satiety (allowing the child to eat a full serving) while maintaining a baseline for digestive health.
- **Lipid stability:** The fat content at this level was reduced from 1.96% to 0.64% during extrusion. This significant reduction minimizes the risk of the porridge going rancid, which is essential for the safety and palatability of products used in school feeding programs.

6.3.3 Effect of Extrusion on Functional Properties of Maize Porridge Flour Enriched with Crickets

The overall effect of extrusion processing on physical properties of maize porridge flour enriched with cricket is shown in **Table 6.4**. It was found that extrusion processing significantly increased the water absorption index (WAI), water solubility index (WSI) and water holding capacity (WHC) by 112.2, 333.33 and 220.39% respectively, but also significantly reduced the bulk density (BD) of the maize porridge flour enriched with cricket by 10.21%.

The extrusion process significantly altered the functional properties of the maize-cricket composite flour across all measured parameters. Extrusion processing increased the water absorption index and water solubility index of the blends by two and four times respectively when compared to their corresponding non-extruded blends unlike bulk density which was greatly reduced as shown in Table 6.4.

This observation on increase in hydration properties can be attributed to the thermochemical reactions such as gelatinization, texturization and Maillard among others that take place during extrusion hence increasing hydrophilicity capacity of flour components (Filli et al., 2013; S. Patil et al., 2021). Reactions such as texturization that occur during extrusion results in reduction of bulk density could be as a result of increased porosity of the extruded flour that reduces the mass per unit volume (Pasqualone et al., 2021; Webb et al., 2020).

Table 6.4: Overall Effect of Extrusion Processing on Functional Properties of Maize-Cricket Flour

Parameter	WAI	WSI	BD (g/ml)	WHC (ml/g)
Raw	2.53±0.02 ^b	0.03±0.00 ^b	1.47±0.01 ^a	1.03±0.07 ^b
Extruded	5.37±0.19 ^a	0.13±0.03 ^a	1.32±0.02 ^b	3.30±0.24 ^a
t-value	15.11	3.34	-7.46	9.00
p-value	<0.001	0.003	<0.001	<0.001
Difference (%)	112.25	333.33	-10.21	220.39

Key: WAI= Water Absorption Index; WSI= Water Solubility Index; BD= Bulk Density; WHC= Water Holding Capacity. Means with the same letter along the column are not significantly different

6.3.3.1 Hydration Properties (WAI, WHC, and WSI)

The most dramatic shifts occurred in the flour's interaction with water. The Water Absorption Index (WAI) increased by 112.25% ($P < 0.001$), while Water Holding Capacity (WHC) surged by 220.39% ($P < 0.001$). These increases are primarily attributed to the intense mechanical shear and thermal energy during extrusion, which cause starch gelatinization and the unfolding of cricket proteins. These structural changes expose more hydrophilic sites, allowing the flour to bind and retain significantly more water.

Higher WAI and WHC indicate that the extruded flour will yield a thicker, more cohesive porridge with less flour required, which is critical for the consistency of complementary foods for children. On the other hand, The Water Solubility Index (WSI) increased by 333.33% ($p = 0.003$). This reflects the degradation of starch granules and protein molecules into smaller, more soluble fragments. A higher WSI is often associated with improved digestibility and a smoother mouthfeel in porridges.

6.3.3.2 Bulk Density (BD) and Energy Density

There was a significant reduction in Bulk Density from 1.47 to 1.32 g/ml (-10.21%; $p < 0.001$). In extrusion cooking, a decrease in BD is usually a result of the expansion (puffing) of the melt as it exits the die, creating a more porous structure. For school-going children, a lower bulk density is advantageous as it allows for the preparation of a nutrient-dense porridge that is not overly "heavy" or "bulky," supporting higher caloric intake in smaller volumes.

6.3.3.3 Summary of Key Effects of Extrusion on Functional Properties

- Enhanced Hydration: Extrusion more than doubled the water absorption capacity (+112 %) and tripled the water holding capacity (+220 %), ensuring superior thickening power.
- Significant solubility gains: The 333 % increase in WSI suggests substantial starch breakdown, which typically translates to easier preparation and better consumer palatability.
- Improved energy density: The 10 % reduction in bulk density indicates a lighter, expanded product that can be reconstituted into a nutrient-dense, easily consumable porridge.

6.3.4 Effect of Extrusion Processing and Substitution Level on Functional Properties of Maize-Cricket Flour at Different Substitution Levels

Effect of extrusion processing and substitution level of cricket in maize flour on physical properties is shown in **Table 6.5**. The physical characteristics (Water Absorption Index, Water Solubility Index, Bulk Density, and Water Holding Capacity) were significantly impacted by both the processing method and the level of cricket powder inclusion.

It was found that extrusion processing significantly affected the functional properties of the maize porridge flour at all levels of cricket substitution. WAI, WSI and WHC significantly increased on extrusion as substitution levels of cricket in maize flour increased from 0% to 20% but BD significantly decreased. Maize flour with 0% cricket

level had the highest increase of WSI and WHC at 2800 and 353% respectively and highest decrease in BD at 15.07% on extrusion processing as compared with other substitutional levels. It was observed that for raw blends (non-extruded) WAI and WHC increased on addition of cricket up to 10% then started decreasing, WSI increased with increase in substitution while BD initially decreased but increased after 10% substitution level.

Besides extrusion, level of cricket substitution in the maize flour had a significant effect on functional properties as indicated in **Table 6.3**. Among the non-extruded blends, increasing substitution level of cricket caused increase in WSI, reduced BD initially but increased later and also increased WAI and WHC increased initially but increased later. On the contrary, upon extrusion WHC decreased with increase in substitution level, WAI, BD increased initially but decreased afterwards, WAI initially increased and started decreasing. This could be attributed to the changing composition of the blends which affects the hydrophobic-hydrophilic sites as well as porosity.

Table 6.5: Effect of Extrusion on Physical Properties of Maize-Cricket Flour at Different Substitution Levels

Sub. Level	Parameter	WAI	WSI	BD (g/ml)	WHC (ml/g)
0%	Raw	2.41±0.03 ^b	0.01±0.00 ^b	1.46±0.01 ^a	1.00±0.12 ^b
	Extruded	4.83±0.16 ^a	0.29±0.02 ^a	1.24±0.01 ^b	4.53±0.18 ^a
	t-value	30.29	19.00	124.00	25.70
	p-value	0.001	0.003	<0.0001	0.0015
	Difference (%)	100.41	2800.00	-15.07	353.00
10%	Raw	2.59±0.02 ^b	0.03±0.00 ^b	1.43±0.00 ^a	1.26±0.18 ^b
	Extruded	6.36±0.05 ^a	0.06±0.00 ^a	1.36±0.01 ^b	3.33±0.07 ^a
	t-value	117.25	83.50	107.66	50.45
	p-value	<0.001	0.001	<0.001	0.0004
	Difference (%)	145.56	100.00	-4.90	164.29
15%	Raw	2.57±0.02 ^b	0.04±0.00 ^b	1.50±0.01 ^a	1.07±0.07 ^b
	Extruded	5.08±0.08 ^a	0.09±0.01 ^a	1.38±0.01 ^b	2.80±0.12 ^a
	t-value	64.51	15.02	108.66	24.27
	p-value	0.002	0.004	<0.001	0.002
	Difference (%)	97.67	125.00	-8.00	161.68
20%	Raw	2.56±0.04 ^b	0.04±0.00 ^b	1.49±0.01 ^a	0.80±0.00 ^b
	Extruded	5.20±0.19 ^a	0.08±0.00 ^a	1.30±0.01 ^b	2.53±0.24 ^a
	t-value	26.83	33.14	115.12	10.57
	p-value	0.001	0.001	<0.001	0.009
	Difference (%)	103.13	100.00	-12.75	216.25

Key: WAI= Water Absorption Index; WSI= Water Solubility Index; BD= Bulk Density; WHC= Water Holding Capacity. Means with the same letter along the column are not significantly different.

6.3.4.1 Impacts of Extrusion and Substitution Levels on Functional Properties

6.3.4.1.1 Interaction between Substitution Levels and Hydration (WAI & WHC)

The Water Absorption Index (WAI) and Water Holding Capacity (WHC) increased significantly across all substitution levels following extrusion. Interestingly, the 10% substitution level showed the highest post-extrusion WAI at 6.36 pm 0.05 g/g, representing a 145.56% increase from its raw state. The presence of cricket protein at moderate levels (10%) likely interacts synergistically with gelatinized maize starch to create a matrix capable of trapping more water. At 20% substitution, while WHC remained high (2.53 pm 0.24 g/g), the percentage increase was lower than the 0% control, suggesting that very high insect protein concentrations might interfere with the starch's ability to fully expand and bind water.

6.3.4.1.2. Solubility and Bulk Density Trends

The Water Solubility Index (WSI) saw its most radical transformation at the 0% level (2800 % increase), though it remained consistently higher in all extruded samples compared to raw. This indicates that while crickets add nutrition, the maize starch fraction is the primary driver of solubility changes during extrusion.

Bulk Density (BD) decreased across all levels, with the most significant drop at the 0% substitution level (-15.07%) and the 20% level (-12.75 %). The decrease in BD is a positive indicator of puffing or expansion, which reduces the flour's weight-to-volume ratio, making the final porridge less heavy for children while maintaining nutrient density.

6.3.4.1.3 Summary of Key Impacts of Extrusion and Substitutional Levels on Functional Properties

The key highlights on the effect of extrusion and substitutional levels on functional properties of maize cricket porridge flour are summarized below.

- Optimal hydration at 10%: The 10% substitution level yielded the most functional flour in terms of water absorption (6.36 g/g), which translates to better thickening efficiency.
- Significant physical transformation: Extrusion increased the WHC of the 0% control by 353% and the 20% blend by 216%, proving that even with high insect inclusion, the process remains effective at modifying texture.
- Consistency in expansion: All formulations exhibited a decrease in bulk density (4.90 % to 15.07 % reduction), ensuring the product remains suitable for easy reconstitution into porridge.
- Solubility Improvement: Even at the highest substitution (20%), solubility doubled (100 % increase) from 0.04 to 0.08 g/g, which aids in a smoother mouthfeel.

6.3.5 Effect of Extrusion on Pasting Properties of Maize Porridge Flour Enriched with Crickets

Effect of extrusion processing on pasting properties of maize porridge flour enriched with cricket is shown in **Table 6.6**. It was found that extrusion processing of maize porridge flour enriched with cricket significantly reduced all pasting properties except peak 2 temperature. The highest significant reduction was observed in final viscosity, peak 2 viscosity, peak 1 viscosity and trough viscosity at 95.19, 95.22, 89.18 and 89.05%, respectively. While the lowest significant reduction was observed in peak 1 temperature and trough temperature at 34.67 and 11.12% respectively. Extrusion processing only increased peak 2 temperature of maize flour substituted by cricket by 0.16%.

It was found that extrusion processing significantly reduced all pasting properties of maize porridge flour at all levels of cricket substitution except for peak 2 temperature. It was observed that for raw (non-extruded) formulas, increasing cricket substitution levels caused decrease in peak 2 viscosity and final viscosity but trough temperature increased but remained stagnant at 95.00. But for peak 1 viscosity, peak 1 temperature and trough viscosity increased initially but started to decrease with increase with substitution levels of cricket increased after 10%. On the other hand, it was observed

that for extruded formulas, peak 1 viscosity, peak 2 viscosity, trough viscosity and final viscosity increased initially but started to decrease with increase with substitution levels of cricket increased after 10%. On the contrary, peak 1 temperature initially decreased but started to increase with increase with substitution levels of cricket increased after 10%.

Table 6.6: Overall Effect of Extrusion Processing on Pasting Properties of Maize-Cricket Flour

Parameter	P1Visc	P1Temp	T_Visc	T_Temp	P2Visc	P2Temp	F_Visc.
Raw	2952.7±9.75 ^a	94.81±0.02 ^a	1406.58±7.98 ^a	94.99±0.01 ^a	8847.92±2.23 ^a	24.76±0.17 ^a	8760.75±8.57 ^a
Extruded	319.58±9.90 ^b	61.94±9.97 ^b	154.08±5.40 ^b	84.43±1.40 ^b	424.58±3.06 ^b	24.80±0.17 ^a	421.33±3.20 ^b
t-value	-18.43	-3.30	-20.88	-7.54	-27.71	0.19	-26.04
p-value	<0.001	0.003	<0.001	<0.001	<0.001	0.851	<0.001
Diff. (%)	-89.18	-34.67	-89.05	-11.12	-95.22	0.16	-95.19

Key: P1Visc= Peak 1 Viscosity; P1Temp= Peak 1 Temperature; T_Visc= Trough Viscosity; T_Temp= Trough Temperature; P2Visc= Peak 2 Viscosity; P2Temp= Peak 2 Temperature; F_Visc= Final Viscosity; Diff.= Difference. Means with the same letter along the column are not significantly different.

6.3.5.1 Transformation of Pasting Properties of Maize –Cricket Blend under Extrusion

Pasting properties describe the behavior of starch-based flours when subjected to heating and cooling in water. In this study, extrusion caused a categorical collapse of traditional pasting parameters. Peak viscosity (P1Visc) decreased by 89.18% (from 2952.7 to 319.58), indicating that the starch granules were pre-gelatinized and physically ruptured during processing. Final Viscosity (FVisc.) decreased by 95.19%, showing that the extruded flour does not set into a thick, hard gel upon cooling.

The significant transformation in pasting properties increase suitability of the extruded porridge for children. Raw maize porridge is often bulky and to make it drinkable for a child, it must be diluted with water, which thins out the nutrients. Because the extruded flour has such low viscosity, a much higher concentration of flour (and thus more protein and minerals) can be packed into a single cup of drinkable porridge. A 95% reduction in final viscosity allows for the preparation of high-energy-density porridges that remain fluid.

6.3.5.1.1 Significance of Peak 2 Temperature

In the analysis of pasting properties, Peak 2 Temperature (P2Temp) represents the temperature at which the second viscosity peak occurs during the cooling phase of the Rapid Visco Analyzer (RVA) cycle. The results indicate that while extrusion caused radical shifts in nearly every other functional and nutritional parameter, the P2Temp remained statistically unchanged. Specifically, the temperature recorded was $24.76 \pm 0.17^\circ\text{C}$ for raw samples and $24.80 \pm 0.17^\circ\text{C}$ for extruded samples ($p=0.851$).

The stability of P2 Temperature has remarkable significance. Firstly, it speaks to thermostability of the protein-starch matrix. The stability of P2Temp suggests that the molecular reorganization required to reach maximum setback viscosity during cooling is independent of the initial extrusion treatment. Secondly, it indicates that there exists a constant retrogradation trigger. In starch-based systems, P2Temp often aligns with the point where amylose chains begin to re-associate (retrogradation) as the paste cools. The lack of change indicates that the trigger temperature for this structural

setting remains a constant property of the maize-cricket composite, regardless of the high-shear processing.

Thirdly, a stable P2 temperature is a positive indication for product consistency. For the production of porridge for school-going children, this stability is beneficial. It ensures that the temperature at which the porridge reaches its final set or thickness is predictable, allowing for standardized preparation instructions across both raw and processed flours. Finally, stability of P2 temperature indicates unaltered cooling rheology. While extrusion drastically reduced the magnitude of viscosity (P2Visc dropped by over 95%), the timing of the cooling transition remained fixed. This implies that the presence of cricket proteins did not shift the fundamental thermal transition points of the maize starch during the cooling phase.

Therefore, the non-significant difference ($p=0.851$) in P2Temp confirms that while extrusion is transformative for digestibility and peak viscosity, it does not alter the fundamental thermal threshold at which the maize-cricket matrix begins its final structural stabilization during cooling.

6.3.5.1.2 Impact of Peak Viscosities on Product Qualities

The transformation of the pasting profile—from Peak 1 Viscosity (*P1V*) to Peak 2 Viscosity (*P2V*) and Final Viscosity (*FV*)—provides a comprehensive look at how extrusion re-engineered the maize-cricket matrix. In this study, every viscosity marker experienced a categorical collapse of approximately 89% to 95%.

In peak 1 viscosity (*P1V*) or the heating phase, raw flour exhibited a high *P1V* of 2952.7 ± 9.75 cP, representing the point where starch granules swell to their maximum volume during heating. This value dropped by 89.18% to 319.58 ± 9.90 cP. This indicates that the starch was "pre-gelatinized" during extrusion. The mechanical shear and heat in the extruder barrel had already ruptured the starch granules, leaving little capacity for further swelling during the RVA test.

In peak 2 viscosity (*P2V*) or the cooling phase, as the paste cooled, raw samples showed a massive setback or re-thickening to 8847.92 ± 2.23 cP. Extruded samples showed a drastic reduction of 95.22%, reaching only 424.58 ± 3.06 cP. *P2V* reflects the crystallization of amylose chains (retrogradation). The low *P2V* in extruded samples suggests that the starch molecules were broken down into smaller dextrans during processing, which lack the structural integrity to form a thick, rigid gel upon cooling.

In final viscosity (*FV*) or the stable end-point, the raw flour ended with a very high final viscosity of 8760.75 ± 8.57 cP. The extruded flour settled at a significantly lower 421.33 ± 3.20 cP, a decrease of 95.19%. Final Viscosity indicates the ability of the material to form a stable, viscous paste after the cooling cycle. The minimal *FV* for extruded flour proves it produces a consistently fluid product that does not thicken into a heavy mass over time.

6.3.5.1.3 Significance of Pasting Transformation on a School Feeding Targeted Product

The 95% reduction in final viscosity is perhaps the most critical functional success of this preliminary study. It transforms a bulky maize staple into a concentrated vehicle for cricket-derived proteins and minerals. By ensuring the porridge remains fluid at high solids concentrations, extrusion allows school children to consume significantly more protein and energy per cup of porridge than would be possible with traditional raw flour.

The radical transformation of the pasting profile—characterized by a 95.19% reduction in final viscosity—represents a critical breakthrough in the development of complementary foods for school-going children. In traditional maize-based porridges, the high starch content leads to nutrient bulk, where the porridge becomes too thick to consume at high concentrations. To make such a product drinkable for a child, it must be heavily diluted, which significantly reduces the energy and protein density per serving.

By pre-gelatinizing the starch and reducing the peak viscosity from 2952.7 cP to 319.58 cP, the extrusion process effectively thins the molecular structure of the flour without losing its caloric value. This allows for a high-solid formulation, where more cricket-enriched flour can be incorporated into the same volume of water while maintaining a fluid, and easy to swallow consistency.

The stability of the P2 temperature (24.80°C) further ensures that the product maintains a predictable texture during cooling, avoiding the formation of a rigid, unpalatable gel. Ultimately, the collapse of the viscosity markers (P1, P2, and Final Viscosity) serves as the functional foundation for this research. It ensures that the 10% and 20% cricket formulations—which were found to be nutritionally superior—are also physically optimized to deliver maximum nutrition in a volume appropriate for a child's stomach capacity.

6.4 Conclusions

In conclusion, based on data describing effect of substitution levels and extrusion on nutritional properties of the maize-cricket porridge flour, five key highlights emerge:

- i. Optimal protein bioavailability: Extrusion improved protein digestibility by approximately 10–13% across various formulations, peaking at the 10% substitution level (59.72 %).
- ii. Nutrient-dense fortification: Increasing cricket levels from 0% to 20% effectively doubled the protein content in the raw flours, providing a superior baseline for child nutrition.
- iii. Improved product stability: The drastic reduction in fat content (e.g., a 70% decrease at the 20% level) suggests that extruded maize-cricket flour will have higher oxidative stability than raw mixes.
- iv. Preservation of minerals: The stability of ash content ensures that the micronutrient benefits of *Scapsipedus icipe* are not lost to high-heat processing.
- v. The best nutritionally balanced formulation: Although the 20% substitution provides the highest total protein, the 10% substitution level is the most balanced because it maximizes the efficiency of the protein through the highest digestibility rate while ensuring the product is easy to digest and shelf-stable.

The analysis of physical properties reveals that cricket substitution at 10% provides the best functional synergy with the extrusion process. At this level, the flour achieves its peak water absorption capacity, which is essential for creating the desired porridge consistency for school-going children. While higher substitution levels (15% and 20%) are nutritionally superior in terms of raw protein, they slightly dampen the hydration gains compared to the 10% level. Therefore, the 10% blend is the most functional candidate under the existing extrusion conditions.

CHAPTER SEVEN

OPTIMIZATION OF EXTRUSION CONDITIONS FOR THE EXTRUSION OF A CRICKET ENRICHED MAIZE PORRIDGE FLOUR AND EFFECT ON NUTRITIONAL AND FUNCTIONAL PRODUCT QUALITIES.

7.1 Introduction

Globally today's consumers have a high demand for healthy and nutritious foods that have desirable taste, smell and readily available in the market (Sahu et al., 2022). Due to the changing feeding habits among teenagers, change in working hours, eating times and increased number of single person households the demands of breakfast foods and snacks is on the rise. Foods or snacks made from a single commodity often do not meet the nutritional needs of consumers. Thus, blending of different food ingredients results with an end product with desired quality standards that fits within the demands of consumers (Haritha et al., 2012).

In Kenya some of the proposals aimed at improving the nutritional quality of staple foods such as maize has been blending of cereals with other ingredients such as edible insects, vitamin and mineral premixes, legumes among others. Traditionally consumed whole, insects are increasingly being processed as demand for sustainable protein rises. Naseem et al., (2021) argues that innovations in processing techniques holds the potential of making insects a more viable source of food. Blending of cereals with crickets may have many nutritional benefits due considerably high protein, fat, vitamin and mineral content of edible insects such as crickets. Some of the technologies being focused on in preparing cereal blends is extrusion.

Extrusion is a food processing technology that has been used in preparing extrudates in the food industry. Extrusion is a high temperature short time process that involves use of heat, pressure and mechanical shear force which causes changes in gelatinization of starch, protein denaturation, enzyme inactivation as well as reduction of anti- nutritional factors (S. Singh et al., 2007b). Other changes that occur during extrusion processing involves physicochemical changes such binding, cleavage, loss of native conformation as well as thermal degradation (Steel et al., 2012). Therefore,

in extrusion processing, optimization of key nutrients such as proteins is a critical step in the processing of these cereal blends so as to meet the protein needs of a vast wide of population that may not be able to purchase conventional sources of protein such as meat and fish (Sahu, 2021).

Cereals processed using technology that minimize nutrient loss and combination of cereals with local legumes has been reported as one of the vehicle for delivering protein and minerals to at-risk populations because of their wide spread consumption, stability during storage and versatility in the production of arrays of food products (Wang et al., 2021). Given the nutrient potential of edible crickets (*Scapsipedus icipe* and *Gryllus bimaculatus*) to bridge the nutrient gap in maize, particularly regarding improving the quality of protein by providing the limiting amino acids (lysine and tryptophan), this study aimed at optimizing extrusion conditions to ensure maximum protein and other nutrient retention for the cricket enriched maize porridge flour. Further, this study aimed at investigating the effect of optimizing extrusion conditions on functional properties of the resultant cricket-maize porridge flour blends.

Optimization is the method used for coming up with optimal processing conditions and combination of ingredients with the best output (Bas, 2007). Modelling precedes optimization and helps establish a quantitative relationship between independent and dependent/response variables (Bas, 2007). In the food industry, models are used to help food scientists to think about processes that are too complicated to understand in every detail (Yolmeh & Jafari, 2017).

Modelling and optimization help to establish quantified relationships between input and output variables. They help to make informed decisions on a process with the objective of improving efficiency and minimizing cost while maintaining quality. Response Surface Methodology is the method most commonly used in the food industry to model and optimize food processes. RSM is a statistical technique that optimizes food processes by understanding relationships between different process factors (such as temperature, speed, moisture, heat) and final product quality (such as nutrient quality/content, hydration or viscosity).

In food process modeling and optimization, Response Surface Methodology (RSM) serves as a strategic framework for refining product quality. It begins by defining the key factors—such as temperature and time—that most significantly impact the final output. Rather than relying on exhaustive or random trials, RSM employs a structured experimental design that minimizes the total number of tests while still capturing the complex interactions between variables. The resulting experimental data is used to build a mathematical model that predicts how quality attributes, like protein content, fluctuate under different conditions. Ultimately, this model allows producers to identify the ideal point of processing settings, ensuring a protein-rich porridge that achieves the desired nutritional profile. As such, RSM was used in this study to establish optimal extrusion conditions for optimal nutritional and functional product properties.

This chapter details the optimization of extrusion parameters to define, for the first time, the ideal processing conditions for a cricket-enriched maize porridge flour. RSM was selected over traditional Full Factorial Design (FFD) due to its superior efficiency. While FFD requires an exhaustive and often cost-prohibitive number of experimental runs, RSM utilizes a fractional approach—such as Central Composite Design (CCD) or Box-Behnken Design (BBD)—to generate high-fidelity predictive models with significantly fewer trials (Danbaba & Idakwo, 2019). Data generated in this study will pave way for increased utilization of edible crickets in food to food fortification initiatives at commercial scale hence contribute to reduction of food insecurity and subsequently curb malnutrition.

7.2 Methodology (Materials and Methods)

7.2.1 Experimental Design

A Box-Behnken design (BBD) of Response Surface Methodology (RSM) was used to optimize 4 factors: Type of cricket species (*G. bimaculatus* and *S. icipe*), Barrel temperature (120⁰C -160⁰C), screw speed (37-53 rpm) and feed moisture (11-17%). A total of 39 experimental runs, were generated in a randomized manner. The factors were chosen based on the literature (Atukuri et al., 2019; Harper & Group, 2019; Kaur et al., 2014; Nahemiah et al., 2018) their significant effect on the responses, and their

workability (within the allowed working range). The complete BBD with coded and uncoded levels of the factors are shown in Table 7.1. The value for the total block is 1, with the experiments carried out in a randomized order.

Functional relationships between the independent variables (temperature, moisture content and screw speed) and dependent variables (protein, other nutrients, functional properties) were determined using multiple regression technique by fitting second order equation.

Table 7.1: Box-Behnken Design Optimization Combinations of Extrusion Parameters and Insect Species

StdOrder	RunOrder	PtType	Barrel Temperature	Screw Speed	Feed moisture	Insect
33	1	-1	135	45	11	<i>G. bimaculatus</i>
40	2	0	135	45	14	<i>G. bimaculatus</i>
39	3	0	135	45	14	<i>G. bimaculatus</i>
30	4	-1	160	45	14	<i>G. bimaculatus</i>
10	5	-1	160	45	14	<i>S. icipe</i>
35	6	0	135	45	14	<i>G. bimaculatus</i>
3	7	1	120	50	12	<i>S. icipe</i>
29	8	-1	110	45	14	<i>G. bimaculatus</i>
19	9	0	135	45	14	<i>S. icipe</i>
22	10	1	150	40	12	<i>G. bimaculatus</i>
25	11	1	120	40	16	<i>G. bimaculatus</i>
16	12	0	135	45	14	<i>S. icipe</i>
11	13	-1	135	37	14	<i>S. icipe</i>
9	14	-1	110	45	14	<i>S. icipe</i>
28	15	1	150	50	16	<i>G. bimaculatus</i>
24	16	1	150	50	12	<i>G. bimaculatus</i>
13	17	-1	135	45	11	<i>S. icipe</i>
37	18	0	135	45	14	<i>G. bimaculatus</i>
21	19	1	120	40	12	<i>G. bimaculatus</i>
36	20	0	135	45	14	<i>G. bimaculatus</i>
12	21	-1	135	53	14	<i>S. icipe</i>
7	22	1	120	50	16	<i>S. icipe</i>
23	23	1	120	50	12	<i>G. bimaculatus</i>
31	24	-1	135	37	14	<i>G. bimaculatus</i>
1	25	1	120	40	12	<i>S. icipe</i>
14	26	-1	135	45	17	<i>S. icipe</i>
34	27	-1	135	45	17	<i>G. bimaculatus</i>
6	28	1	150	40	16	<i>S. icipe</i>
2	29	1	150	40	12	<i>S. icipe</i>
38	30	0	135	45	14	<i>G. bimaculatus</i>
5	31	1	120	40	16	<i>S. icipe</i>
8	32	1	150	50	16	<i>S. icipe</i>
26	33	1	150	40	16	<i>G. bimaculatus</i>
18	34	0	135	45	14	<i>S. icipe</i>
4	35	1	150	50	12	<i>S. icipe</i>
15	36	0	135	45	14	<i>S. icipe</i>

StdOrder	RunOrder	PtType	Barrel Temperature	Screw Speed	Feed moisture	Insect
32	37	-1	135	53	14	<i>G. bimaculatus</i>
17	38	0	135	45	14	<i>S. icipe</i>
27	39	1	120	50	16	<i>G. bimaculatus</i>
20	40	0	135	45	14	<i>S. icipe</i>

7.2.2 Statistical Modeling and Optimization: Optimization Process Steps

7.2.2.1 The Iterative RSM Workflow [Box-Behnken Design (BBD) Approach]

The optimization of the cricket-enriched maize porridge followed a systematic five-step iterative process, specifically tailored to handle both discrete species variations and continuous processing parameters.

Step 1: Selection of independent variables and domain definition: Based on preliminary literature reviews and equipment workability, four independent factors were selected (Atukuri et al., 2019; Nahemiah et al., 2018; Pathania et al., 2013) These factors were chosen for their known significant influence on the macro-structural and nutritional transition of the extrudates:

- X₁: Cricket Species (Categorical: *G. bimaculatus* and *S. icipe*)
- X₂: Barrel Temperature (120°C – 160°C)
- X₃: Screw Speed (37 – 53 rpm)
- X₄: Feed Moisture (11% – 17%)

Step 2: Experimental design and randomization: A Box-Behnken Design (BBD) was employed to generate the experimental matrix. To ensure high-fidelity modeling and to account for experimental error, a total of 39 experimental runs were generated. The design was executed in a single block (Block = 1) with the order of runs fully randomized to minimize the influence of unexplained variability or time-dependent trends. The variables were coded at three levels (low -1, medium 0, and high +1), as detailed in Table 7.1 of this study.

Step 3: Mathematical modeling and regression analysis: The functional relationships between the independent variables (X₁, X₂, X₃, X₄) and the dependent responses (Y)—including protein content, micronutrient retention, and functional properties—were

determined. A second-order (quadratic) polynomial equation was fitted to the experimental data using multiple regression techniques:

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i < j}^k \beta_{ij} X_i X_j + \varepsilon$$

Where:

- Y : Predicted response (e.g., Protein content)
- β_0 : Intercept coefficient
- $\beta_i, \beta_{ii}, \beta_{ij}$: Linear, quadratic, and interaction coefficients, respectively.

Step 4: Statistical validation (ANOVA): The adequacy of the fitted models was rigorously evaluated through Analysis of Variance (ANOVA). For a model to be considered a good fit for the cricket-maize matrix it should meet defined thresholds namely: the Lack of Fit must be non-significant ($P > 0.05$); the Coefficient of Determination (R^2) should be high (typically > 0.80), indicating that the model explains a significant portion of the observed variance; the F-values must be checked to determine the significance of individual factors and their interaction effects (e.g., how species type interacts with temperature).

Step 5: Multi-objective optimization and validation: The final step involved identifying the optimal processing zone that satisfies all nutritional and functional requirements simultaneously. This was achieved through the assessment of the desirability function (D), which scales all responses between 0 and 1. To confirm the model's predictive accuracy, a final extrusion trial was conducted at the suggested optimal parameters. The observed experimental values were then compared against the predicted values to calculate the percentage deviation.

7.2.3 Statistical Analysis and ANOVA Structure

The statistical significance of the model terms was evaluated using ANOVA at a 95% confidence level ($\alpha = 0.05$). Because the study involves a categorical factor (species),

the ANOVA table is structured to reveal not only the linear effects of temperature or moisture but also the interaction effects between the insect type and processing conditions. Optimization was carried out at 95% confidence level using Minitab statistical software version 22. *Post-hoc* analysis was done using Tukey's Honestly Significant Difference method.

The key ANOVA components for the 4-factor BBD as applied in this study are described below:

- Model significance: A high F-value and $P < 0.05$ were used to indicate that the model successfully predicts the nutritional/functional outcomes.
- Species effect (X_1): Was used to determine if switching from *G. bimaculatus* to *S. icipe* significantly shifts the baseline protein or functional quality.
- Interaction terms (X_1X_2 , X_1X_3 , etc.): These were important in explaining how factors interact to influence the outcome, for example, they were used to tell whether *S. icipe* requires a higher barrel temperature than *G. bimaculatus* to achieve the same bulk density.
- Lack of Fit: This test was used to compare the residual error to the pure error from the replicated runs. A non-significant Lack of Fit ($P > 0.05$) is required to validate the model's predictive power.

In terms of reporting the BBD experimental matrix, the 39-run matrix was designed to provide a high degrees of freedom value for error estimation. The inclusion of the two species as a categorical factor allows for the generation of separate response surfaces or a combined model with a species-specific intercept as demonstrated in Table 7.2.

Table 7.2: The Box-Behnken Design (BBD) Experimental Matrix

Source of Variation	Degrees of Freedom (df)	Mean Square	F-value	p-value
Model	k	MS _{model}	F _{calc}	<0.05
Linear (X ₁ ,X ₂ ,X ₃ ,X ₄)	4	-	-	-
Square (X ₁₂ ...X ₄₂)	4	-	-	-
Interaction (X ₁ X ₂ ...)	6	-	-	-
Residual (Error)	N-k-1	MS _{res}	-	-
Lack of Fit	m	MS _{LOF}	F _{LOF}	>0.05
Pure Error	n	MS _{PE}	-	-
Total	38	-	-	-

7.2.4 Visualizing the Optimization: Variation and 3D Plots

Following the ANOVA, deviation plots were used to compare the effects of all factors at a specific point in the design space. This allowed for a direct visual comparison of the interaction effect, for example, how sensitive the cricket-maize flour is to moisture versus temperature. Subsequently, 3D response surface plots were generated. These plots visualize the topography of the optimization, showing how the interaction between, for example, feed moisture and barrel temperature creates a peak (optimal) zone for protein content.

7.2.5 Extrusion Processing

Extrusion was done at Peak Value Industries Limited in Mukono Uganda. The extruder (DP70-III Double Screw inflating food Machine, China) used was a twin screw extruder with a die diameter of 26mm, barrel length of 1.56m, feed rate of 30 Hz and cutter rate of 50 Hz. Extrusion runs were done according to combination of extrusion conditions described in **Table 7.1**. Resultant maize-cricket extruded flour samples for both cricket species were each drawn according to the various runs and subjected to laboratory analysis to determine nutritional and functional effects of extrusion process.

7.2.6 Crude Protein determination

The determination of crude protein content for the maize-cricket porridge formulations was conducted using the Kjeldahl method, following the standardized protocol established by AOAC Official Method 2001.11 (AOAC, 2009). This analytical procedure was executed in three sequential stages: acid digestion, distillation, and titration.

Initially, approximately 1.0 g of the homogenized sample was subjected to digestion in a Kjeldahl flask using concentrated sulfuric acid (H_2SO_4) in the presence of a copper-based catalyst tablet. This process facilitated the oxidative destruction of organic matter, converting all organic nitrogen into ammonium sulfate $[(NH_4)_2SO_4]$. Following the completion of digestion, the resulting solution was cooled and neutralized through addition of 40% sodium hydroxide (NaOH).

During the distillation phase, the liberated ammonia gas (NH₃) was steam-distilled into a receiving flask containing a 4% boric acid (H₃BO₃) indicator solution. The captured ammonia was then quantified through potentiometric titration using a standardized 0.1 N hydrochloric acid (HCl) solution. The total nitrogen content was calculated based on the volume of titrant consumed. To estimate the crude protein content, the resulting nitrogen value was multiplied by the conventional conversion factor of 6.25, a standard predicated on the assumption that the protein matrix contains approximately 16% nitrogen. All analyses were performed in triplicate to ensure statistical precision and reproducibility

7.4 Results and Discussion

7.4.1 Effect of Optimizing Extrusion Conditions on Crude Protein of Blends Enriched with Different Cricket Species

The optimization model Analysis of Variance (ANOVA) of barrel temperature, screw speed, feed moisture and type of cricket (*Scapsipedus icipe* and *Gryllus bimaculatus*) used on crude protein is presented in Table 7.3. It was found that the model was significant at $P < 0.0001$. However, the linear and quadratic terms did not have a significant effect on crude protein during optimization. On other hand, all two-way interactions for extrusion parameters (barrel temperature, screw speed, feed moisture) and insect species (*Scapsipedus icipe* and *Gryllus bimaculatus*) significantly affected crude protein during processing except the interaction between the insect type and feed moisture as well as screw speed and feed moisture. Lack of fit was not significant with $P = 0.078$.

Table 7.3 demonstrates the significance of the optimization model, affirming its capability to predict the impact of optimizing extrusion parameters on crude protein. Individually, barrel temperature, screw speed, and feed moisture exhibited no significant impact on crude protein levels of blends during optimization. However, their interaction influenced crude protein content. Hence this implies that during extrusion of blends enriched with *Scapsipedus icipe* and *Gryllus bimaculatus*, crude protein is affected by interaction of extrusion parameters but not independent parameters.

Additionally, the insignificance of the lack of fit in the optimization model suggests that there exists an optimal combination (Wan Hassan et al., 2020) of barrel temperature, screw speed, and feed moisture for blends containing *Scapsipedus icipe* and *Gryllus bimaculatus*. Temperature affects Maillard reactions and other biochemical reactions such as racemization. Screw speed (shear pressure) increases exposure to reactants (such surface area). While moisture functions as a plasticizer, enabling starch molecules to absorb water and expand, thus facilitating the gelatinization process by breaking down starch granules and disrupting their crystalline structure (Gao et al., 2022; Pismag et al., 2024; Q. Wang et al., 2021). The physical and chemical properties of major food constituents, that is, proteins, carbohydrates, and lipids, are invariably altered during processing. These changes involve both intra- and inter-component interactions/reactions.

Table 7.3: Analysis of Variance (ANOVA) of Extrusion Processing Conditions Optimization on Crude Protein of Blends Enriched with Different Insects Species

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	13	20.7418	1.59552	7.30	0.000
Linear	4	0.1752	0.04379	0.20	0.936
Temperature	1	0.1113	0.11133	0.51	0.482
Screw Speed	1	0.0010	0.00102	0.00	0.946
Feed Moisture	1	0.0353	0.03534	0.16	0.691
Insect	1	0.0264	0.02637	0.12	0.731
Square	3	0.7883	0.26277	1.20	0.329
Temperature*Temperature	1	0.2543	0.25426	1.16	0.291
Screw Speed*Screw Speed	1	0.0041	0.00413	0.02	0.892
Feed Moisture*Feed Moisture	1	0.2241	0.22408	1.03	0.321
2-Way Interaction	6	15.2359	2.53932	11.62	0.000
Temperature*Screw Speed	1	0.9725	0.97253	4.45	0.045
Temperature*Feed Moisture	1	1.0348	1.03480	4.73	0.039
Temperature*Insect	1	7.1790	7.17904	32.85	0.000
Screw Speed*Feed Moisture	1	0.5889	0.58889	2.69	0.113
Screw Speed*Insect	1	1.3546	1.35461	6.20	0.020
Feed Moisture*Insect	1	0.3818	0.38184	1.75	0.198
Error	26	5.6827	0.21856		
Lack-of-Fit	6	2.3041	0.38402	2.27	0.078
Pure Error	20	3.3785	0.16893		
Total	39	26.4244			

Key: DF= Degree of Freedom; Adj SS= Adjusted Sum of Squares; Adj MS= Adjusted Mean Squares

The regression equations showing the relationship between extrusion parameters and crude protein for each insect species during extrusion are shown in Table 7.4. Regression model for predicting crude protein for *Scapsipedus icipe* had R² of 0.836 while for *Gryllus* was 0.869. It was noted that the linear factors for both insects had negative coefficients while interaction terms had positive coefficients. However, the square terms of the regression model for both insects had negative coefficients except feed moisture.

Apart from individual extrusion variables showing no significant impact on crude protein during optimization, regression models presented in Table 7.4 reveal that they had negative coefficients. This suggests that while the temperature, screw speed, and feed moisture increased during the optimization process, crude protein content in the blends tended to decrease, although not significantly. However, for both insect species, the interactions exhibited positive coefficients, with some being significant, as demonstrated in Table 7.3.

Table 7.4: Regression Equation for Optimizing Extrusion Processing Conditions on Crude Protein in Blends Enriched with Different Cricket Species

Insect	Regression model	R²
<i>S. icipe</i>	Crude protein = 103.6 - 0.085 Temperature - 1.556 Screw Speed - 7.56 Feed Moisture - 0.000976 Temperature*Temperature - 0.0022 Screw Speed*Screw Speed + 0.0821 Feed Moisture*Feed Moisture + 0.00380 Temperature*Screw Speed + 0.00979 Temperature*Feed Moisture + 0.0852 Screw Speed*Feed Moisture	0.836
<i>G. bimaculatus</i>	Crude protein = 86.6 - 0.012 Temperature - 1.445 Screw Speed - 7.40 Feed Moisture - 0.000976 Temperature*Temperature - 0.0022 Screw Speed*Screw Speed + 0.0821 Feed Moisture*Feed Moisture + 0.00380 Temperature*Screw Speed + 0.00979 Temperature*Feed Moisture + 0.0852 Screw Speed*Feed Moisture	0.869

The effect of interactions of extrusion processing conditions during optimization of crude protein in blends enriched with insects is shown in Figure 7.1. The first interaction is between screw speed and barrel temperature, the highest crude protein was observed at the lowest barrel temperature of 120 and the lowest SS of 40 but as

both increased, they caused a reduction of protein in the blends. The second interaction is feed moisture and barrel temperature whereby the highest crude protein was observed at the lowest FM and lowest BT. The third interaction is feed moisture and screw speed. Highest crude protein was observed at lowest SS and FM and also at the highest FM and SS, but in between the crude protein decreased. Figure 7.1 presents the visual of the interactions in surface plots.

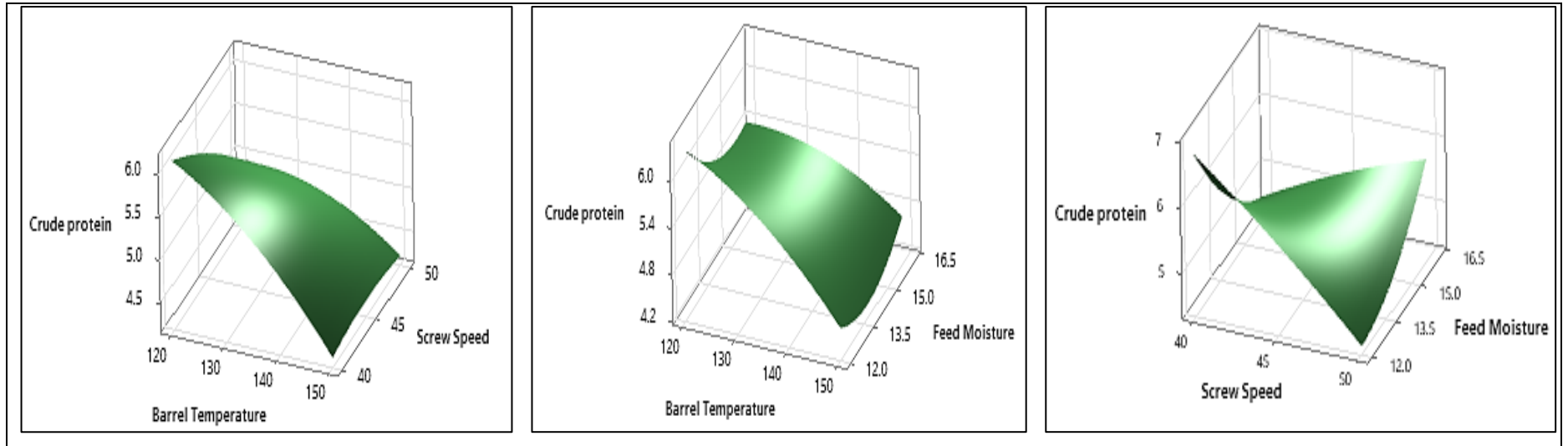


Figure 7.1: Effect of Extrusion Processing Conditions on the Optimization of Crude Protein in Blends Enriched with Crickets

Figure 7.2 presents optimum conditions for extrusion where barrel temperature was established to be 120, screw speed 40 rpm and feed moisture of 12%. However, under these optimum conditions blends with *Scapsipedus icipe*, with a reliability of 93.8% ($d=0.9377$) are expected to obtain 7.7% protein. But regarding blends with *Gryllus bimaculatus* under the same optimum conditions, the protein achievable was 5.8% with a reliability 43.5% (0.4347). This implies that *Scapsipedus icipe* is a better insect species for protein enrichment of maize or any other cereal than *Gryllus bimaculatus* since the probability of getting target protein in blends is about 94% as opposed to 44% for the latter.

Response optimizer for crude protein from *Scapsipedus icipe* and *Gryllus bimaculatus* in blends is shown in Figure 7.2. For both the blends with *Scapsipedus icipe* and *Gryllus bimaculatus*, the optimum extrusion conditions were: 120°C barrel temperature, 40 rpm screw speed and 12% feed moisture level. However, these conditions had a **desirability** of 0.9377 in blends with *Scapsipedus icipe* while blends with *Gryllus bimaculatus* recorded a **desirability** of 0.4347.

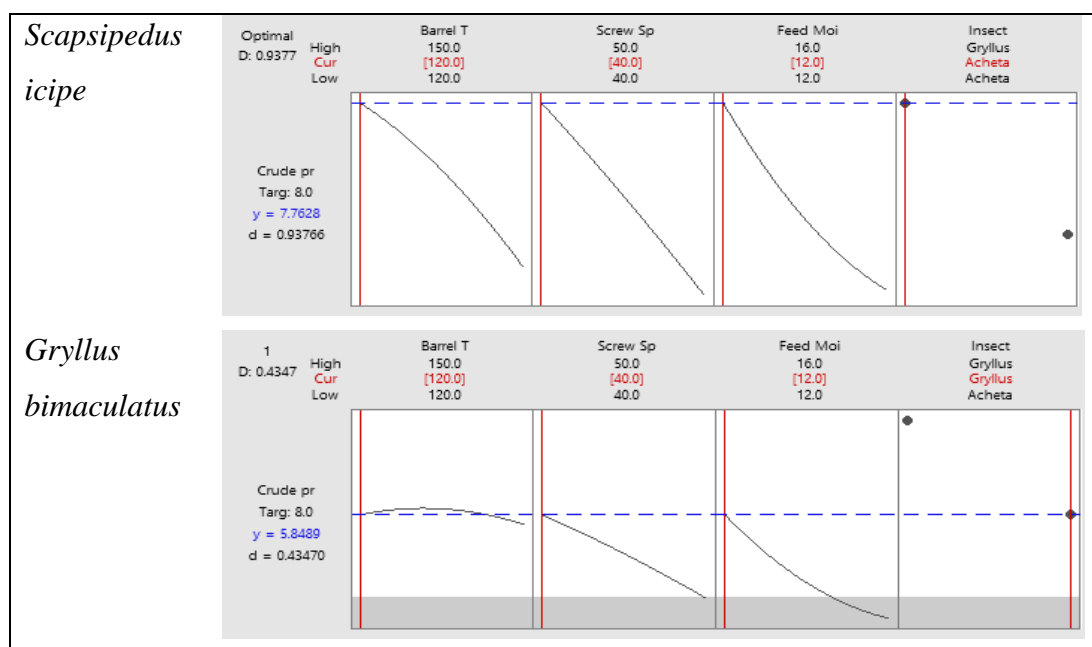


Figure 7.2: Response Optimizer *Scapsipedus icipe* and *Gryllus bimaculatus*

7.5 Conclusion

This study optimized extrusion conditions to yield a cricket fortified maize porridge flour that is appreciably higher in protein. The analysis of the effect of optimizing extrusion conditions on product properties showed notable changes in the protein behaviour of the final product.

Optimum conditions for extrusion were found to be at a barrel temperature of 120 °C, screw speed of 40 rpm and feed moisture of 12% with *S. icipe* blends presenting a remarkable reliability of 93.8% with a higher achievable protein level (7.7%) while *G. bimaculatus* blends reported a much lower reliability of 43.5% with a lower achievable protein level (5.8%). This implies that *S. icipe* is a better insect species for protein enrichment of maize or any other cereal than *G. bimaculatus* since the probability of getting target protein in blends is about 94% as opposed to 44% for the latter.

CHAPTER EIGHT

CONCLUSION AND RECOMMENDATIONS

8.1 CONCLUSION

8.1.1 Nutrient Composition of Crickets *S. Icipe* and *G. Bimaculatus*

The nutrient characterization of *S. icipe* and *G. bimaculatus* confirms their status as viable alternatives to conventional protein sources for the fortification of maize-based supplementary foods. While both species share a similar crude protein content of approximately 56.8% to 56.9%, their specific biological and micronutrient advantages differ significantly:

8.1.1.1 Protein Quality and Amino Acid Adequacy

Both species are good protein sources, containing seven essential amino acids (EAAs). Notably, they provide at least twice the recommended levels of lysine and methionine for children and adolescents. However, *S. icipe* demonstrated a superior biological value with a significantly higher protein digestibility of 87.8%. This yields a protein digestibility corrected amino acid score (PDCAAS) of (87.77%) comparable to premium animal proteins like egg and beef, and consistently higher than most plant-based proteins.

The extruded corn-cricket porridge evaluated in this study containing 16.52 g/100g of crude protein with an in vitro digestibility of 54.5%, provides 9.00 g of digestible protein per 100 g serving. Based on WHO/FAO guidelines (WHO/FAO/UNU, 2007), this represents a substantial contribution to the daily requirements of school-going children, meeting approximately 49.1% of the daily Recommended Nutrient Intake (RNI) for a 5-year-old and 23.5% of the RNI for a 12-year-old.

8.1.1.2 Energy and Fatty Acid Profiles

Gryllus bimaculatus emerged as the more energy-dense option, containing significantly higher crude fat (33.51%) and a total energy value of 529.2 Kcal/100g.

The fatty acid profiles showed distinct hierarchies, with *G. bimaculatus* following an SFA > MUFA > PUFA order, while *S. icipe* prioritized polyunsaturated fats in an SFA > PUFA > MUFA configuration.

8.1.1.3 Micronutrient Density

Both species exhibit exceptional mineral and vitamin densities that surpass most common livestock and plant foods documented in the Kenya Food Composition Tables (KFCT).

- **Minerals:** With iron levels reaching up to 12.33 mg/100g, a 100g portion can contribute significantly to the RDA for children under five in a maize-cricket blended porridge. Similarly, zinc levels (19–23 mg/100g) are sufficient to contribute significantly to the RDA across all age groups when whole crickets are formulated with maize based products.
- **Vitamins:** Both species were found to contain various vitamins which are essential to children's growth namely: Vitamins A, D, E, and the B-complex group. Most notably, their folic acid (Vitamin B₉) content is significantly higher than that of eggs, chicken, beef, and a wide array of indigenous and exotic vegetables.

In summary, while *Gryllus bimaculatus* is recommended for maximizing caloric intake and mineral potential, *S. icipe* offers superior protein digestibility and a more favorable PUFA balance. Regardless of the species chosen, the formulated maize-cricket flour provides a robust nutrient matrix—specifically rich in essential amino acids, iron, zinc, and folic acid—this served as a high-impact baseline for the subsequent extrusion optimization and sensory evaluation phases of this study.

8.1.2 Physicochemical Characterization of Cricket Oils and Anti-Nutritional Phytochemical Profile of Whole Ground Cricket Powder

Oils from the edible cricket species and the whole cricket powder in this study have the potential for exploitation in the food industry as depicted by their physicochemical

characteristics and the antinutritional phytochemical composition. These are summarized in the following paragraphs.

8.1.2.1 Synthesis of Lipid Benchmarks and Stability Profiles:

The characterization of the lipid fractions of *S. icipe* and *G. bimaculatus* successfully established the foundational physical and chemical benchmarks required for their industrial application. The refractive indices and saponification values obtained align closely with established benchmarks for premium unsaturated vegetable oils, such as soybean and olive oil. Critically, the chemical indices—specifically the Peroxide Value (PV) and Acid Value (AV)—confirm that when subjected to appropriate pre-treatment, these oils maintain oxidative and hydrolytic stability within the thresholds established by the Codex Alimentarius. These results provide food processors with the empirical data needed to predict the shelf-stability of fortified porridges, ensuring that the addition of cricket-derived ingredients does not compromise the sensory or chemical integrity of the final product.

8.1.2.2 Characterization of the Anti-Nutritional Phytochemical Profile:

Analysis of the anti-nutritional factors (ANFs) reveals that *S. icipe* and *G. bimaculatus* possess a remarkably safe anti-nutritional phytochemical profile, alleviating concerns regarding nutrient sequestration. Both phytates and tannins were found at negligible concentrations (< 10 mg/100g), while oxalate levels remained low (≤ 97 mg/100g). These values are significantly below the inhibitory thresholds typically found in plant-based protein sources like legumes or cereals.

Consequently, the anti-nutritional phytochemical barrier to digestion is minimal, suggesting that the high-protein and mineral content of these crickets is highly bioavailable. This confirms that ground cricket powder is not only a dense nutrient source but one that does not inherently interfere with the absorption of essential divalent cations like calcium and iron in maize-based formulations.

8.1.2.3 Comparative Assessment of *S. icipe* and *G. bimaculatus*:

Direct comparative analysis indicates that while both species offer robust nutritional profiles, they exhibit distinct physiological advantages. *S. icipe* demonstrated a slightly higher degree of lipid unsaturation (higher PV and AV values), which, although nutritionally superior, necessitates more stringent antioxidant controls. Conversely, *G. bimaculatus* exhibited a less stable anti-nutrient phytochemical profile with marginally higher oxalate concentrations. Despite these variations, both species demonstrate sufficient functional similarity to be treated as interchangeable ingredients under a unified regulatory framework, provided that processing protocols are calibrated to their specific enzymatic and phytochemical loads.

The negligible concentrations of phytates and tannins in *S. icipe* and *G. bimaculatus*—coupled with their high mineral density—render them superior to traditional legumes for the fortification of whole maize. When processed via extrusion, the resulting matrix not only secures the lipid fraction through amylose-lipid complexation but also ensures that the inherent phytates load of the maize does not inhibit the dietary bioavailability of essential cations, thereby maximizing the nutritional efficacy of complementary porridges."

8.1.3 Effect of Extrusion on Sensory properties

The sensory evaluation established that both the extrusion process and the levels of cricket meal substitution are decisive factors in the consumer's perception of the formulated porridge.

8.1.3.1 The Role of Extrusion in Quality Enhancement

Extrusion processing significantly influenced the appearance ($P = 0.003$), texture ($P = 0.001$), and mouthfeel ($P = 0.028$) of the resultant porridges. Overall, porridges prepared from extruded formulas were significantly preferred over non-extruded versions in terms of visual and flavor attributes. This suggests that the high-temperature, short-time extrusion process effectively modified the starch-protein matrix to create a more palatable product, though it did not significantly alter the aroma profile ($P = 0.707$).

8.1.3.2 Impact of Substitution Levels

The concentration of cricket flour played a pivotal role in product acceptance:

- **Non-Extruded Products:** Scores for appearance, color, texture, taste, and overall acceptability significantly decreased as cricket incorporation levels increased.
- **Extruded Products:** Increasing substitution from 10% to 20% led to a significant decline in the liking of almost all sensory attributes, with the exception of texture and thickness.
- **The 10% Threshold:** Panelists expressed a high preference for the appearance, color, and mouthfeel of extruded formulas containing 10% cricket meal. In contrast, non-extruded versions at the 10% level were rated better only for taste and aftertaste, further highlighting that extrusion is the superior method for achieving a balanced sensory profile.

8.1.3.3 Sensory Limitations

The decline in preference at higher substitution levels is attributed to the increasing concentration of sensory-impairing compounds naturally present in crickets. While extrusion mitigates some of these issues, it cannot entirely mask the flavor and color shifts associated with high insect inclusion (above 10%).

8.1.4 Preliminary Effect of Extrusion Processing on Nutritional and Functional Properties of a Formulated Maize Cricket Porridge Flour Using Existing Extrusion Process Conditions

8.1.4.1 Effect on Proximate and Protein Digestibility-

The extrusion process significantly altered specific macronutrients and digestibility markers, while others remained relatively stable. The most profound changes occurred in fiber content, fat content, and protein digestibility.

- **Enhanced Protein Digestibility:** The most vital finding for school-going children is the significant increase in protein digestibility (up by approximately

10.7%). This confirms that extrusion effectively denatures proteins and inactivates anti-nutritional factors, making the cricket-maize protein more nutrient bioavailable.

- **Significant Lipid Reduction:** There was a sharp decline in fat content (2.46% to 0.81%). This is common in extrusion due to the formation of amylose-lipid complexes or oil loss under high shear, which can actually benefit the shelf-life of the porridge flour by reducing rancidity.
- **Fiber Degradation:** The significant drop in fiber (3.28 % to 0.95%) suggests that the high mechanical shear and temperature broke down insoluble fiber fractions into smaller, potentially soluble components.
- **Stability of Core Nutrients:** Total protein, carbohydrates (CHO), and ash showed no statistically significant changes, indicating that the extrusion process preserves the fundamental macro-nutrient density of the formulation.

The use of existing maize-based extrusion conditions for this new maize-cricket formulation were found to be effective at improving the nutritional quality of the product. While the process significantly reduces fat and fiber, the substantial gain in protein digestibility validates this processing method as a viable way to produce a more "efficient" food source for children.

Since the core nutrients (protein and minerals/ash) were preserved under these existing conditions, this process served as a successful baseline. These findings gave the required greenlight to proceed with optimization of the extrusion parameters (specifically barrel temperature, screw speed and feed moisture), for attainment of best product qualities (nutritional and functional).

8.1.4.2 Effect of Extrusion and Substitution Levels

The preliminary evaluation demonstrated that extrusion processing under existing conditions was highly effective at enhancing the nutritional profile of maize-cricket composite flours. While the process results in a significant reduction of fiber and fat, these changes are generally favorable for the target demographic of school-going children, as they improve digestibility and potential shelf-life.

Given that the 10% and 20% substitution levels showed the most favorable protein digestibility post-extrusion, these formulations represent the strongest candidates for further optimization. This study successfully establishes that existing industrial extrusion parameters can be optimized to produce a safe, nutrient-dense, and highly digestible insect-enriched porridge.

8.1.4.3 Effect of Extrusion on Pasting Properties

This preliminary study confirmed that applying existing maize-extrusion conditions to a maize-cricket blend could be highly effective if optimized. The process successfully addressed the two primary hurdles of child nutrition: bioavailability (by increasing protein digestibility) and nutrient density (by drastically reducing pasting viscosity to allow for higher flour-to-water ratios). The 10% cricket substitution level was the most successful formulation, providing the highest digestibility and superior hydration properties under the baseline conditions.

The radical transformation of the pasting profile—characterized by a 95.19% reduction in final viscosity—represents a critical breakthrough in the development of complementary foods for school-going children. In traditional maize-based porridges, the high starch content leads to nutrient bulk, where the porridge becomes too thick to consume at high concentrations. To make such a product drinkable for a child, it must be heavily diluted, which significantly reduces the energy and protein density per serving.

By pre-gelatinizing the starch and reducing the peak viscosity from 2952.7 cP to 319.58 cP, the extrusion process effectively thinned the molecular structure of the flour without losing its caloric value. This allowed for a High-Solid formulation, where more cricket-enriched flour can be incorporated into the same volume of water while maintaining a fluid with easy to swallow consistency.

The stability of the P2 temperature (24.80°C) further ensured that the product maintained a predictable texture during cooling, avoiding the formation of a rigid, unpalatable gel. Ultimately, the collapse of the viscosity markers (P1, P2, and Final Viscosity) served as the functional foundation for this research. It ensured that the 10%

and 20% cricket formulations—which were found to be nutritionally superior—were also physically optimized to deliver maximum nutrition in a volume appropriate for a child's stomach capacity.

8.1.5 Optimization of a Tailored Extrusion Process for Maize-Cricket Porridge

The optimization of the extrusion process for the cricket-enriched maize porridge flour using Box-Behnken Design (BBD) successfully identified the critical processing thresholds required to maintain nutritional integrity. The study confirmed that the development of an optimal extrusion process is a multi-factorial challenge, where the interaction between mechanical variables and biological inputs (insect species) dictates the final product quality. Key conclusions on optimization are summarized below:

- **Model Robustness:** The quadratic models for crude protein were highly significant ($P = 0.000$) with a non-significant lack of fit ($P = 0.078$), explaining over 83% of the variation for both species.
- **Thermal and Mechanical Synergy:** The significant interaction between Barrel Temperature and Screw Speed ($P = 0.045$) revealed that high-intensity processing (150°C and 50 rpm) creates a synergistic effect that significantly reduces crude protein retention and therefore optimal thermal temperature was found in the lower range of temperature (120°C- 135°C).
- **Species-Specific Requirements:** The highly significant Temperature \times Insect ($P = 0.000$) and Screw Speed \times Insect ($P = 0.020$) interactions prove that *G. bimaculatus* and *S. icipe* possess distinct sensitivities to thermomechanical stress. This necessitates species-specific calibration to prevent excessive protein denaturation.
- **Protective Role of Moisture:** Feed moisture acts as a critical plasticizer; at higher levels (16.5%–17%), it successfully buffers the protein matrix against thermal degradation, regardless of the insect species used ($P = 0.198$).

8.1.5.1 The Optimal Window

Therefore, to maximize crude protein while ensuring a functional porridge flour, the optimal extrusion parameters were identified in the lower-to-mid temperature range (120°C–135°C) combined with moderate screw speeds (40–45 rpm) and moderate feed moisture (12%–15%).

These conditions minimize the specific mechanical energy (SME) and thermal intensity, ensuring that the cricket-enriched porridge retains its status as a high-protein supplementary food. This study provides a foundational framework for the industrial-scale production of insect-based fortified foods, demonstrating that processing efficiency can be achieved without compromising nutritional density.

8.2 Recommendations

Based on the nutritional, functional, and sensory evidence gathered in this study, the following recommendations are made:

8.2.1 Recommendations for Nutrition and Product Development

- **Optimal Formulation:** For commercial or humanitarian applications, a 10% cricket meal substitution is recommended. This level maximizes nutrient density (specifically iron, zinc, and lysine) while remaining within the threshold of high consumer acceptability.
- **Targeted Nutritional Intervention:** Given that 100g of this 10% blend can meet approximately 20% of the iron RNI for school aged children (5-12 years), 49% of the RNI protein for a 5-year old and 23.5% of the RNI for a 12-year old, this formulation should be prioritized for complementary and school feeding programs in regions with high rates of iron-deficiency anemia and protein-energy malnutrition.
- **Compensate for Lipid and Fiber Loss:** The significant reduction in fat (2.46 % to 0.81%) and fiber (3.28% to 0.95\%) suggests that the existing process conditions are quite rigorous and optimized conditions are highly recommended. In the event that the existing extrusion conditions are used for

processing the maize –cricket porridge flour, the following actions are recommended:

- i. **Lipid Fortification:** Consider if the final porridge requires a small post-extrusion addition of healthy fats or if the initial cricket inclusion ratio can be raised to offset this loss, as fats are essential for fat-soluble vitamin absorption in children.
 - ii. **Fiber Balance:** While lower fiber improves energy density for children, ensuring a baseline level remains for gut health is important.
- **Monitor Mineral Retention (Ash):** As the ash content remained stable during this preliminary run (0.71% raw vs 0.59 % extruded), it is recommended to conduct a detailed micro-nutrient analysis (specifically Iron, Zinc, and Calcium) during the formulation optimization. This ensures that the cricket-to-maize ratio provides the Recommended Dietary Allowance (RDA) for the target age group.
 - **Formulation Selection:** Adopt the 10% substitution as the primary formulation for immediate product development due to its peak functional synergy.
 - **Preparation Protocols:** Utilize the low-viscosity data to standardize "High-Solid" recipes that maximize caloric intake per serving.
 - **Prioritize the 10% Substitution Level for Digestibility Efficiency:** While higher substitution levels increase total protein, the 10% cricket substitution achieved the highest absolute protein digestibility (59.72%) after extrusion. This level should be considered the primary benchmark for balancing protein quantity with maximum biological utilization.
 - **Energy Density Calibration:** Use the low-viscosity data to develop high-solid porridge recipes (e.g., 20 % -25 % solids instead of the traditional 10 %) to maximize caloric intake for school children.
 - **Monitor viscosity for caloric density:** The significant reduction in fiber and the modification of carbohydrates during extrusion (as seen in the P -values for carbohydrates and fiber) will likely lower the viscosity of the cooked porridge. It is recommended to capitalize on this by creating a drinkable yet nutrient-

dense porridge that allows children to consume more calories per serving without feeling prematurely full.

8.2.2 Recommendations for Food Industry

- **Processing Standard: Extrusion technology** should be utilized as the standard processing method. It not only improves the digestibility but is essential for enhancing the visual and textural attributes that consumers prefer.
- **Functional Property Benchmarking:** The optimal formulation should not only be the most nutritious but also the most functional. Data from this study (particularly chapter 6) should be used to set acceptability thresholds for:
 - i. **Water Solubility Index (WSI):** To ensure the porridge is easy to prepare.
 - ii. **Viscosity:** To ensure the porridge is nutrient-dense but thin enough for young children to consume easily.

8.2.3 Recommendations for Future Research

- **Flavor Masking Research:** Future studies should investigate the use of natural flavor enhancers (such as vanilla, cocoa, or indigenous fruit powders) to mask the sensory-impairing compounds of crickets, potentially allowing for substitution levels beyond 10% without a decline in palatability.
- **Target Maximum Protein Bioavailability:** Since extrusion significantly increased protein digestibility from 43.78% to 54.50%, future research should involve testing increasing levels of cricket powder (*Scapsipedus icipe*). The goal is to find the saturation point where the protein density is maximized without negatively affecting the mechanical flow of the extruder or the final digestibility score.
- **Establish a Nutritional Ceiling at 20% Substitution:** The 20% substitution level successfully doubled the raw protein content compared to the 0% control. However, it also introduced the highest raw fiber content (6.10%). Future trials should monitor if the significant fiber reduction during extrusion at this level

(down to 1.53%) maintains the desired stool-bulking properties necessary for child health.

- **Leverage fat reduction for shelf-stability:** The significant drop in fat content across all levels—particularly the reduction from 4.35% to 1.31% at the 20% level—should be used as a rationale for extended shelf-life studies. This processing "loss" is a strategic gain for preventing rancidity in school feeding programs.
- **Validate micronutrient bioavailability:** since Ash content (minerals) remained statistically stable during extrusion, future research should move beyond total ash to measure the bio-availability of specific minerals like Iron and Zinc, which are vital for cognitive development in school-aged children.

8.2.4 Recommendations for Policy

- There is need to update the Kenya Food Composition tables by adopting the nutrient composition data of both cricket species analyzed in this study into the national reference data tables – Kenya Food Composition Tables.
- School Feeding Programs: Given the significant contribution of the maize cricket porridge to daily nutrient requirements of school age children, it is recommended to policy makers as a viable option to be added into the national food basket for school meals and the school feeding programmes in Kenya

REFERENCES

- Abah, C. R., Ishiwu, C. N., Obiegbuna, J. E., & A. A. Oladejo. (2020). Nutritional Composition, Functional Properties and Food Applications of Millet Grains. *Asian Food Science Journal*, 14(2), 9–19. <https://doi.org/10.9734/AFSJ/2020/v14i230124>
- Abdullahi, N., Igwe, E. C., Dandago, M. A., & Yunusa, A. K. (2021). Consumption of Edible-Insects: the Challenges and the Prospects. *Food ScienTech Journal*, 3(1), 1. <https://doi.org/10.33512/fsj.v3i1.10468>
- Abodi, M. A., Obare, G. A., & Kariuki, I. M. (2021). Supply and demand responsiveness to maize price changes in Kenya: An application of error correction autoregressive distributed lag approach Supply and demand responsiveness to maize price changes in Kenya: An application of error correction autoregress. *Cogent Food & Agriculture*, 7(1). <https://doi.org/10.1080/23311932.2021.1957318>
- Aboge, D. O., Orinda, M. A., & Konyole, S. O. (2021). Acceptability Of Complementary Porridge Enriched With Crickets (*Acheta Domesticus*) Among Women Of Reproductive Age In Alego-Usonga Sub-County, Kenya. *African Journal of Food, Agriculture, Nutrition and Development*, 21(5), 18066–18082. <https://doi.org/10.18697/ajfand.100.20330>
- Acosta-Estrada, B. A., Reyes, A., Rosell, C. M., Rodrigo, D., & Ibarra-Herrera, C. C. (2021). Benefits and Challenges in the Incorporation of Insects in Food Products. *Frontiers in Nutrition*, 8(June). <https://doi.org/10.3389/fnut.2021.687712>
- Adamek, M., Adamkova, A., Mlcek, J., Borkovcova, M., & Bednarova, M. (2018). Acceptability and sensory evaluation of energy bars and protein bars enriched with edible insects. *Potravinarstvo Slovak Journal of Food Sciences*, 12(1), 431–437.
- Adams, Z. S., Wireko Manu, F. D., Agbenorhevi, J., & Oduro, I. (2019). Improved Yam-Baobab-Tamarind flour blends: Its potential use in extrusion cooking.

Scientific African, 6, e00126. <https://doi.org/10.1016/j.sciaf.2019.e00126>

Adegboye, A. R. A. (2022). Potential Use of Edible Insects in Complementary Foods for Children: A Literature Review. *International Journal of Environmental Research and Public Health*, 19(8). <https://doi.org/10.3390/ijerph19084756>

Adeyeye, E. I., & Awokunmi, E. E. (2010). *Chemical composition of female and male giant African cricket, brachytrypes membranaceus L.* 1(4), 125–136.

Adeyeye, E. I., & Olaleye, A. A. (2016). Nutrient Content of Five Species of Edible Insects Consumed in South-West Nigeria. *EC Nutrition*, 56, 1285–1297.

Agrahar-Murugkar, D. (2020). Food to food fortification of breads and biscuits with herbs, spices, millets and oilseeds on bio-accessibility of calcium, iron and zinc and impact of proteins, fat and phenolics. *Lwt*, 130(February), 109703. <https://doi.org/10.1016/j.lwt.2020.109703>

Ahmad, S., & Pradyuman, W. (2016). Influence of different mixtures of ingredients on the physicochemical , nutritional and pasting properties of extruded snacks. *Journal of Food Measurement and Characterization*, 10, 1–10. <https://doi.org/10.1007/s11694-016-9353-9>

Ahmed, I., Diseases, N., Drive, V., & East, J. (2025). *The nutritional value of grasshoppers and locusts – a review.* 25(2), 455–465. <https://doi.org/10.2478/aoas-2024-0077>

Aidoo, O. F., Osei-Owusu, J., Asante, K., Dofuor, A. K., Boateng, B. O., Debrah, S. K., Ninsin, K. D., Siddiqui, S. A., & Chia, and S. Y. (2023). *Insects as food and medicine : a sustainable solution for global health and environmental challenges.* June, 1–14. <https://doi.org/10.3389/fnut.2023.1113219>

Akhtar, Y., & Isman, M. B. (2017). Insects as an Alternative Protein Source. In *Proteins in Food Processing: Second Edition* (Second Edi). Elsevier Ltd. <https://doi.org/10.1016/B978-0-08-100722-8.00011-5>

- Akpossan, R. A., Due, E. A., Koffi, D. M., & Kouame, P. (2015). Fatty acids, mineral composition and physico-chemical parameters of imbrasia oyemensis larvae oil with unusual arachidonic acid content. *Food and Environment Safety, 14*(4), 358–367.
- Akpuaka, M. U., & Nwankwor, E. (2000). Extraction, analysis and utilization of a drying-oil from Tetracarpidium conophorum. *Bioresource Technology, 73*(2), 195–196. [https://doi.org/10.1016/S0960-8524\(99\)00159-5](https://doi.org/10.1016/S0960-8524(99)00159-5)
- Akullo, J., Agea, J. G., Obaa, B. B., Okwee-Acai, J., & Nakimbugwe, D. (2018). Nutrient composition of commonly consumed edible insects in the Lango sub-region of northern Uganda. *International Food Research Journal, 25*(February), 159–165.
- Alamu, O. T., Amao, A. O., Nwokedi, C. I., Oke, O. A., & Lawa, I. O. (2013). Diversity and nutritional status of edible insects in Nigeria: A review. *International Journal of Biodiversity and Conservation, 5*(4), 215–222. <https://doi.org/10.5897/IJBC12.121>
- Alemu, M. H., Olsen, S. B., Vedel, S. E., Kinyuru, J. N., & Pambo, K. O. (2017). Can insects increase food security in developing countries? An analysis of Kenyan consumer preferences and demand for cricket flour buns. *Food Security, 9*(3), 471–484. <https://doi.org/10.1007/s12571-017-0676-0>
- Allen, L., & Benoist, B. De. (2006). *Guidelines on food fortification with micronutrients*. World Health Organization.
- Alonso, R., Aguirre, A., & Marzo, F. (2000). Effects of extrusion and traditional processing methods on antinutrients and in vitro digestibility of protein and starch in faba and kidney beans. *Food Chemistry, 68*, 159–165.
- Amoah, I., Cobbinah, J. C., Yeboah, J. A., Essiam, F. A., Lim, J. J., Tandoh, M. A., & Rush, E. (2023). Edible insect powder for enrichment of bakery products—A review of nutritional, physical characteristics and acceptability of bakery products to consumers. *Future Foods, 8*.

- Antwi, J., Quaidoo, E., Ohemeng, A., & Bannerman, B. (2022). *Household food insecurity is associated with child's dietary diversity score among primary school children in two districts in Ghana. 1*, 1–9.
- AOAC. (2002). *Official Methods of Analysis* (17th ed.). The Association of Official Analytical Chemists.
- AOAC. (2005a). Association of Official Analytical, Chemists International. In *Official Methods of Analysis* (18th ed.).
- AOAC. (2005b). *Official Method of Analysis. 18th ed, Association of Officiating Analytical Chemists.*
- AOAC. (2009). *Official Methods of Analysis of the Association of Official Analytical Chemists* (15th ed.).
- Aondoakaa, I. P. (2025). *Microbial and insect oils : A sustainable approach to functional lipid. March 2024*, 5–33. <https://doi.org/10.1002/aocs.12851>
- Ardoin, R., Marx, B. D., Boeneke, C., & Prinyawiwatkul, W. (2021). Original article Effects of cricket powder on selected physical properties and US consumer perceptions of whole-wheat snack crackers. *International Journal of Food Science and Technology*, 56(8), 4070–4080. <https://doi.org/10.1111/ijfs.15032>
- Aree, J. Y., & Puwastien, P. (2010). Ecology of Food and Nutrition Edible insects in Thailand : An unconventional protein source ? *Ecology of Food and Nutrition*, December 2014, 37–41. <https://doi.org/10.1080/03670244.1997.9991511>
- Assielou, B., Due, E. A., Koffi, D. M., & Kouame, P. (2015). Physicochemical characterization and fatty acid composition of *Oryctes owariensis* larvae oil. *Food and Environment Safety Journal*, 14(3), 320–326.
- Atukuri, J., Odong, B. B., & Muyonga, J. H. (2019). *Multi-response optimization of extrusion conditions of grain amaranth flour by response surface methodology. December 2018*, 4147–4162. <https://doi.org/10.1002/fsn3.1284>

- Ayieko, M. A., Ogola, H. J., & Ayieko, I. A. (2016). *Introducing rearing crickets (gryllids) at household levels : adoption , processing and nutritional value*. 2(3), 203–211. <https://doi.org/10.3920/JIFF2015.0080>
- Ayieko, M. A., Ogola, H. J., Ayieko, I. A., & Sciences, F. (2016). Introducing rearing crickets (gryllids) at household levels : adoption , processing and nutritional values. *Journal of Insects as Food and Feed*, 2(3), 203–211. <https://doi.org/10.3920/JIFF2015.0080>
- Aynalem, E. G., & Duraisamy, R. (2022). *Formulation and Optimization of Complementary Food Based on Its Nutritional and Antinutritional Analysis*. 2022. <https://doi.org/10.1155/2022/1126031>
- Azam, M., Singh, M., & Verma, D. K. (2016). Textural Properties of Kodo (*Paspalum scrobiculatum* L .) based Soy Fortified Ready to Eat Extruded Snacks using Response Surface Methodology. *Indian Journal of Science and Technology*, 9(January), 1–6. <https://doi.org/10.17485/ijst/2016/v9i4/84142>
- Azlan, A., Prasad, K. N., Khoo, H. E., Abdul-Aziz, N., Mohamad, A., Ismail, A., & Amom, Z. (2010). Comparison of fatty acids, vitamin E and physicochemical properties of *Canarium odontophyllum* Miq. (dabai), olive and palm oils. *Journal of Food Composition and Analysis*, 23(8), 772–776. <https://doi.org/10.1016/j.jfca.2010.03.026>
- Azzollini, D., Derossi, A., Fogliano, V., Lakemond, C. M. M., & Severini, C. (2018). Effects of formulation and process conditions on microstructure , texture and digestibility of extruded insect-riched snacks. *Innovative Food Science & Emerging Technologies*, 45(December 2016), 344–353. <https://doi.org/10.1016/j.ifset.2017.11.017>
- Baiano, A. (2020). Trends in Food Science & Technology Edible insects : An overview on nutritional characteristics , safety , farming , production technologies , regulatory framework , and socio-economic and ethical implications. *Trends in Food Science & Technology*, 100(March 2019), 35–50.

<https://doi.org/10.1016/j.tifs.2020.03.040>

- Banjo, A. D., Lawal, O. A., & Songonuga, E. A. (2006). The nutritional value of fourteen species of edible insects in southwestern Nigeria. *African Journal of Biotechnology*, 5(1684–5315), 298–301. <https://doi.org/10.5897/AJB05.250>
- Barker, D., Fitzpatrick, M. P., & Dierenfeld, E. S. (1998). *Nutrient Composition of Selected Whole Invertebrates*. 134, 123–134.
- Barroso, F. G., & Fabrikov, D. (2022). In Vitro Crude Protein Digestibility of Insects : A Review. *MDPI Insects*, 13(8), 1–19.
- Bas, D. (2007). *Modeling and optimization I: Usability of response surface methodology*. 78, 836–845. <https://doi.org/10.1016/j.jfoodeng.2005.11.024>
- Bawa, M., Songsermpong, S., Kaewtapee, C., & Chanput, W. (2020). Nutritional, sensory, and texture quality of bread and cookie enriched with house cricket (*Acheta domesticus*) powder. *Journal of Food Processing and Preservation*, 44(8), 1–9. <https://doi.org/10.1111/jfpp.14601>
- Bednarova, M., Borkovcova, M., & Komprda, T. (2013). Purine derivate content and amino acid profile in larval stages of three edible insects. *Ournal of the Science of Food and Agriculture*, 94(1), 71–76. <https://doi.org/10.1002/jsfa.6198>
- Belluco, S., Losasso, C., Maggioletti, M., Alonzi, C. C., Paoletti, M. G., & Ricci, A. (2013). Edible insects in a food safety and nutritional perspective: A critical review. *Comprehensive Reviews in Food Science and Food Safety*, 12(3), 296–313. <https://doi.org/10.1111/1541-4337.12014>
- Bernard, J. B., Allen, M. E., & Ullrey, D. E. (1997). Feeding captive insectivorous animals: nutritional aspects of insects as food. *Nutrition Advisory Group Handbook*, 25(August), 7.
- Biro, B., Sipos, M. A., Kovacs, A., Badak-Kerti, K., Pastztor-Huszar, K., & Gere, A. (2020). Cricket-Enriched Oat Biscuit : Technological Analysis and Sensory

- Evaluation. *Foods*, 9(11), 1–16.
- Bogusz, R., Piasecka-Ienartowicz, I., Wiktor, A., Nowacka, M., & Brzezi, R. (2026). *Characteristics of Oils Extracted from Yellow Mealworm (Tenebrio molitor L.) Dried with the Infrared-Convective Method*. 1–16.
- Botella-Martínez, C., Lucas-González, R., Pérez-Álvarez, J. A., Fernández-López, J., & Viuda-Martos, M. (2020). Assessment of chemical composition and antioxidant properties of defatted flours obtained from several edible insects. *Food Science and Technology International*, 108201322095885. <https://doi.org/10.1177/1082013220958854>
- Brai, A., Pasqualini, C., Poggialini, F., & Vagaggini, C. (2025). *Insects as Source of Nutraceuticals with Antioxidant, Antihypertensive, and Antidiabetic Properties: Focus on the Species Approved in Europe up to 2024*.
- Bravo-Núñez, Á., & Gómez, M. (2019). Physicochemical properties of native and extruded maize flours in the presence of animal proteins. *Journal of Food Engineering*, 243, 49–56. <https://doi.org/10.1016/j.jfoodeng.2018.09.005>
- Bresciani, A., Cardone, G., Jucker, C., Savoldelli, S., & Marti, A. (2022). Technological Performance of Cricket Powder. *Insects*, 13(6), 546.
- Bukkens, S. G. F. (1997). The nutritional value of edible insects. *Ecology of Food and Nutrition*, 36(2–4), 287–319. <https://doi.org/10.1080/03670244.1997.9991521>
- Burns-whitmore, B., Froyen, E. B., & Isom, K. A. (2024). *Vitamin D and Calcium — An Overview, Review of Metabolism, and the Importance of Co-Supplementation*. 588–608.
- Camacho-Hernández, I. L., Zazueta-Morales, J. J., Gallegos-Infante, J. A., Aguilar-Palazuelos, E., Rocha-Guzmán, N. E., Navarro-Cortez, R. O., Jacobo-Valenzuela, N., & Gómez-Aldapa, C. A. (2014). Effect of extrusion conditions on physicochemical characteristics and anthocyanin content of blue corn third-generation snacks. *CYTA - Journal of Food*, 12(4), 320–330.

<https://doi.org/10.1080/19476337.2013.861517>

- Camire, A. L., & Clydesdale, F. M. (1982). Analysis of Phytic Acid in Foods by HPLC. *Journal of Food Science*, 47(2), 575–578.
- Camire, M. E., Camire, A., & Krumhar, K. (1990). Chemical and nutritional changes in foods during extrusion. *Critical Reviews in Food Science & Nutrition*, 29(1), 35–57. <https://doi.org/10.1080/10408399009527513>
- Carlson, S. E., & Colombo, J. (2017). *Docosahexaenoic Acid and Arachidonic Acid Nutrition in Early Development*. 63(1), 453–471. <https://doi.org/10.1016/j.yapd.2016.04.011.Docosahexaenoic>
- Chadare, F. J., Idohou, R., Nago, E., Affonfere, M., Agossadou, J., Fassinou, T. K., Kénou, C., Honfo, S., Azokpota, P., Linnemann, A. R., & Hounhouigan, D. J. (2019). Conventional and food-to-food fortification: An appraisal of past practices and lessons learned. *Food Science and Nutrition*, 7(9), 2781–2795. <https://doi.org/10.1002/fsn3.1133>
- Chakravorty, J., Ghosh, S., Megu, K., Jung, C., & Meyer-Rochow, V. B. (2016). Nutritional and anti-nutritional composition of *Oecophylla smaragdina* (Hymenoptera: Formicidae) and *Odontotermes* sp. (Isoptera: Termitidae): Two preferred edible insects of Arunachal Pradesh, India. *Journal of Asia-Pacific Entomology*, 19(3), 711–720. <https://doi.org/10.1016/j.aspen.2016.07.001>
- Chakravorty, J., Ghosh, S., & Meyer-rochow, V. B. (2011). *Practices of entomophagy and entomotherapy by members of the Nyishi and Galo tribes, two ethnic groups of the state of Arunachal Pradesh*. 1–14. <https://doi.org/10.1186/1746-4269-7-5>
- Chan, E., Masatcioglu, T. M., & Koksel, F. (2019). Effects of different blowing agents on physical properties of extruded puffed snacks made from yellow pea and red lentil flours. *Journal of Food Process Engineering*, 42(3), 1–8. <https://doi.org/10.1111/jfpe.12989>
- Charoenngam, N., & Holick, M. F. (2020). *and Disease. Figure 1*, 1–28.

- Chen, X., Feng, Y., & Chen, Z. (2009). Common edible insects and their utilization in China: INVITED REVIEW. *Entomological Research*, 39(5), 299–303. <https://doi.org/10.1111/j.1748-5967.2009.00237.x>
- Cheseto, X., Baleba, S. B. S., Tanga, C. M., Kelemu, S., & Torto, B. (2020a). Chemistry and sensory characterization of a bakery product prepared with oils from African edible insects. *Foods*, 9, 800. <https://doi.org/10.3390/foods9060800>
- Cheseto, X., Baleba, S. B. S., Tanga, C. M., Kelemu, S., & Torto, B. (2020b). Chemistry and sensory characterization of a bakery product prepared with oils from African edible insects. *Foods*, 9(6). <https://doi.org/10.3390/foods9060800>
- Christensen, D. L., Orech, F. O., Mungai, M. N., Larsen, T., Friis, H., & Aagaard-Hansen, J. (2006). Entomophagy among the Luo of Kenya: A potential mineral source? *International Journal of Food Sciences and Nutrition*, 57(3–4), 198–203. <https://doi.org/10.1080/09637480600738252>
- Ciudad-mulero, M., Barros, L., Cámara, M., Morales, P., & Ferreira, I. C. F. R. (2018). Function extruded snack-type products developed from. *Food Function*, 9(2), 819–829. <https://doi.org/10.1039/c7fo01730h>
- Codex Alimentarius. (1992). *Programme mixte FAO/OMS sur les normes alimentaires*.
- Collavo, A., Cropscience, B., Huang, Y., & Paoletti, M. G. (2005). *Housecricket smallscale farming in Ecological implications of minilivestock: potential of insects, rodents, frogs and snails. January*.
- Crider, K. S., Bailey, L. B., & Berry, R. J. (2011). *Folic Acid Food Fortification—Its History, Effect, Concerns, and Future Directions*. 370–384. <https://doi.org/10.3390/nu3030370>
- Dagevos, H. (2021). A Literature Review of Consumer Research on Edible Insects: Recent Evidence and New Vistas from 2019 Studies. *Journal of Insects as Food and Feed*, 7(3), 249–259. <https://doi.org/10.3920/JIFF2020.0052>

- Dahdouh, S., Grande, F., Nájera, S., Vincent, A., Gibson, R., Bailey, K., King, J., Rittenschober, D., & Charrondiére, U. R. (2019). Development of the FAO / INFOODS / IZINCG Global Food Composition Database for Phytate. *Journal of Food Composition and Analysis*, 78(January), 42–48. <https://doi.org/10.1016/j.jfca.2019.01.023>
- Dalbhat, C. G., Mahato, D. K., & Mishra, H. N. (2019). Trends in Food Science & Technology Effect of extrusion processing on physicochemical, functional and nutritional characteristics of rice and rice-based products : A review. *Trends in Food Science & Technology*, 85(December 2018), 226–240. <https://doi.org/10.1016/j.tifs.2019.01.001>
- Danbaba, N., & Idakwo, P. Y. (2019). *Predictive Modeling and Optimization of Extrusion Cooking Process for Color Characteristics and Consumer Acceptability of Fortified Rice Snacks*. 13(1), 33–43. <https://doi.org/10.9790/2402-1301013343>
- Danbaba, N., Nkama, I., & Halidu, M. (2019). *Use of Response Surface Methodology (RSM) for Composite Blends of Low Grade Broken Rice Fractions and Full-fat Soybean Flour by a Twin-screw Extrusion Cooking Process*. 8(April), 14–29.
- Deroy, O., Reade, B., & Spence, C. (2015). *The insectivore ' s dilemma , and how to take the West out of it*. 44, 44–55. <https://doi.org/10.1016/j.foodqual.2015.02.007>
- Di Mattia, C., Battista, N., Sacchetti, G., & Serafini, M. (2019). Antioxidant Activities in vitro of Water and Liposoluble Extracts Obtained by Different Species of Edible Insects and Invertebrates. *Frontiers in Nutrition*, 6, 106. <https://doi.org/10.3389/fnut.2019.00106>
- Ding, Q., Ainsworth, P., Plunkett, A., Tucker, G., & Marson, H. (2006). The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. *Journal of Food Engineering*, 73, 142–148. <https://doi.org/10.1016/j.jfoodeng.2005.01.013>
- Djuricic, I., & Calder, P. C. (2021). *Beneficial Outcomes of Omega-6 and Omega-3*

Polyunsaturated Fatty Acids on Human Health : An Update for 2021.

- Dobermann, D., Swift, J. A., & Field, L. M. (2017). Opportunities and hurdles of edible insects for food and feed. *Nutrition Bulletin*, 42(4), 293–308. <https://doi.org/10.1111/nbu.12291>
- Durst, P., & Johnson, D. (2010). Forest insects as food: humans bite back. In *FAO*. [https://doi.org/ISBN 978-92-5-106488-7](https://doi.org/ISBN%20978-92-5-106488-7)
- Džima, M., Juráček, M., Bíro, D., Šimko, M., Gálik, B., Rolinec, M., Hanušovský, O., Kapusniaková, M., Kolbaská, K., & Vargová, E. (2025). *Chitin and Carbohydrate Composition of Eight Insect Species Used as Feed and Food*. 2025(4), 343–351.
- Ekop, & And Akpan, A. I. (2010). Proximate and anti-nutrient composition of four edible insects in Akwa Ibom State. *Nigeria World Journal of Applied Science and Technology*, 2(2), 224–231. www.wojast.com
- Ekpo, K. E., Onigbinde, A. O., & Asia, I. O. (2009). Pharmaceutical potentials of the oils of some popular insects consumed in southern Nigeria. *African Journal of Pharmacy and Pharmacology*, 3(2), 051–057.
- Eliasson, A. C. (2010). Gelatinization and retrogradation of starch in foods and its implications for food quality. In *Chemical Deterioration and Physical Instability of Food and Beverages*. Woodhead Publishing Limited. <https://doi.org/10.1533/9781845699260.2.296>
- Eromosele, C. O., & Paschal, N. H. (2003). Characterization and viscosity parameters of seed oils from wild plants. *Bioresource Technology*, 86(2), 203–205. [https://doi.org/10.1016/S0960-8524\(02\)00147-5](https://doi.org/10.1016/S0960-8524(02)00147-5)
- Espinoza, D. O., Boucher, J., Macotela, Y., Emanuelli, B., Ba, A. M., Gall, W., & Kahn, C. R. (2011). *Dietary Leucine - An Environmental Modifier of Insulin Resistance Acting on Multiple Levels of Metabolism*. 6(6). <https://doi.org/10.1371/journal.pone.0021187>

et al WHO, UNICEF, USAID. (2010). Indicators for Assessing Infant and Young Child Feeding Practices. *World Health Organization, WHA55 A55/*, 19. http://apps.who.int/iris/bitstream/handle/10665/44306/9789241599290%7B%5C_%7Deng.pdf?sequence=1%7B%5C%25%7D0Ahttp://whqlibdoc.who.int/publications/2008/9789241596664%7B%5C_%7Deng.pdf%7B%5C%25%7D5Cnh <http://www.unicef.org/programme/breastfeeding/innocenti.ht>

Falade, O. S., Adekunle, A. S., Aderogba, M. A., Atanda, S. O., Harwood, C., & Adewusi, S. R. (2007). Physicochemical properties, total phenol and tocopherol of some Acacia seed oils. *Journal of the Science of Food and Agriculture*, 88, 263–268. <https://doi.org/10.1002/jsfa>

FAO, WHO, U. (2001). *Human energy requirements Report of a Joint FAO/WHO/UNU Expert Consultation*. <https://www.fao.org/3/y5686e/y5686e00.htm>

FAO/GOK. (2018a). *Kenya food composition tables*. FAO.

FAO/GOK. (2018b). *Kenya Food Composition Tables*.

FAO/Government of Kenya. (2019). *Kenya Food Composition Tables*. <http://www.b4fn.org/resources/publications/publication-item/kenya-food-composition-tables-2018/>

FAO/WHO/UNU. (2007). *Protein and amino acid requirements. Report of a joint FAO/WHO/UNU expert consultation: protein and amino acid requirements in human nutrition*.

FAO. (2006). *Policy Brief: Food Security*. <https://reliefweb.int/report/world/policy-brief-food-security-issue-2-june-2006>

FAO. (2009). *World Summit on Food Security* (Issue November 2009).

FAO. (2013a). Edible insects. Future prospects for food and feed security. In *Food and Agriculture Organization of the United Nations* (Vol. 171, Issue January).

- FAO. (2013b). Edible insects. Future prospects for food and feed security. In *Food and Agriculture Organization of the United Nations* (Vol. 171). <https://doi.org/10.1017/CBO9781107415324.004>
- FAO. (2013c). *The state of food and agriculture: Food systems for better nutrition*.
- FAO, & WHO. (2001). Human Vitamin and Mineral Requirements. *Human Vitamin and Mineral Requirements*, 303. <https://doi.org/10.1016/B978-0-323-06619-8.10013-1>
- Farell, J. (2010). Digestion and absorption of nutrients and vitamins. In M. Feldman, L. S. Friedman, & L. J. Brandt (Eds.), *Gastrointestinal and liver disease. Pathophysiology/Diagnosis/Management* (9th Editio, pp. 1695–1734). Saunders Elsevier.
- Fellows, P. J. (2022). *Food Processing Technology Principles and Practice* (Fifth Edit). Woodhead Publishing. <https://doi.org/10.1016/C2019-0-04416-0>
- Fenta, T., & Kumar, Y. (2019). Evaluation of Processing Conditions for Lentil and Corn Blend Extrudate. In *Advances of Science and Technology* (Vol. 274, pp. 582–598). Springer International Publishing. <https://doi.org/10.1007/978-3-030-15357-1>
- Fernandez-Cassi, X., Supeanu, A., Jansson, A., Boqvist, S., & Vagsholm, I. (2018). Novel foods: A risk profile for the house cricket (*acheta domesticus*). *EFSA Journal*, 16(Special Issue), 1–15. <https://doi.org/10.2903/j.efsa.2018.e16082>
- Fernstrom, J. D. (2018). *4th Amino Acid Assessment Workshop Branched-Chain Amino Acids and Brain Function. January*, 1539–1546.
- Filli, K. B., Nkama, I., & Jideani, V. A. (2013). The effect of extrusion conditions on the physical and functional properties of millet–bambara groundnut based fura. *American Journal of Food Science and Technology*, 1(4), 87–101. <https://doi.org/10.12691/ajfst-1-4-5>

- Finke, M. D. (2002a). Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo Biology*, 21(3), 269–285. <https://doi.org/10.1002/zoo.10031>
- Finke, M. D. (2002b). Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo Biology*, 21(3), 269–285. <https://doi.org/10.1002/zoo.10031>
- Finke, M. D. (2004). Nutrient contents of insects. In *Encyclopedia of Entomology* (pp. 2623–2646).
- Finke, M. D. (2007). Estimate of Chitin in Raw Whole Insects. *Zoo Biology*, 26(2), 93–104. <https://doi.org/10.1002/zoo>
- Finke, M. D., & Oonincx, D. (2014). Insects as food for insectivores. In *Mass Production of Beneficial Organisms* (pp. 511–540). INC. <https://doi.org/10.1016/B978-0-12-822106-8.00019-1>
- Frango, B. E., & Hautrive, T. P. (2012). CORTES CÁRNEOS COMERCIAIS DE AVESTRUZ , SUÍNO ,. *Brazilian Journal of Food {&} Nutrition*, 327–334.
- Gadzama, I. U. (2025). Effects of extrusion on insect-based feeds: Nutritional enhancement and processing challenges. *Journal of Agriculture and Biotechnology*.
- Galbraith, G. M. P. (2008). Chitin induces accumulation in tissue of innate immune cells associated with allergy. *Yearbook of Dermatology and Dermatologic Surgery*, 2008(7140), 182–183. [https://doi.org/10.1016/s0093-3619\(08\)70817-7](https://doi.org/10.1016/s0093-3619(08)70817-7)
- Gao, Y., Sun, Y., Zhang, Y., Sun, Y., & Jin, T. (2022). Extrusion Modification: Effect of Extrusion on the Functional Properties and Structure of Rice Protein. *Processes*, 10(9), 1–14. <https://doi.org/10.3390/pr10091871>
- Garcia-Segovia, P., Igual, M., & Martinez-Monzo, J. (2020). Physicochemical Properties and Consumer. *Foods*, 9(7).

- Gbenyi, D., Nkama, I., & Badau, M. (2016). Modeling Mineral Profile of Extruded Sorghum Bambara Groundnut Breakfast Cereals. *British Journal of Applied Science & Technology*, 17(4), 1–14. <https://doi.org/10.9734/bjast/2016/28700>
- Ghosh, S., Lee, S., & Jung, C. (2017). Nutritional composition of five commercial edible insects in South Korea. *Journal of Asia-Pacific Entomology*, 20(2), 686–694. <https://doi.org/10.1016/j.aspen.2017.04.003>
- Ghosh, S., Lee, S. M., Jung, C., & Meyer-Rochow, V. B. (2017). Nutritional composition of five commercial edible insects in South Korea. *Journal of Asia-Pacific Entomology*, 20(2), 686–694. <https://doi.org/10.1016/j.aspen.2017.04.003>
- Ghosh, S., Suri, D., & Uauy, R. (2012). *Assessment of protein adequacy in developing countries : quality matters*. <https://doi.org/10.1017/S0007114512002577>
- Gibson, R. S. (2011). *Combating Micronutrient Deficiencies : Food-based Approaches*. CAB International and FAO.
- Gogus, U., & Smith, C. (2010). N-3 omega fatty acids: a review of current knowledge. *International Journal of Food Science and Technology*, 45(3), 417–436. <https://doi.org/10.1111/j.1365-2621.2009.02151.x>
- Gonzalez, C. M., Garzon, R., & Rosell, C. M. (2019). Insects as ingredients for bakery goods. a comparison study of. *Innovative Food Science & Emerging Technologies*, 51, 205–210.
- Goredema-Matongera, N., Ndhlela, T., Magorokosho, C., Kamutando, C. N., Biljon, A. van, & Labuschagne, M. (2021). *Multinutrient Biofortification of Maize (Zea mays L.) in Africa: Current Status, Opportunities and Limitations*. 1–24.
- Gravel, A., & Doyen, A. (2020). The use of edible insect proteins in food : Challenges and issues related to their functional properties. *Innovative Food Science and Emerging Technologies*, 59(October 2019), 102272. <https://doi.org/10.1016/j.ifset.2019.102272>

- Grillenberger, M., Neumann, C. G., Murphy, S. P., Bwibo, N. O., Veer, P. Van, Hautvast, J. G. A. J., & West, C. E. (2018). *Animal Source Foods to Improve Micronutrient Nutrition and Human Function in Developing Countries Food Supplements Have a Positive Impact on Weight Gain and the Addition of Animal Source Foods Increases Lean Body Mass of. May*, 3957–3964.
- Guillén, M. D., & Cabo, N. (2002). Fourier transform infrared spectra data versus peroxide and anisidine values to determine oxidative stability of edible oils. *Food Chemistry*, 77(4), 503–510. [https://doi.org/10.1016/S0308-8146\(01\)00371-5](https://doi.org/10.1016/S0308-8146(01)00371-5)
- Guiné, R. P. F., Correia, P., Coelho, C., & Costa, C. A. (2021). The role of edible insects to mitigate challenges for sustainability. *Open Agriculture*, 6(1), 24–36. <https://doi.org/10.1515/opag-2020-0206>
- Gulati, P., Brahma, S., & Rose, D. J. (2020). Impacts of extrusion processing on nutritional components in cereals and legumes : Carbohydrates , proteins , lipids , vitamins , and minerals. In *Extrusion Cooking*. Elsevier Inc. <https://doi.org/10.1016/B978-0-12-815360-4.00013-4>
- Gulati, P., & Rose, D. J. (2018). Effect of extrusion on folic acid concentration and mineral element dialyzability in 2 Great Northern beans (*Phaseolus vulgaris* L.). *Food Chemistry*, 269, 118–124.
- Guy, R. obin. (2001). *Extrusion Cooking: Technologies and Applications* (Vol. 61). Woodhead publishing. books.google.com
- H. Nouredini, B. C. Teoh, L. D. C. (1992). Densities of vegetable oils and fatty acids. *Journal of the American Oil Chemists' Society*, 69(12), 1184–1188. <https://doi.org/https://doi.org/10.1007/BF02637677>
- Halloran, A., Hanboonsong, Y., Roos, N., & Bruun, S. (2017). Life cycle assessment of cricket farming in north-eastern Thailand. *Journal of Cleaner Production*, 156, 83–94. <https://doi.org/10.1016/j.jclepro.2017.04.017>
- Haritha, D., Vijayalakshmi, V., & Gulla, S. (2012). Development and evaluation of

- garlic incorporated ready-to-eat extruded snacks. *Journal of Food Science and Technology*, 51(11), 3425–3431. <https://doi.org/10.1007/s13197-012-0853-2>
- Harper, J. M. (1981). *Extrusion of Foods (Vol. 1 & 2)* (7th Editio). CRC Press.
- Harper, J. M., & Group, F. (2019). *Extrusion of Foods V olume I*. CRC Press. api.taylorfrancis.com
- Hasan, M. N., & Sultan, M. Z. (2014). Significance of Fermented Food in Nutrition and Food Science. *Journal of Scientific Research*, 6(2), 373–386.
- Homann, A. M., Ayieko, M. A., Konyole, S. O., & Roos, N. (2017). Acceptability of biscuits containing 10% cricket (*Acheta domesticus*) compared to milk biscuits among 5-10-year-old Kenyan schoolchildren. *Journal of Insects as Food and Feed*, 3(2), 95–103. <https://doi.org/10.3920/jiff2016.0054>
- Hou, L., Shi, Y., Zhai, P., & Le, G. (2007). Antibacterial activity and in vitro anti-tumor activity of the extract of the larvae of the housefly (*Musca domestica*). *Journal of Ethnopharmacology*, 111(2), 227–231. <https://doi.org/10.1016/j.jep.2006.11.015>
- HSU, H. W., VAVAK, D. L., SATTERLEE, L. D., & MILLER, G. A. (1977). a Multienzyme Technique for Estimating Protein Digestibility. *Journal of Food Science*, 42(5), 1269–1273. <https://doi.org/10.1111/j.1365-2621.1977.tb14476.x>
- Huis, V. (2013). *Edible insects Future prospects for food and feed security*. FAO.
- Huis, A. van, Itterbeeck, J. Van, Klunder, H., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). *Edible insects Future prospects for food and feed security*. Food and Agriculture Organization of the United Nations.
- Hur, S. J., Lim, B. O., Decker, E. A., & McClements, D. J. (2011). In vitro human digestion models for food applications. *Food Chemistry*, 125(1), 1–12. <https://doi.org/10.1016/j.foodchem.2010.08.036>
- Ifie, S. E., Dangana, R. S., Swase, D., Okon, M. Ben, Makena, W., Agunloye, M. O.,

- Ugwu, C. N., Ifie, J. E., Odoma, S., Babangida, A. I., Aja, P. M., & Augustine, A. (2026). *Nutritional composition of Zea mays L : A comprehensive Review of Macronutrients , Micronutrients , and Bioactive.* 1–26.
- Igiehon, N. O., Babalola, O. O., Cheseto, X., & Torto, B. (2021). Effects of rhizobia and arbuscular mycorrhizal fungi on yield, size distribution and fatty acid of soybean seeds grown under drought stress. *Microbiological Research*, 242, 126640. <https://doi.org/10.1016/j.micres.2020.126640>
- Igual, M., García-Segovia, P., & Martínez-Monzó, J. (2020a). Effect of *Acheta domesticus* (house cricket) addition on protein content, colour, texture, and extrusion parameters of extruded products. *Journal of Food Engineering*, 282, 110032. <https://doi.org/10.1016/j.jfoodeng.2020.110032>
- Igual, M., García-Segovia, P., & Martínez-Monzó, J. (2020b). Effect of *Acheta domesticus* (house cricket) addition on protein content, colour, texture, and extrusion parameters of extruded products. *Journal of Food Engineering*, 282(December 2019). <https://doi.org/10.1016/j.jfoodeng.2020.110032>
- Imathiu, S. (2020). Benefits and food safety concerns associated with consumption of edible insects. *NFS Journal*, 18, 1–11. <https://doi.org/10.1016/j.nfs.2019.11.002>
- Jacob, A. A., Emenike, A. F., Kayode, A., Olesgun, O., Uzoma, A., & Rukayat, K. Q. (2013). Entomophagy: A Panacea for Protein-Deficient-Malnutrition and Food Insecurity in Nigeria. *Journal of Agricultural Science*, 5, 25–31.
- Jermacz, I., Maj, J., Morzycki, J. . W., & Wojtkielewicz, A. (2008). *GC-MS Analysis of β -Carotene Ethenolysis Products and their Synthesis as Potentially Active Vitamin A Analogues GC-MS Analysis of β -Carotene Ethenolysis Products and their Synthesis as Potentially Active Vitamin A Analogues.* 6516. <https://doi.org/10.1080/15376510701623656>
- Jimenez-garcia, S. N., Vazquez-cruz, M. A., Garcia-mier, L., Contreras-medina, L. M., Guevara-gonzález, R. G., & Garcia-trejo, J. F. (2018). Properties of Secondary Metabolites in Berries. In *Therapeutic Foods*. Elsevier Inc.

<https://doi.org/10.1016/B978-0-12-811517-6/00013-1>

- Jonas-Levi, A., & Martinez, J. J. I. (2017). The high level of protein content reported in insects for food and feed is overestimated. *Journal of Food Composition and Analysis*, *62*, 184–188. <https://doi.org/10.1016/j.jfca.2017.06.004>
- Joseph, M., Guo, Q., Lindshield, B., & Adedeji, A. A. (2025). *Characterization of Extruded Sorghum-Soy Blends to Develop Pre-Cooked and Nutritionally Dense Fortified Blended Foods*.
- Kaplan, M., Karaman, K., Kardes, Y. M., & Kale, H. (2019). Phytic acid content and starch properties of maize (*Zea mays L.*): Effects of irrigation process and nitrogen fertilizer Running title : Effect of irrigation and fertilizer on maize starch and phytic acid. *Food Chemistry*. <https://doi.org/10.1016/j.foodchem.2019.01.029>
- Kariuki, G. M., Njaramba, J., & Ombuki, C. (2020). Maize Output Supply Response to Climate Change in Kenya : An Econometric Analysis. *European Scientific Journal*, *16*(3), 63–83. <https://doi.org/10.19044/esj.2020.v16n3p63>
- Kauppi, S. M., Pettersen, I. N., & Boks, C. (2019). Consumer acceptance of edible insects and design interventions as adoption strategy. *International Journal of Food Design*, *4*(1), 197–207. <https://doi.org/10.1386/ijfd.4.1.39>
- Kaur, G. J., Rehal, J., Singh, A. K., Singh, B., Kaur, A., & Kendra, K. V. (2014). *OPTIMIZATION OF EXTRUSION PARAMETERS FOR DEVELOPMENT OF READY-TO-EAT BREAKFAST CEREAL USING RSM*. *33*(2), 77–86. <https://doi.org/10.5958/0976-0563.2014.00580.6>
- Kelemu, S., Niassy, S., Torto, B., Fiaboe, K., Affognon, H., Tonnang, H., Maniania, N. K., & Ekesi, S. (2015). African edible insects for food and feed: Inventory, diversity, commonalities and contribution to food security. *Journal of Insects as Food and Feed*, *1*(2), 103–119. <https://doi.org/10.3920/JIFF2014.0016>
- Kenya, F. of. (2018). *Kenya Food Composition Tables*. Food and Agriculture

Organization (FAO). <http://www.fao.org/3/19120EN/i9120en.pdf>

- Khatab, R. Y., & Arntfield, S. D. (2009). Nutritional quality of legume seeds as affected by some physical treatments 2. Antinutritional factors. *LWT - Food Science and Technology*, 42(6), 1113–1118. <https://doi.org/10.1016/j.lwt.2009.02.004>
- Khatun, H., Claes, J., Smets, R., Winne, A. De, Akhtaruzzaman, M., & Van, M. (2021). Characterization of freeze-dried, oven-dried and blanched house crickets (*Acheta domesticus*) and Jamaican field crickets (*Gryllus assimilis*) by means of their physicochemical properties and volatile compounds. *European Food Research and Technology*, 247, 1291–1305.
- Khorr, E. (2002). Chitin: a biomaterial in waiting: Biomaterials. *Current Opinion in Solid State and Materials Science*, 6(4), 313–317.
- Kim, H. W., Setyabrata, D., Lee, Y. J., Jones, O. G., & Kim, Y. H. B. (2016). Pre-treated mealworm larvae and silkworm pupae as a novel protein ingredient in emulsion sausages. *Innovative Food Science and Emerging Technologies*, 38, 116–123. <https://doi.org/10.1016/j.ifset.2016.09.023>
- Kinyuru, J., Kipkoech, C., Imathiu, S., Konyole, S., & Roos, N. (2021). Acceptability of cereal-cricket porridge compared to cereal and cereal-milk- porridges among caregivers and nursery school children in Uasin Gishu, Kenya. *International Journal of Tropical Insect Science*, 41(3), 2007–2013. <https://doi.org/10.1007/s42690-020-00388-1>
- Kinyuru, J. N. (2020). Oil characteristics and influence of heat processing on fatty acid profile of wild harvested termite (*Macrotermes subhylanus*) and long-horned grasshopper (*Ruspolia differens*). *International Journal of Tropical Insect Science*. <https://doi.org/10.1007/s42690-020-00337-y>
- Kinyuru, J. N., & G. M. Kenji, S. N. M. and M. A. (2010). Nutritional potential of longhorn grasshopper (. *Journal of Agriculture, Science and Technology*, 1(1), 32–46.

- Kinyuru, J. N., G. M. Kenji, S. N. M., & Ayieko, M. (2010). Nutritional potential of longhorn grasshopper (. *Journal of Agriculture, Science and Technology*, 1(1), 32–46.
- Kinyuru, J. N., Kenji, G. M., Njoroge, S. M., & Ayieko, M. (2010). Effect of processing methods on the in vitro protein digestibility and vitamin content of edible winged termite (*Macrotermes subhylanus*) and grasshopper (*Ruspolia differens*). *Food and Bioprocess Technology*, 3(5), 778–782.
- Kinyuru, J. N., Konyole, S. O., Roos, N., Onyango, C. a., Owino, V. O., Owuor, B. O., Estambale, B. B., Friis, H., Aagaard-Hansen, J., & Kenji, G. M. (2013). Nutrient composition of four species of winged termites consumed in western Kenya. *Journal of Food Composition and Analysis*, 30(2), 120–124. <https://doi.org/10.1016/j.jfca.2013.02.008>
- Kipkoech, C. (2019). *Nutrient profile, prebiotic potential of edible cricket, and effect of cricket based porridge on growth, haemoglobin and safety acid levels of school children* (Vol. 23, Issue 3). Jomo Kenyatta University of Agriculture and Technology.
- KNBS. (2020). *Economic Survey*.
- KNBS. (2022). *Kenya Demographic and Health Survey 2022:Key Indicators Report*.
- Konyole, S. O., Kinyuru, J. N., Owuor, B. O., Kenji, G. M., Onyango, C. A., Estambale, B. B., Friis, H., Roos, N., & Owino, V. O. (2012). Acceptability of Amaranth Grain-based Nutritious Complementary Foods with Daga Fish (*Rastrineobola argentea*) and Edible Termites (*Macrotermes subhylanus*) Compared to Corn Soy Blend Plus among Young Children/Mothers Dyads in Western Kenya. *Journal of Food Research*, 1(3), 111. <https://doi.org/10.5539/jfr.v1n3p111>
- Kothakota, A., Jindal, N., & Thimmaiah, B. (2013). Full Length Research Paper A study on evaluation and characterization of extruded product by using various by-products. *African Journal of Food Science*, 7(December), 485–497.

<https://doi.org/10.5897/AJFS2013.1065>

- Kou, L., & Adámková, A. (2016). Nutritional and sensory quality of edible insects. *NFS Journal*, 4, 22–26. <https://doi.org/10.1016/j.nfs.2016.07.001>
- Kouřimská, L., & Adámková, A. (2016). Nutritional and sensory quality of edible insects. *NFS Journal*, 4, 22–26. <https://doi.org/10.1016/j.nfs.2016.07.001>
- Kröncke, N., Bösch, V., Woyzichovski, J., & Benning, R. (2018). Comparison of suitable drying processes for mealworms (*Tenebrio molitor*). *Innovative Food Science and Emerging Technologies*, 50, 20–25. <https://doi.org/10.1016/j.ifset.2018.10.009>
- Kruger, J., Taylor, J. R. N., Ferruzzi, M. G., & Debelo, H. (2020). What is food-to-food fortification? A working definition and framework for evaluation of efficiency and implementation of best practices. *Comprehensive Reviews in Food Science and Food Safety*, 19(6), 3618–3658. <https://doi.org/10.1111/1541-4337.12624>
- Kruka, V. R., Cadena, E. R., & Long, T. E. (1995). cloud-point Determination for Crude oil. *Journal of Petroleum Technology*, 47(8), 681–687. <https://doi.org/10.2118/31032-PA>
- Kumar, N., Sarkar, B. C., & Sharma, H. K. (2010). Development and characterization of extruded product of carrot pomace, rice flour and pulse powder. *African Journal of Food Science*, 4(11), 703–717.
- Kumari, M., & Jain, S. (2012). Tannins: An Antinutrient with Positive Effect to Manage Diabetes. *Research Journal of Recent Sciences*, 1(12), 70–73. www.isca.in
- Kunatsa, Y., Chidewe, C., & Zvidzai, C. J. (2020). Phytochemical and anti-nutrient composite from selected marginalized Zimbabwean edible insects and vegetables. *Journal of Agriculture and Food Research*, 2, 100027. <https://doi.org/10.1016/j.jafr.2020.100027>

- Kurpad, A. V., Raj, T., El-khoury, A., Beaumier, L., Kuriyan, R., Srivatsa, A., Borgonha, S., Selvaraj, A., Regan, M. M., & Young, V. R. (2001). *Lysine requirements of healthy adult Indian subjects , measured by an indicator amino acid balance technique 1 – 3*. 900–907.
- Kutwah, M. A., David-kigaru, D. M., & Kobia, J. (2026). *Are teenagers in Kenya physically active ? The nexus between physical activity and nutrition status of Kenyan teenagers : A cross-sectional study*. 1–21. <https://doi.org/10.1371/journal.pgph.0005807>
- Kweyu, R., Makokha, M., & Asokan, S. M. (2026). *Climate change and food insecurity : perspectives from Kalama in Machakos County ,. February*. <https://doi.org/10.3389/fsufs.2026.1763455>
- Lam, A. C. Y., Karaca, A. C., Tyler, R. T., & Nickerson, M. T. (2018). Pea protein isolates : Structure , extraction , and functionality. *Food Reviews International*, 34(2), 126–147. <https://doi.org/10.1080/87559129.2016.1242135>
- Laroche, M., Perreault, V., Marciniak, A., Gravel, A., Chamberland, J., & Doyen, A. (2019). Comparison of conventional and sustainable lipid extraction methods for the production of oil and protein isolate from edible insect meal. *Foods*, 8(11). <https://doi.org/10.3390/foods8110572>
- Larrea, M. A., Chang, Y. K., & Martínez Bustos, F. (2005a). Effect of some operational extrusion parameters on the constituents of orange pulp. *Food Chemistry*, 89(2), 301–308. <https://doi.org/10.1016/j.foodchem.2004.02.037>
- Larrea, M. A., Chang, Y. K., & Martínez Bustos, F. (2005b). Effect of some operational extrusion parameters on the constituents of orange pulp. *Food Chemistry*, 89(2), 301–308. <https://doi.org/10.1016/j.foodchem.2004.02.037>
- Latunde-Dada, G. O., Yang, W., & Aviles, M. V. (2016). In vitro iron availability from insects and sirloin beef 1. *Ournal of Agricultural and Food Chemistry*, 64(44), 8420–8424. <https://doi.org/10.1021/acs.jafc.6b03286>

- Latunde-Dada, G. O., Yang, W., & Vera Aviles, M. (2016). In Vitro Iron Availability from Insects and Sirloin Beef. *Journal of Agricultural and Food Chemistry*, 64(44), 8420–8424. <https://doi.org/10.1021/acs.jafc.6b03286>
- Layman, D. K., & Walker, D. A. (2018). Branched-Chain Amino Acids : Metabolism , Physiological Function , and Application Potential Importance of Leucine in Treatment of Obesity and the. *The Journal of Nutrition*, 1(April), 319–323. <https://pubmed.ncbi.nlm.nih.gov/16365106/>
- Lee, C. G., Da Silva, C. A., Lee, J. Y., Hartl, D., & Elias, J. A. (2008). Chitin regulation of immune responses: an old molecule with new roles. *Current Opinion in Immunology*, 20(6), 684–689. <https://doi.org/10.1016/j.coi.2008.10.002>
- Lee, D. Y., Lee, S. Y., Yun, S. H., Lee, J., Jr, E. M., Park, J., Choi, Y., Han, D., & Kim, J. S. (2024). *Current Technologies and Future Perspective in Meat Analogs Made from Plant , Insect , and Mycoprotein Materials : A Review*. 44(1), 1–18.
- Lee, M. H., Kim, T., Yoon, J., In, H., Kang, M., Won, H., & Choi, Y. (2022). Physicochemical characteristics and aroma patterns of oils prepared from edible insects. *LWT*, 167(August), 113888. <https://doi.org/10.1016/j.lwt.2022.113888>
- Lehtovaara, V. J., Valtonen, A., Sorjonen, J., Hiltunen, M., Rutaro, K., Malinga, G. M., Nyeko, P., & Roininen, H. (2017). The fatty acid contents of the edible grasshopper *Ruspolia differens* can be manipulated using artificial diets. *Journal of Insects as Food and Feed*, 3(4), 253–262. <https://doi.org/10.3920/JIFF2017.0018>
- Li, M., Hasjim, J., Xie, F., Halley, P. J., & Gilbert, R. G. (2014). Shear degradation of molecular , crystalline , and granular structures of starch during extrusion. *Starch-Stärke*, 66(7–8), 595–605. <https://doi.org/10.1002/star.201300201>
- Liang, Z., Zhu, Y., Leonard, W., & Fang, Z. (2024). Recent advances in edible insect processing technologies. *Food Research International*, 182(February), 114137. <https://doi.org/10.1016/j.foodres.2024.114137>

- Libert, B., & Franceschi, V. R. (1987). Oxalate in Crop Plants. *Journal of Agricultural and Food Chemistry*, 35(6), 926–938. <https://doi.org/10.1021/jf00078a019>
- Lisboa, H. M., Andrade, R., Batista, L., Costa, M. E., & Sarinho, A. (2025). *Harnessing Insects as Novel Food Ingredients : Nutritional , Functional , and Processing Perspectives.*
- Lisboa, H. M., Nascimento, A., Sarinho, A., & Maria, F. (2024). *Unlocking the Potential of Insect-Based Proteins : Sustainable Solutions for Global Food Security and Nutrition.*
- Liu, D., Cai, J., Xie, C. chu, Liu, C., & Chen, Y. hua. (2010). Purification and partial characterization of a 36-kDa chitinase from *Bacillus thuringiensis* subsp. *colmeri*, and its biocontrol potential. *Enzyme and Microbial Technology*, 46(3–4), 252–256. <https://doi.org/10.1016/j.enzmictec.2009.10.007>
- Liu, S., Sun, J., Yu, L., Zhang, C., Bi, J., Zhu, F., Qu, M., & Yang, Q. (2012). Antioxidant activity and phenolic compounds of *Holotrichia parallela* Motschulsky extracts. *Food Chemistry*, 134(4), 1885–1891. <https://doi.org/10.1016/j.foodchem.2012.03.091>
- Lopez-Huertas, E. (2010). Health effects of oleic acid and long chain omega-3 fatty acids (EPA and DHA) enriched milks. A review of intervention studies. *Pharmacological Research*, 61(3), 200–207. <https://doi.org/10.1016/j.phrs.2009.10.007>
- Lthwab, S. A. A., & Alhomaïd, R. M. (2021). Effect of migratory locust (*Locusta migratoria*) powder incorporation on nutritional and sensorial properties of wheat flour bread. *British Food Journal*, 123(11), 3576–3591. <https://doi.org/10.1108/BFJ-11-2020-1052>
- Macharia, T. N., Ochola, S., & Mutua, M. K. (2018). *Association between household food security and infant feeding practices in urban informal settlements in Nairobi , Kenya.* <https://doi.org/10.1017/S2040174417001064>

- Mafu, A., Ketnawa, S., Phongthai, S., Schonlechner, R., & Rawdkuen, S. (2022). Whole Wheat Bread Enriched with Cricket Powder as an Alternative Protein. *Foods*, 11(14), 2142.
- Magara, H. J. O., Niassy, S., Ayieko, M. A., Mukundamago, M., Egonyu, J. P., Tanga, C. M., Kimathi, E. K., Ongere, J. O., Fiaboe, K. K. M., Hugel, S., Orinda, M. A., Roos, N., & Ekesi, S. (2021). Edible Crickets (Orthoptera) Around the World: Distribution, Nutritional Value, and Other Benefits—A Review. *Frontiers in Nutrition*, 7(January), 1–23. <https://doi.org/10.3389/fnut.2020.537915>
- Mahungu, S. M., Diaz-Mercado, S., Li, J., Schwenk, M., Singletary, K., & Faller, J. (1999). Stability of isoflavones during extrusion processing of corn/soy mixture. *Journal of Agricultural and Food Chemistry*, 47(1), 279–284. <https://doi.org/10.1021/jf980441q>
- Maiyo, N. C., Khamis, F. M., Okoth, M. W., Abong, G. O., Subramanian, S., Egonyu, J. P., Xavier, C., Ekesi, S., Omuse, E. R., Nakimbugwe, D., Ssepuuya, G., Ghemoh, C. J., & Tanga, C. M. (2022). *Nutritional Quality of Four Novel Porridge Products Blended with Edible Cricket (Scapsipedus icipe) Meal for Food*.
- Mariod, A. A. (2017). Fatty acid profile and physico-chemical properties of some edible insects. *Journal of the American Oil Chemists' Society*, 94(1), 111–120.
- Mariod, A. A. (2020). *Edible Insects Processing, Health and Nutritional Advantages*. Elsevier.
- Martínez-monz, J., & Igual, M. (2020). Effect of Acheta domesticus (house cricket) addition on protein content , colour , texture , and extrusion parameters of extruded products. *Journal of Food Engineering*, 282(March), 1–7. <https://doi.org/10.1016/j.jfoodeng.2020.110032>
- Matengo, L. A. (2016). *Influence of school feeding programme on children's 'participation in pre-school in Kisumu east sub-county, Kenya* [University of Nairobi]. <http://hdl.handle.net/11295/99770>

- Meng, X., Threinen, D., Hansen, M., & Driedger, D. (2010). Effects of extrusion conditions on system parameters and physical properties of a chickpea flour-based snack. *Food Research International*, 43(2), 650–658. <https://doi.org/10.1016/j.foodres.2009.07.016>
- Mertz, E. T., Hassen, M. M., & Cairns Whittern, C. (1984). Pepsin digestibility of proteins in sorghum and other major cereals. *Proceedings of the National Academy of Sciences of the United States of America*, 81(1 D), 1–2. <https://doi.org/10.1073/pnas.81.1.1>
- Meyer-Rochow, V. B., Gahukar, R. T., Ghosh, S., & Jung., C. (2021). *Chemical Composition, Nutrient Quality and Acceptability of Edible Insects Are Affected by Species, Developmental Stage, Gender, Diet, and Processing Method*.
- Mihaela Hăbeanu, A. G. and T. M. (2023). *Nutritional Value of Silkworm Pupae (Bombyx mori) with Emphases on Fatty Acids Profile and Their Potential*.
- Millward, D. J. (2012). *Knowledge Gained from Studies of Leucine Consumption in Animals and Humans 1 – 3*. 5. <https://doi.org/10.3945/jn.111.157370.2212S>
- MOH. (2011). *The Kenya National Micronutrient Survey*.
- MOH. (2019). *Addressing Adolescent Malnutrition final.pdf*.
- Mohammed, I., Forsido, S. F., & Kuyu, C. G. (2024). Optimization of barrel temperature and feed moisture content for better physicochemical and sensory properties of extruded snacks from blends of finger millet, sweet potato, and soybean composite flour using response surface methodology. *Discover Applied Sciences*, 6(4). <https://doi.org/10.1007/s42452-024-05822-4>
- Montowska, M., Rybicka, I., & Fornal, E. (2019). Nutritional value , protein and peptide composition of edible cricket powders. *Food Chemistry*, 289(March), 130–138. <https://doi.org/10.1016/j.foodchem.2019.03.062>
- Moreki, J. C., Tiroesele, B., & Chiripasi, S. C. (2012). Prospects of Utilizing Insects

as Alternative Sources of Protein in Poultry Diets in Botswana: a Review. *Journal of Animal Science and Biotechnology*, 2(28), 649–658. www.grjournals.com

Moscicki, L. (2011). *Extrusion-Cooking Techniques: Applications, Theory and Sustainability*. Wiley VCH.

Mouritsen, O. G., Duelund, L., Calleja, G., & Frøst, M. B. (2017). Flavour of fermented fish, insect, game, and pea sauces: Garum revisited. *International Journal of Gastronomy and Food Science*, 9(May), 16–28. <https://doi.org/10.1016/j.ijgfs.2017.05.002>

Mousavi, S. M., Mofrad, M. D., do Nascimento, I. J. B., Milajerdi, A., Mokhtari, T., & Esmailzadeh, A. (2020). The effect of zinc supplementation on blood pressure: a systematic review and dose–response meta-analysis of randomized-controlled trials. *European Journal of Nutrition*, 59(5), 1815–1827. <https://doi.org/10.1007/s00394-020-02204-5>

Muhammad, H. S., Javed, F., & Park, J. (2023). Applications of HPP for Microbial Food Safety. In *Advances in Food Applications for High Pressure Processing Technology* (pp. 15–29).

Murugu, D. K., Onyango, A. N., Ndiritu, A. K., Osuga, I. M., Xavier, C., Nakimbugwe, D., & Tanga, C. M. (2021). From Farm to Fork: Crickets as Alternative Source of Protein, Minerals, and Vitamins. *Frontiers in Nutrition*, 8(August). <https://doi.org/10.3389/fnut.2021.704002>

Musundire, R., Zvidzai, C. J., Chidewe, C., Samende, B. K., Chemura, A., Technology, P., & Way, O. M. (2016). Habitats and nutritional composition of selected edible insects in Zimbabwe. *Journal of Insects as Food and Feed*, 2(3), 189–198. <https://doi.org/10.3920/JIFF2015.0083>

Musundire, R., Zvidzai, C. J., Chidewe, C., Samende, B. K., & Manditsera, F. A. (2014). Nutrient and anti-nutrient composition of *Henicus whellani* (Orthoptera: Stenopelmatidae), an edible ground cricket, in south-eastern Zimbabwe. *International Journal of Tropical Insect Science*, 34(4), 223–231.

<https://doi.org/10.1017/S1742758414000484>

- Muzzarelli, R. A. A. (2010). Chitins and chitosans as immunoadjuvants and non-allergenic drug carriers. *Marine Drugs*, 8(2), 292–312. <https://doi.org/10.3390/md8020292>
- Mwangi, M. N., Oonincx, D. G. A. B., Stouten, T., Veenenbos, M., Melse-Boonstra, A., Dicke, M., & Van Loon, J. J. A. (2018). Insects as sources of iron and zinc in human nutrition. *Nutrition Research Reviews*, 31(2), 248–255. <https://doi.org/10.1017/S0954422418000094>
- Nahemiah, D., Nkama, I., Badau, M., & Idakwo, P. Y. (2018). *STATISTICAL MODELING AND OPTIMIZATION OF PROCESSING CONDITIONS OF TWIN-SCREW EXTRUDED RICE-LEGUME INSTANT BREAKFAST GRUEL. January 2019.*
- Naseem, R., Majeed, W., Rana, N., Koch, E. B. de A., & Naseem, M. R. (2021). Entomophagy: an innovative nutritional and economic navigational tool in race of food security. *International Journal of Tropical Insect Science*, 41(3), 2211–2221. <https://doi.org/10.1007/s42690-020-00284-8>
- Negash, Y. A., Amare, D. E., Bitew, B. D., & Dagne, H. (2019). Assessment of quality of edible vegetable oils accessed in Gondar City, Northwest Ethiopia. *BMC Research Notes*, 12(1), 1–5. <https://doi.org/10.1186/s13104-019-4831-x>
- No, H. K., Meyers, S. P., Prinyawiwatkul, W., & Xu, Z. (2007). Applications of chitosan for improvement of quality and shelf life of foods: A review. *Journal of Food Science*, 72(5). <https://doi.org/10.1111/j.1750-3841.2007.00383.x>
- Noguchi, A., Mosso, K., Aymaro, C., & Jeunick, J. (1982). *Maillard reactions during extrusion-cooking of protein enriched biscuits.* 15(2), 105–110.
- Nolle, N., Hornstein, A., & Lambert, C. (2024). *Vitamin D fortification of selected edible insect species through.* 444(October 2023). <https://doi.org/10.1016/j.foodchem.2024.138679>

- Nowak, V., Persijn, D., Rittenschober, D., & Charrondiere, U. R. (2016a). Review of food composition data for edible insects. *Food Chemistry*, *193*, 39–46. <https://doi.org/10.1016/j.foodchem.2014.10.114>
- Nowak, V., Persijn, D., Rittenschober, D., & Charrondiere, U. R. (2016b). Review of food composition data for edible insects. *Food Chemistry*, *193*, 39–46. <https://doi.org/10.1016/j.foodchem.2014.10.114>
- Nyangena N Dorothy, Hippolyte, A., Ekesi, S., Nakimbugwe, D., & Fiaboe, K. K. M. (2020). *Effects of Traditional Processing Techniques on the Nutritional and Microbiological Quality of Four East Africa*. 1–16.
- Ochieng, B. O., Anyango, J. O., Khamis, F. M., Ekesi, S., Egonyu, J. P., Subramanian, S., Nduko, J. M., Nakimbugwe, D., Cheseto, X., & Tanga, C. M. (2023). Nutritional characteristics, microbial loads and consumer acceptability of cookies enriched with insect (*Ruspolia differens*) meal. *Lwt*, *184*(June), 115012. <https://doi.org/10.1016/j.lwt.2023.115012>
- Ochola, S., & Masibo, P. K. (2014). *life associated with poor eating habits in earlier life . Countries Dietary Intake of Schoolchildren and*. 499–505. <https://doi.org/10.1159/000365125>
- Oh, W. Y., Pyo, S., Lee, K. R., Lee, B. K., Shin, D. H., Cho, S. I., & Lee, S. M. (2003). Effect of *Holotrichia diomphalia* larvae on liver fibrosis and hepatotoxicity in rats. *Journal of Ethnopharmacology*, *87*(2–3), 175–180. [https://doi.org/10.1016/S0378-8741\(03\)00140-5](https://doi.org/10.1016/S0378-8741(03)00140-5)
- Olielo, T. (2013). *Short Communication* (Vol. 13, Issue 4).
- Oliveira, L. C., Rosell, C. M., & Steel, C. J. (2015). Original article Effect of the addition of whole-grain wheat flour and of extrusion process parameters on dietary fibre content , starch transformation and mechanical properties of a ready-to-eat breakfast cereal. *International Journal of Food Science and Technology*, *50*, 1504–1514. <https://doi.org/10.1111/ijfs.12778>

- Oluwole, O., Ibidapo, O., Arowosola, T., Raji, F., 2, R. P. Z., Alasqah, I., Lho, L. H., Han, H., & Raposo, A. (2023). *Sustainable transformation agenda for enhanced global food and nutrition security: a narrative review*. August, 1–12. <https://doi.org/10.3389/fnut.2023.1226538>
- Omotoso, O. T., & Adesola, A. A. (2018). Comparative studies of the nutritional composition of some insect orders. *International Journal of Entomology and Nematology Research*, 2(1), 1–9.
- Omotoso, T. O., & Adesola, A. A. (2018). *Comparative studies of the nutritional composition of some insect orders*. 2(1), 1–26.
- Oniszczyk, T., Agnieszka, W., Biernacka, B., Szponar, J., & Soja, J. (2023). Nutritional Characteristics of New Generation Extruded Snack Pellets with Edible Cricket Flour Processed at Various Extrusion Conditions. *Antioxidants*, 12(6).
- Oonincx, D. G. A. B., & Finke, M. D. (2021). Nutritional value of insects and ways to manipulate their composition. *Journal of Insects as Food and Feed*, 7(5), 639–659. <https://doi.org/10.3920/JIFF2020.0050>
- Oonincx, D. G. A. B., Van Broekhoven, S., Van Huis, A., & Van Loon, J. J. A. (2015). Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS ONE*, 10(12), 1–20. <https://doi.org/10.1371/journal.pone.0144601>
- Oonincx, D. G. A. B., van Itterbeeck, J., Heetkamp, M. J. W., van den Brand, H., van Loon, J. J. A., & van Huis, A. (2010). An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. *PLoS ONE*, 5(12), 1–7. <https://doi.org/10.1371/journal.pone.0014445>
- Opitz, S. E. W., & Müller, C. (2009). Plant chemistry and insect sequestration. *Chemoecology*, 19(3), 117–154. <https://doi.org/10.1007/s00049-009-0018-6>
- Organization, W. H. (2012). Guideline: Potassium intake for adults and children.

Geneva.

- Orinda, M. A. (2018). *EFFECTS OF HOUSING AND FEED ON GROWTH AND TECHNICAL EFFICIENCY OF PRODUCTION OF Acheta domesticus (L) AND Gryllus bimaculatus FOR SUSTAINABLE COMMERCIAL CRICKET PRODUCTION IN THE LAKE VICTORIA REGION, KENYA* (Issue October).
- Otero, P., Gutierrez-docio, A., Navarro, J., Reglero, G., & Martin, D. (2020). Extracts from the edible insects *Acheta domesticus* and *Tenebrio molitor* with improved fatty acid profile due to ultrasound assisted or pressurized liquid extraction. *Food Chemistry*, 314(December 2019), 126200. <https://doi.org/10.1016/j.foodchem.2020.126200>
- Palermo, M., & Fogliano, V. (2014). The effect of cooking on the phytochemical content of vegetables. *Journal of the Science of Food and Agriculture*, 94, 1057–1070. <https://doi.org/10.1002/jsfa.6478>
- Pangaribowo, E. H., Gerber, N., & Torero, M. (2013). *Food and Nutrition Security Indicators: A Review* (Issue 108).
- Park, H., Ahn, H., Kim, S., Lee, C., Byun, M., & Lee, G. (2006). *Determination of the phytic acid levels in infant foods using different analytical methods*. 17, 727–732. <https://doi.org/10.1016/j.foodcont.2005.05.007>
- Pasqualone, A., Costantini, M., Labarbuta, R., & Summo, C. (2021). Production of extruded-cooked lentil flours at industrial level: Effect of processing conditions on starch gelatinization, dough rheological properties and techno-functional parameters. *Lwt*, 147, 111580. <https://doi.org/10.1016/j.lwt.2021.111580>
- Pastor-cavada, E., Drago, S. R., González, R. J., Juan, R., & Pastor, J. E. (2011). Author ' s personal copy Effects of the addition of wild legumes (*Lathyrus annuus* and *Lathyrus clymenum*) on the physical and nutritional properties of extruded products based on whole corn and brown rice. *Food Chemistry*, 128(4), 961–967. <https://doi.org/10.1016/j.foodchem.2011.03.126>

- Pathania, S., Singh, B., Sharma, S., & Sharma, V. (2013). *Optimization of extrusion processing conditions for preparation of an instant grain base for use in weaning foods*. 3(3), 1040–1049.
- Patil, S., Kaur, C., Puniya, M. K., Mahapatra, A., Dhakane-Lad, J., Jalgaonkar, K., & Mahawar, M. K. (2021). Functional Properties of Extruded Corn Flour. *Turkish Journal of Agricultural Engineering Research*, 2(1), 167–174. <https://doi.org/10.46592/turkager.2021.v02i01.012>
- Patil, S. S., Brennan, M. A., Mason, S. L., & Brennan, C. S. (2016). The effects of fortification of legumes and extrusion on the protein digestibility of wheat based snack. *Foods*, 5(2), 1–8. <https://doi.org/10.3390/foods5020026>
- Pauter, P., Róžańska, M., Wiza, P., Dworczak, S., Grobelna, N., Sarbak, P., & Kowalczewski, P. (2018). Effects of the replacement of wheat flour with cricket powder on the characteristics of muffins. *Acta Scientiarum Polonorum, Technologia Alimentaria*, 17(3), 227–233. <https://doi.org/10.17306/J.AFS.0570>
- Payne, C. L. R., Scarborough, P., Rayner, M., & Nonaka, K. (2015). A systematic review of nutrient composition data available for twelve commercially available edible insects, and comparison with reference values. *Trends in Food Science & Technology*. <https://doi.org/10.1016/j.tifs.2015.10.012>
- 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. <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 pro fi ling models developed to combat over- and undernutrition*. September 2015, 285–291. <https://doi.org/10.1038/ejcn.2015.149>
- Payne, C. L. R., Scarborough, P., Rayner, M., & Nonaka, K. (2016c). 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*, 70(3), 285–291. <https://doi.org/10.1038/ejcn.2015.149>

Pinstrup-andersen, P. (2009). *Food security: definition and measurement*. 5–7. <https://doi.org/10.1007/s12571-008-0002-y>

Pismag, R. Y., Polo, M. P., Hoyos, J. L., Bravo, J. E., & Roa, D. F. (2024). Effect of extrusion cooking on the chemical and nutritional properties of instant flours: a review. *F1000Research*, 12, 1–25. <https://doi.org/10.12688/f1000research.140748.2>

Poelaert, C., Francis, F., Alabi, T., Megido, R. C., Crahay, B., Bindelle, J., Beckers, Y., Unit, N., Tech, G. A., Teaching, T., Unit, G., Tech, G. A., Teaching, T., Unit, E. E., Tech, G. A., & Teaching, T. (2018). Protein value of two insects , subjected to various heat treatments , using growing rats and the protein digestibility-corrected amino acid score. *Journal of Insects as Food and Feed*, 4(2), 77–87. <https://doi.org/10.3920/JIFF2017.0003>

Popova, A., & Mihaylova, D. (2019). *Antinutrients in Plant-based Foods : A Review*. 68–76. <https://doi.org/10.2174/1874070701913010068>

Prabha, K., Ghosh, P., Abdullah, S., Joseph, R. M., Krishnan, R., Singh, S., & Chandra, R. (2021). Recent development , challenges , and prospects of extrusion technology. *Future Foods*, 3(September 2020), 100019. <https://doi.org/10.1016/j.fufo.2021.100019>

Press, F. (1987). Postponement of the 10th edition of the RDAs. *Journal of the American Dietetic Association*, 85(12), 1644–1645.

Price, M. L., & Butler, L. G. (1977). Rapid visual estimation and spectro- photometric determination of tannin content of sorghum grain. *Journal of Agricultural and Food Chemistry*, 25, 1268–1273.

R Core Team. (2021). *R: A language and environment for statistical computing R*

Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>. R Foundation for Statistical Computing, Vienna, Austria. <https://www.r-project.org/>.

- Ramos-Bueno, R. P., González-Fernández, M. J., Sánchez-Muros-Lozano, M. J., García-Barroso, F., & Guil-Guerrero, J. L. (2016). Fatty acid profiles and cholesterol content of seven insect species assessed by several extraction systems. *European Food Research and Technology*, 242(9), 1471–1477. <https://doi.org/10.1007/s00217-016-2647-7>
- Ramos-Elorduy, J., González, E. A., Hernández, A. R., & Pino, J. M. (2002). Use of *Tenebrio molitor* (Coleoptera: Tenebrionidae) to recycle organic wastes and as feed for broiler chickens. *Journal of Economic Entomology*, 95(1), 214–220. <https://doi.org/10.1603/0022-0493-95.1.214>
- Ramos-Elorduy, J., Moreno, J. M. P., Prado, E. E., Perez, M. A., Otero, J. L., & De Guevara, O. L. (1997). Nutritional value of edible insects from the state of Oaxaca, Mexico. *Journal of Food Composition and Analysis*, 10(2), 142–157. <https://doi.org/10.1006/jfca.1997.0530>
- Ramos-Elorduy, J., Pino, M. J. M., & LandrondeGon, L. J. (1997). Edible insects of Oaxaca State Mexico and their nutritive value. *Journal of Food Composition and Analysis*, 10, 142–157.
- Ramos-Elorduy, Pino, M. J. m, & Ladron, L. J. (1997). Edible insects of Oaxaca State Mexico and their nutritive value. *Journal of Food Composition and Analysis*, 10, 142–157.
- Ranum, P., Pena-Rosa, J. P., & Garcia-Casal, M. N. (2014). Global maize production , utilization , and consumption. *Annals of the New York Academy of Sciences*, 1312, 105–112. <https://doi.org/10.1111/nyas.12396>
- Rao, R., Ellenna, K., Maree, T., Alaa, P., Din, E., Bekhit, A., & Carne, A. (2022). Edible insects: A bibliometric analysis and current trends of published. *International Journal of Tropical Insect Science*, 3335–3355. <https://doi.org/10.>

1007/s42690-022-00814-6

- Replacement, P., Peterson, A., Madden, J., Huang, E., Amin, S., & Lammert, A. (2022). Will It Cricket? Product Development and Evaluation of Cricket (*Acheta domesticus*) Powder Replacement in Sausage, Pasta, and Brownies. *Foods*, *11*(19), 3128.
- Riaz, M. N. (2020). *Extruders in Food Applications* (Second edi). CRC Press.
- Riaz, M. N., Asif, M., Ali, R., Riaz, M. N., Asif, M., & Ali, R. (2009). Stability of Vitamins during Extrusion. *Critical Reviews in Food Science and Nutrition*, *49*(4), 361–368. <https://doi.org/10.1080/10408390802067290>
- Ribeiro, L., Cunha, L. M., García-Segovia, P., Martínez-Monzó, J., & Igual, M. (2021). Effect of the house cricket (*Acheta domesticus*) inclusion and process temperature on extrudate snack properties. *Journal of Insects as Food and Feed*, *7*(7), 1117-1130. <https://doi.org/https://doi.org/10.3920/JIFF2020.0126>
- Ricardo, U., Anura, K., Kwaku, T., Gloria, E. O., Grant, A. A., Yasuhiko, T., & Shibani, G. (2015). *Role of Protein and Amino Acids in Infant and Young Child Nutrition : Protein and Amino Acid Needs and Relationship with Child Growth*. 192–194.
- Rodrigues, A., & Adegboye, A. (2025). *Potential Use of Edible Insects in Complementary Foods for Children : A Literature Review*.
- Rodrigues Amorim Adegboye, A., Bawa, M., Keith, R., Twefik, S., & Tewfik, I. (2021). Edible Insects: Sustainable nutrient-rich foods to tackle food insecurity and malnutrition. *World Nutrition*, *12*(4), 176–189. <https://doi.org/10.26596/wn.2021124176-189>
- Rumpold, B.A., Schluter, O. A. (2013). Nutritional composition and safety aspects of edible insects. *Molecular Nutrition and Food Research*, *57*, 802–823. <https://doi.org/10.1002/mnfr.201200735>

- Rumpold, B. A., & Schlüter, O. K. (2013a). Nutritional composition and safety aspects of edible insects. *Molecular Nutrition and Food Research*, 57(5), 802–823. <https://doi.org/10.1002/mnfr.201200735>
- Rumpold, B. A., & Schlüter, O. K. (2013b). Potential and challenges of insects as an innovative source for food and feed production. *Innovative Food Science and Emerging Technologies*, 17, 1–11. <https://doi.org/10.1016/j.ifset.2012.11.005>
- Rweyemamu, L. M. P., & Mrema, G. D. (2015). Physical properties of extruded snacks enriched with soybean and moringa leaf powder. *African Journal of Food Science and Technology*, 6(1), 28–34.
- S´anchez-Estrada, M. de la L., Aguirre-becerra, H., & Ang, A. (2024). *Bioactive compounds and biological activity in edible insects : A review*. 10(October 2023). <https://doi.org/10.1016/j.heliyon.2024.e24045>
- Saaka, M., & Osman, S. M. (2013). *Does Household Food Insecurity Affect the Nutritional Status of Preschool Children Aged 6 – 36 Months? 2013*. <https://doi.org/10.1155/2013/304169>
- Sahu, C. (2021). Optimization of maize – millet based soy fortified composite flour for preparation of RTE extruded products using D-optimal mixture design. *Journal of Food Science and Technology*, 58(7), 2651–2660. <https://doi.org/10.1007/s13197-020-04771-1>
- Sahu, C., Patel, S., & Tripathi, A. K. (2022). Effect of extrusion parameters on physical and functional quality of soy protein enriched maize based extruded snack. *Applied Food Research*, 2(1), 1–8.
- Sales-Campos, H., Reis de Souza, P., Crema Peghini, B., Santana da Silva, J., & Ribeiro Cardoso, C. (2013). An Overview of the Modulatory Effects of Oleic Acid in Health and Disease. *Mini-Reviews in Medicinal Chemistry*, 13(2), 201–210. <https://doi.org/10.2174/1389557511313020003>
- Samuel, A., & John, O. (2015). *Physico-Chemical and Functional Properties of*

Cookies Produced from Sweet Potato- Maize Flour Blends. 43, 48–58.

- Sandrin, R., Caon, T., Zibetti, A. W., & Francisco, A. De. (2018). Effect of extrusion temperature and screw speed on properties of oat and rice flour extrudates. *Journal of the Science of Food and Agriculture*, 98(9), 3427–3436.
- Sangketkit, C., Savage, G. P., Martin, R. J., & Mason, S. L. (2001). Oxalate Content of Raw and Cooked Oca (*Oxalis tuberosa*). *Journal of Food Composition and Analysis*, 14, 389–397. <https://doi.org/10.006/jfca.2000.0982>
- Santiago-l, L., Vallejo-cordoba, B., & Castro-l, C. (2020). An insight to fermented edible insects : A global perspective and prospective Adri a. *Food Research International*, 137(September). <https://doi.org/10.1016/j.foodres.2020.109750>
- Sanya, E., Okoth, M. W., Abong, G. O., & Mugalavai, V. K. (2020). Consumers acceptability of extruded maize-sorghum composite flours fortified with grain amaranth, baobab and orange fleshed sweet potatoes. *African Journal of Food Science*, 14(9), 274–284. <https://doi.org/10.5897/ajfs2020.1996>
- Šárka, E., Smrčková, P., Chena Aldao, D. A., Sałamtaş, M., Koláček, J., & Pour, V. (2015). Influence of process parameters and added starches on resistant starch content and sensory properties of maize extrudates. *Starch/Staerke*, 67(9–10), 737–744. <https://doi.org/10.1002/star.201500059>
- Sayanjali, S., Ying, D., Sanguansri, L., Buckow, R., Augustin, M. A., & Gras, S. L. (2017). The effect of extrusion on the functional properties of oat fibre. *LWT - Food Science and Technology*, 84, 106–113. <https://doi.org/10.1016/j.lwt.2017.05.025>
- Seker, M. (2005). Selected properties of native or modified maize starch / soy protein mixtures extruded at varying screw speed. *Journal of the Science of Food and Agriculture*, 85(August 2004), 1161–1165. <https://doi.org/10.1002/jsfa.2086>
- Seth, D., & Badwaik, L. S. (2015). Effect of feed composition , moisture content and extrusion temperature on extrudate characteristics of yam-corn-rice based snack

- food. *Journal of Food Science and Technology*, 52(March), 1830–1838. <https://doi.org/10.1007/s13197-013-1181-x>
- Shimomura, Y., & Harris, R. A. (2006). Metabolism and physiological function of branched-chain amino acids: Discussion of session. *Journal of Nutrition*, 136(1), 232–233. <https://doi.org/10.1093/jn/136.1.232s>
- Simopoulos, A. P. (2004). Omega-6/Omega-3 Essential Fatty Acid Ratio and Chronic Diseases. *Food Reviews International*, 20(1), 77–90. <https://doi.org/10.1081/FRI-120028831>
- Singh, A. K., Raju, P., Arora, S., Borad, G., Sanket, Meena, & TRTM, P. (2018). Effect of extrusion processing parameters on hardness and crispiness of milk protein-maize based extrudates. *International Journal of Chemical Studies*.
- Singh, S., Gamlath, S., & Wakeling, L. (2007a). Original article Nutritional aspects of food extrusion : a review. 916–929. <https://doi.org/10.1111/j.1365-2621.2006.01309.x>
- Singh, S., Gamlath, S., & Wakeling, L. (2007b). Original article Nutritional aspects of food extrusion : a review. *International Journal of Food Science and Technology*, 42, 916–929. <https://doi.org/10.1111/j.1365-2621.2006.01309.x>
- Sipponen, M. H., Mäkinen, O. E., Rommi, K., Heiniö, R. L., Holopainen-Mantila, U., Hokkanen, S., Hakala, T. K., & Nordlund, E. (2018). Biochemical and sensory characteristics of the cricket and mealworm fractions from supercritical carbon dioxide extraction and air classification. *European Food Research and Technology*, 244(1), 19–29. <https://doi.org/10.1007/s00217-017-2931-1>
- Siriamornpun, S., & Li, D. U. O. (2006). Polyunsaturated fatty acid content of edible insects in thailand. 13, 277–285.
- Smets, R., Nakimbugwe, D., & Borgh, M. Van Der. (2019). Nutrient composition of the long-horned grasshopper *Ruspolia differens* Serville : Effect of swarming season and sourcing geographical area. *Food Chemistry*, 301(March), 1–9.

<https://doi.org/10.1016/j.foodchem.2019.125305>

- Sogari, G., Menozzi, D., & Mora, C. (2018). This document is discoverable and free to researchers across the globe due to the work of AgEcon Search . Help ensure our sustainability . Sensory-liking Expectations and Perceptions of Processed and Unprocessed Insect Products. *International Journal on Food System Dynamics*, 9(4), 314–320.
- Sprecher, H. (2000). *Metabolism of highly unsaturated n -3 and n -6 fatty acids*. 1486, 219–231.
- Srisuksai, K., Limudomporn, P., Kovitvadh, U., Thongsuwan, K., & Imaram, W. (2024). *Physicochemical properties and fatty acid profile of oil extracted from black soldier fly larvae (Hermetia illucens)*. 17.
- Starčević, K., Gavrilović, A., Gottstein, Ž., & Mašek, T. (2017). Influence of substitution of sunflower oil by different oils on the growth, survival rate and fatty acid composition of Jamaican field cricket (*Gryllus assimilis*). *Animal Feed Science and Technology*, 228, 66–71. <https://doi.org/10.1016/j.anifeedsci.2017.04.007>
- Steel, C. J., Gabriela, M., Leoro, V., Schmiele, M., Ferreira, R. E., & Chang, Y. K. (2012). Thermoplastic Extrusion in Food Processing. In *Thermoplastic elastomers* (Issue 2001, pp. 1–27).
- Steinfeld, H., Gerber, P., & Wassenaar, T. D. (2006). *Livestock's long shadow: environmental issues and options*. Food & Agriculture Org. Food & Agriculture Organization. books.google.com
- Struck, S., Straube, D., Zahn, S., & Rohm, H. (2018). Interaction of wheat macromolecules and berry pomace in model dough: Rheology and microstructure. *Journal of Food Engineering*, 223, 109–115. <https://doi.org/10.1016/j.jfoodeng.2017.12.011>

- Suksomboon, A., Limroongreungrat, K., Sangnark, A., & Thititumjariya, K. (2011). Original article Effect of extrusion conditions on the physicochemical properties of a snack made from purple rice (Hom Nil) and soybean flour blend. *International Journal of Food Science and Technology*, 46, 201–208. <https://doi.org/10.1111/j.1365-2621.2010.02471.x>
- Sukwuttichai, P. (2026). *Global prevalence of iron deficiency anaemia among children aged 5 – 12 years : a systematic review and meta-analysis*. 16. <https://doi.org/10.7189/jogh.16.04027>
- Tan, H. S. G., van den Berg, E., & Stieger, M. (2016). The influence of product preparation, familiarity and individual traits on the consumer acceptance of insects as food. *Food Quality and Preference*, 52, 222–231. <https://doi.org/10.1016/j.foodqual.2016.05.003>
- Tao, J. (2016). *Potential utilization of edible insects in extruded rice products to address malnutrition issues in developing countries*.
- Tassoni, L., Marzoli, F., & Saviane, A. (2022). *Nutritional Composition of Bombyx mori Pupae : A Systematic Review*. 1–21.
- Tellez-Morales, J. A., Santos, B. H., Navarro-Cortez, R. O., & Rodrigues-Mirandas, J. (2022). Impact of the addition of cricket flour (*Sphenarium purpurascens*) on the physicochemical properties, optimization and extrusion conditions of extruded nixtamalized corn flour. *Applied Food Research*, 2(2), 100–149.
- ThermoFisherScientific. (2017). *Determination of water- and fat-soluble vitamins by HPLC*. <https://documents.thermofisher.com/TFS-Assets/CMD/Technical-Notes/tn-72488-hplc-water-fat-soluble-vitamins-tn72488-en.pdf>
- Tiencheu, B., Womeni, H. M., Linder, M., Mbiapo, F. T., Villeneuve, P., Fanni, J., & Parmentier, M. (2013). Changes of lipids in insect (*Rhynchophorus phoenicis*) during cooking and storage. *European Journal of Lipid Science and Technology*, 115(2), 186–195. <https://doi.org/10.1002/ejlt.201200284>

- Tomé, D., & Bos, C. (2007). Lysine requirement through the human life cycle. *Journal of Nutrition*, 137(6), 9–12. <https://doi.org/10.1093/jn/137.6.1642s>
- Toweet, S. K., Nyakundi, C., Okemwa, S., Adrian, E., Ochieng, O., Weru, M. W., Oguta, J. O., Omondi, E., Wambiya, A., Kibe, P., Ng, L., & Akoth, C. (2026). *Factors associated with timely complementary feeding among children aged 6 – 23 months in Kenya ; a cross-sectional study.*
- Townsend, J. R., Kirby, T. O., Sapp, P. A., Gonzalez, A. M., Marshall, T. M., Esposito, R., Gumpricht, E., & Townsend, J. R. (2023). *Nutrient synergy : definition , evidence , and future directions. October.* <https://doi.org/10.3389/fnut.2023.1279925>
- Truby, H., Baic, S., Fox, K. R., Livingstone, M. B. E., Logan, C. M., Ian, A., Morgan, L. M., Taylor, M. A., & Millward, D. J. (2007). *Randomised controlled trial of four commercial weight loss programmes in the UK: initial findings from the BBC “diet trials.”* 80(May 2006). <https://doi.org/10.1136/bmj.38833.411204.80>
- Tumuluru, J., Sokhansaj, S., Bandyopathy, S., & Bawa, A. (2013). Changes in Moisture, Protein, and Fat Content of Fish and Rice Flour Coextrudates during Single-Screw Extrusion Cooking. *Technology, Food {&} Bioprocess.*
- Tzompa-Sosa, D. A., Dewettinck, K., Provijn, P., Brouwers, J. F., de Meulenaer, B., & Oonincx, D. G. A. B. (2021). Lipidome of cricket species used as food. *Food Chemistry*, 349. <https://doi.org/10.1016/j.foodchem.2021.129077>
- Tzompa-sosa, D. A., Dewettinck, K., Provijn, P., Brouwers, J. F., Meulenaer, B. De, & Oonincx, D. G. A. B. (2021). Lipidome of cricket species used as food. *Food Chemistry*, 349(December 2020), 129077. <https://doi.org/10.1016/j.foodchem.2021.129077>
- Udousoro, I. I., Udo, E. S., Udoh, A. P., & Udoanya, E. E. (2018). Proximate and Antinutrients Compositions , and Health Risk Assessment of Toxic Metals in Some Edible Vegetables. *Nigerian Journal of Chemical Research*, 23(2), 51–62.

- Ugur, A. E., Berkay, B., Oztop, H. M., & Alpas, H. (2020). Effects of High Hydrostatic Pressure (HHP) Processing and Temperature on Physicochemical Characterization of Insect Oils Extracted from *Acheta domesticus* (House Cricket) and *Tenebrio molitor* (Yellow Mealworm). *Waste and Biomass Valorization*, 0123456789. <https://doi.org/10.1007/s12649-020-01302-z>
- UNICEF. (2021). *THE CRISIS OF DIETS IN EARLY LIFE 2021 Child Nutrition Report*.
- United States Dairy Export Council. (2004). *Reference manual for US whey and lactose products*. Retrieved from file:///C:/Users/Aleky/Downloads/ReferenceManualForWheyAndLactose%7B%5C_%7DEnglish1.pdf
- van Berkum, S., Dengerink, J., & Ruben, R. (2018). The food systems approach: sustainable solutions for a sufficient supply of healthy food. *Memorandum*, 064, 32. Retrieved from www.wur.eu/economic-research%0Ahttp://library.wur.nl/WebQuery/wurpubs/538076
- van Huis, A. (2013). Potential of Insects as Food and Feed in Assuring Food Security. *Annual Review of Entomology*, 58(1), 563–583. <https://doi.org/10.1146/annurev-ento-120811-153704>
- Van Huis, A. (2016). Edible insects are the future? *Proceedings of the Nutrition Society*, 75(3), 294–305. <https://doi.org/10.1017/S0029665116000069>
- van Huis, A., Itterbeeck, J. Van, Klunder, H., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). *Edible insects Future prospects for food and feed security*. Food and Agriculture Organization of the United Nations.
- Venter, J. P., Kotzé, A. F., Auzély-Velty, R., & Rinaudo, M. (2006). Synthesis and evaluation of the mucoadhesivity of a CD-chitosan derivative. *International Journal of Pharmaceutics*, 313(1–2), 36–42. <https://doi.org/10.1016/j.ijpharm.2006.01.016>

- Vilakati, N., & Taylor, J. R. N. (2016). Effects of processing and addition of a cowpea leaf relish on the iron and zinc nutritive value of a ready-to-eat sorghum-cowpea porridge aimed at young children Nokuthula Vilakati. *LWT - Food Science and Technology*, *73*, 467–472.
- Viuda-martos, M., Ruiz-navajas, Y., Fernández-lópez, J., Sendra, E., Sayas-barberá, E., & Pérez-álvarez, J. A. (2011). Antioxidant properties of pomegranate (*Punica granatum L.*) bagasses obtained as co-product in the juice extraction. *Food Research International*, *44*(5), 1217–1223. <https://doi.org/10.1016/j.foodres.2010.10.057>
- Wahyudi, W., Wardana, I. N. G., Widodo, A., & Wijayanti, W. (2018). *Improving Vegetable Oil Properties by Transforming Fatty Acid Chain Length in Jatropha Oil and Coconut*. <https://doi.org/10.3390/en11020394>
- Wainwright, P. E. (1992). Do essential fatty acids play a role in brain and behavioral development? *Neuroscience and Biobehavioral Reviews*, *16*(2), 193–205. [https://doi.org/10.1016/S0149-7634\(05\)80180-0](https://doi.org/10.1016/S0149-7634(05)80180-0)
- Wan Hassan, W. N. F., Ismail, M. A., Lee, H. S., Meddah, M. S., Singh, J. K., Hussin, M. W., & Ismail, M. (2020). Mixture optimization of high-strength blended concrete using central composite design. *Construction and Building Materials*, *243*, 118251. <https://doi.org/10.1016/j.conbuildmat.2020.118251>
- Wang, D., Bai, Y. Y., Li, J. H., & Zhang, C. X. (2004). Nutritional value of the field cricket (*Gryllus testaceus* Walker). *Insect Science*, *11*(4), 275–283. <https://doi.org/10.1111/j.1744-7917.2004.tb00424.x>
- Wang, D., Shao, W. Z., Chuan, X. Z., Yao, Y. B., Shi, H. A., & Ying, N. X. (2005). Evaluation on nutritional value of field crickets as a poultry feedstuff. *Asian-Australasian Journal of Animal Sciences*, *18*(5), 667–670. <https://doi.org/10.5713/ajas.2005.667>

- Wang, Q., Li, L., & Zheng, X. (2021). Recent advances in heat-moisture modified cereal starch: Structure, functionality and its applications in starchy food systems. *Food Chemistry*, 344(November 2020), 128700. <https://doi.org/10.1016/j.foodchem.2020.128700>
- Wang, S., & Nickerson, M. T. (2019). Effect of barrel temperature and feed moisture on the physical properties of chickpea , sorghum , and maize extrudates and the functionality of their resultant flours — Part 1. *Cereal Chemistry*, 96(November 2018), 609–620. <https://doi.org/10.1002/cche.10149>
- Wanjala, W. N., Mary, O., & Symon, M. M. (2020). Influence of Feed Rate, Moisture and Mixture Composition from Composites Containing Rice (<i>Oryza sativa</i>), Sorghum [<i>Sorghum bicolor</i> (L.) Moench] and Bamboo (<i>Yushania alpina</i>) Shoots on Physical Propert. *Food and Nutrition Sciences*, 11(08), 807–823. <https://doi.org/10.4236/fns.2020.118057>
- Waterman, P., & Mole, S. (1994). *Analysis of phenolic plant metabolites*. Blackwell Scientific Publications.
- Watkins, K., Fiala, O., Haag, P., & Zubairi, A. (2024). *School feeding and the Sustainable Development Goals transform food systems and strengthen equity. September.*
- Webb, D., Plattner, B. J., Donald, E., Funk, D., Plattner, B. S., & Alavi, S. (2020). Role of chickpea flour in texturization of extruded pea protein. *Journal of Food Science*, 85(12), 4180–4187. <https://doi.org/10.1111/1750-3841.15531>
- WHO/FAO/UNU. (2007). *PROTEIN PROTEIN PROTEIN AND AND AND AMINO AMINO AMINO ACID ACID ACID REQUIREMENTS REQUIREMENTS REQUIREMENTS IN IN IN NUTRITION NUTRITION a of Joint a Joint.*
- WHO. (2007). *Protein and amino acid requirements in human nutrition : report of a joint FAO/WHO/UNU expert consultation*. Retrieved from <https://apps.who.int/iris/handle/10665/43411>

WHO. (2018). *Micronutrients*.

WHO. (2025). *global anaemia estimates*.

Wilkinson, K., Muhlhausler, B., Motley, C., Crump, A., Bray, H., & Ankeny, R. (2018). Australian consumers' awareness and acceptance of insects as food. *Insects*, 9(2), 1–11. <https://doi.org/10.3390/insects9020044>

Wineman, A., Ekwueme, M. C., Bigayimpunzi, L., & Martin-daihirou, A. (2022). *School Meal Programs in Africa : Regional Results From the 2019 Global Survey of School Meal Programs*. 10(May), 1–11. <https://doi.org/10.3389/fpubh.2022.871866>

Wolf, B. (2010). Polysaccharide functionality through extrusion processing. *Current Opinion in Colloid and Interface Science*, 15(1–2), 50–54. <https://doi.org/10.1016/j.cocis.2009.11.011>

Womeni, H. M., Linder, M., Tiencheu, B., Mbiapo, F. T., Villeneuve, P., Fanni, J., & Parmentier, M. (2009). Oils of insects and larvae consumed in Africa: Potential sources of polyunsaturated fatty acids. *Oleagineux Corps Gras Lipides*, 16(4), 230–235. <https://doi.org/10.1684/ocl.2009.0279>

Xia, W., Liu, P., Zhang, J., & Chen, J. (2011). Biological activities of chitosan and chitooligosaccharides. *Food Hydrocolloids*, 25(2), 170–179. <https://doi.org/10.1016/j.foodhyd.2010.03.003>

Yang, J., Wong, R. K., Park, M., Wu, J., Cook, J. R., York, D. A., Deng, S., Markmann, J., Naji, A., Wolf, B. A., & Gao, Z. (2006). *Leucine Regulation of Glucokinase and ATP Synthase*. 55(January), 193–201.

Yang, L. F., Siriamornpun, S., & Li, D. (2006). Polyunsaturated fatty acid content of edible insects in Thailand. *Journal of Food Lipids*, 13(3), 277–285. <https://doi.org/10.1111/j.1745-4522.2006.00051.x>

- Yang, Q., Yang, Y., Luo, Z., Xiao, Z., Ren, H., Li, D., & Yu, J. (2016). Effects of lecithin addition on the properties of extruded maize starch. *Journal of Food Processing and Preservation*, *40*, 20–28. <https://doi.org/10.1111/jfpp.12579>
- Yi A, C., A, N. Q., A, H. Z., B, Q. X., & C, Z. L. (2022). Extrusion processing: A strategy for improving the functional components, physicochemical properties, and health benefits of whole grains. *Food Research International*, *Volume 160*(111681).
- Yi, L., Lakemond, C. M. M., Sagis, L. M. C., Eisner-Schadler, V., van Huis, A., & a.J.S. van Boekel, M. (2013). Extraction and characterisation of protein fractions from five insect species. *Food Chemistry*, *141*(4), 3341–3348. <https://doi.org/10.1016/j.foodchem.2013.05.115>
- Yolmeh, M., & Jafari, S. M. (2017). Applications of Response Surface Methodology in the Food Industry Processes. *Food and Bioprocess Technology*. <https://doi.org/10.1007/s11947-016-1855-2>
- Yu, L., Peng, X. X., Yang, C., Liu, Y. H., & Fan, Y. P. (2002). Determination of oxalic acid in plant tissue and root exudates by reversed phase high performance liquid chromatography. *Chinese Journal of Analytical Chemistry*, *30*, 1119–1122.
- Zafar, A., Shaheen, M., Tahir, A. B., DaSilva, A. P. G., Manzoor, H. Y., & Zia, S. (2023). Unraveling the nutritional, biofunctional, and sustainable food application of edible crickets: A comprehensive review. *Trends in Food Science & Technology*, *18*, 104–254.
- Zambrano, Y., Contardo, I., & Bouchon, P. (2022). Effect of Extrusion Temperature and Feed Moisture Content on the Microstructural Properties of Rice-Flour Pellets and Their Impact on the Expanded Product. *Foods*, *11*(2), 1–18.
- Zhang, X., Chen, Y., Zhang, R., Zhong, Y., Luo, Y., Xu, S., Liu, J., Xue, J., & Guo, D. (2016). Address : The Key Laboratory of Biology and Genetics Improvement of Maize in arid Area of. *Journal of Cereal Science*. <https://doi.org/10.1016/j.jcs.2016.01.005>

- Zhang, Y., Guo, K., Leblanc, R. E., Loh, D., Schwartz, G. J., & Yu, Y. (2007). *Increasing Dietary Leucine Intake Reduces Diet-Induced Obesity and Improves Glucose and Cholesterol Metabolism in Mice via Multimechanisms*. 56(June), 1647–1654. <https://doi.org/10.2337/db07-0123>.BAT
- Zielińska, E., Baraniak, B., Karaś, M., Rybczyńska, K., & Jakubczyk, A. (2015). Selected species of edible insects as a source of nutrient composition. *Food Research International*, 77, 460–466. <https://doi.org/10.1016/j.foodres.2015.09.008>
- Zielińska, E., Pankiewicz, U., & Sujka, M. (2021). Nutritional, physiochemical, and biological value of muffins enriched with edible insects flour. *Antioxidants*, 10, 1122. <https://doi.org/10.3390/antiox10071122>
- Zondo, S., Munyai, T. C., Siwela, M., & Hlongwane, Z. T. (2026). Nutritional value and consumer acceptance of food products fortified with edible insects : a systematic review. *Cogent Food & Agriculture*, 12(1). <https://doi.org/10.1080/23311932.2025.2602907>

APPENDICES

Appendix I: Sample Collection Questionnaire

Serial No.....

Introduction

This questionnaire accompanies the collection of cricket samples that are reared in Kenya. These samples are meant for research purpose only and not for any other purpose. The samples will be used for laboratory analysis to determine nutrient composition at JKUAT. The data is collected by a PhD student at JKUAT.

The data generated from this study will contribute to informing Kenyans on the content of nutrients contained in crickets and will help promote consumption of crickets. This will also inform the food industry who can possibly provide a big market for cricket farmers.

I request your support to buy cricket samples from your farm for 2 species of crickets: *Acheta domesticus* and *Gryllus bimaculatus*. I also request your support to answer a few questions that will help in the laboratory analysis.

1. Farm

Location.....

.....

2. Name of

Farmer.....

.....(optional)

3. Which species of crickets are you rearing?

i. *Acheta domesticus*

ii. *Gryllus Bimaculatus*

iii. Other

4. How old is this batch.....

5. What do you feed them?
.....
.....
.....
6. When do you feed them?.....
7. How is the feed program from hatching stage to adult stage?
.....
.....
.....
8. What is the composition of the feed?
 - i. Made at home
 - ii. Bought
 - iii. If made at home, what is the composition and form?
.....
.....
.....
 - iv. If bought, which feed? Tick as appropriate. Chick mash, Growers mash, Layers mash, Broiler starter, Broiler finisher, other.
9. What is the average temperatures in this area/ in the cricket house?
 - i. Morning temperatures.....
 - ii. Afternoon temperature (2.00pm).....
 - iii. Night temperature.....
10. What is the mode of consumption of your crickets?
 - i. Cooked and eaten whole at home
 - ii. Sold as raw
 - iii. Sold as dried
 - iv. Sold as ground powder
11. What is the commonest method of cooking crickets eaten in your home?
 - i. Boiled
 - ii. Fried
 - iii. Other

12. What is your market like?

- i. Open market
- ii. Contracted buyers
- iii. Other

13. What motivates you to farm crickets?

- i. Ready market
- ii. Source of income
- iii. Source of protein
- iv. Other

14. What unique observations have you made about crickets and rearing them that you would like more research to be done on?.....

Thank you for your support.

Appendix II: Sensory Evaluation Questionnaire

SENSORY EVALUATION FORM FOR INSTANT PORRIDGE

Name:.....Gender (M/F):.....Date.....

You are requested to make sensory evaluation of the porridge as presented to you and evaluate their overall acceptability basing on the parameters shown below. Please grade the samples on the scale of 1 to 9 by placing your score in the box next to the sensory parameter under each sample in the table.

Rinse your mouth with water provided before tasting, re-tasting and in between products, then evaluate the products in front of you.

Score the products using the hedonic scale below			
Like extremely	9		
Like very much	8		
Like moderately	7		
Like slightly	6		
Neither like nor dislike	5		
Dislike slightly	4		
Dislike moderately	3		
Dislike very much	2		
Dislike extremely	1		
Quality Attributes	Formulation		
	324	538	946
Appearance			
Color			
Flavor			
Aroma			
Taste			
Mouth feel			
General acceptability			

Which formulation would you buy and why.....

General comments.....

Thank you for participating in this exercise

Appendix III: Informed Consent

Informed Consent for Sensory Evaluation

Project Title: EFFECT OF PROTEIN OPTIMIZATION AND EXTRUSION PROCESSING ON NUTRITIONAL, PHYSICOCHEMICAL AND SENSORY PROPERTIES OF MAIZE-CRICKET (*Scapsipedus icipe* and *Gryllus bimaculatus*) PORRIDGE FLOUR

RE: INVITATION TO PARTICIPATE IN A SENSORY EVALUATION PANEL

Dear Sir/Madam,

We are inviting people to participate in a research study to evaluate sensory attributes of a maize porridge enriched with edible cricket flour. Participants of the study should be 18 years old and above. The lead researcher in this study is Dorothy Murugu, PhD student in the Human Nutrition Department, Jomo Kenyatta University of Agriculture and Technology.

Purpose: This study aims to evaluate the sensory properties of porridge enriched with edible cricket powder. Your participation will help us understand consumer preferences and acceptance of this innovative food product.

Procedures: You will be asked to taste and evaluate porridge samples. You will be provided with a rating scale to assess the appearance, aroma, taste, texture, and overall acceptability of the products. The entire process will take approximately 15 minutes.

Risks and Discomforts: There are no significant risks associated with participating in this study. However, some people could be allergic to edible insect flour. If you have known allergies toward food materials like of insect origin, please do not participate in the study. Otherwise, in case you experience any adverse reactions, please inform the researcher immediately.

Benefits: Your participation will contribute to the development of innovative and nutritious food products.

Confidentiality: All information collected during this study will be kept confidential. Your identity will not be disclosed in any publication or report.

Voluntary Participation: Your participation in this study is entirely voluntary. You are free to withdraw from the study at any time without any penalty.

Questions: If you have any questions about the study, please feel free to ask the researcher, Dorothy Murugu through email: dorothymugane@yahoo.com or phone number 0721782750.

By signing below, you acknowledge that you have read and understood the information provided above and agree to participate in this study.

Participant's Signature..... Date.....

Researcher's Signature..... Date.....

Appendix IV: Photos of Cricket Species Used in This Study



Cricket species 1: *Scapsipedus icipe*



Cricket species 2: Two spotted *Gryllus bimaculatus*

(Source: International Centre for Insect Ecology and Physiology)