

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

<https://doi.org/10.17113/ftb.64.04.26.9628>

original scientific paper

## Technological, Nutritional and Sensory Impacts of Partial Meat Replacement with Insect Powders in Frankfurt-Type Sausages<sup>§</sup>

Running head: Frankfurt-Type Sausages with Cricket and Mealworm Powders

Judit Rodríguez-Párraga<sup>1</sup>, Raquel Lucas-González<sup>1</sup>, Carmen Botella-Martínez<sup>1</sup>, Manuel Viuda-Martos<sup>1</sup>, Fernando Borrás-Rocher<sup>2</sup>, José A. Pérez-Alvarez<sup>1</sup> and Juana Fernández-López<sup>1\*</sup>

<sup>1</sup>Research Group in Food Products Innovations (IPOA), Institute for Agri-Food and Agri-Environmental Research and Innovation, Miguel Hernández University (CIAGRO-UMH), Ctra. Beniel km 3.2 03312 Orihuela, Alicante, Spain

<sup>2</sup>Statistics and Operative Research Department, Miguel Hernández University, Avenida de la Universidad s/n, 03202 Elche, Alicante, Spain

Received: 26 January 2026

Accepted: 31 May 2026



Copyright © 2026 Authors retain copyright and grant the FTB journal the right of first publication under CC-BY 4.0 licence that allows others to share the work with an acknowledgement of the work's authorship and initial publication in the journal

### SUMMARY

*Research background.* The increasing global demand for sustainable protein alternatives has positioned edible insects as promising functional ingredients for the meat industry. This study explores the potential of cricket - *Acheta domesticus* (WAD), and mealworm - *Tenebrio molitor* (WTM) powders to develop hybrid meat products, addressing the need for nutrient-dense and environmentally friendly food options.

*Experimental approach.* Beef lean meat in Frankfurter-type sausages was partially replaced with 7.5 and 15 % of WAD or WTM powders. A comprehensive characterization was performed,

---

\*Corresponding author:  
E-mail: [j.fernandez@umh.es](mailto:j.fernandez@umh.es)

<sup>§</sup>This paper was presented at the 11th International Congress of Food Technologists, Biotechnologists and Nutritionists, 9–12 December 2025, Zagreb, Croatia

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

including proximate composition, mineral and fatty acid profiles, and techno-functional properties (pH, color, residual nitrite level, texture, and emulsion stability). Consumer acceptance was evaluated through a hedonic sensory test with 50 panelists.

*Results and conclusions.* The incorporation of insect powders drastically improved emulsion stability, reducing total expressible fluid by over 70 % in 15 % formulations. Nutritionally, insect-enriched sausages showed significantly higher protein and essential mineral contents (Mg, Mn, and Ca) compared to the control. The lipid profile was also enhanced, with a reduction in saturated fatty acids and improved in atherogenic (AI) and thrombogenic indices (TI), particularly in WAD formulations. While 7.5 % inclusion levels maintained sensory scores similar to the control, 15 % concentrations significantly reduced lightness and redness due to insect pigmentation and Maillard reactions, leading to lower consumer acceptance. Residual nitrites remained well within safety regulations (< 90 mg/kg). Overall, a 7.5 % replacement represents the optimal balance between nutritional enhancement and sensory quality.

*Novelty and scientific contribution.* This work provides a multi-faceted validation of insect powders as stabilizing and fortifying agents in complex meat matrices. By demonstrating that hybrid sausages can meet regulatory safety standards while offering superior nutritional value and technological stability, this research contributes to the development of sustainable, high-protein food alternatives that align with current consumer trends and environmental goals.

**Keywords:** edible insects; frankfurters; hybrid meat products; *T. molitor*; *A. domesticus*; technological quality

## INTRODUCTION

The increasing societal concern regarding the environmental impact associated with food production, together with projections estimating that the global population will exceed 9.7 billion by 2050 [1], has intensified the need to develop strategies that ensure food security in a sustainable manner. Conventional livestock production presents substantial limitations due to its high consumption of natural resources—particularly water, land, and energy—as well as its contribution to greenhouse gas emissions [2]. In response to these pressures, the scientific community and the food industry have accelerated the search for alternatives that reduce dependence on animal-derived proteins without compromising nutritional quality or consumer acceptability.

Within this context, edible insects have emerged in recent years as one of the most promising alternative protein sources [3]. Their high feed conversion efficiency, ability to grow on low-nutrient

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

substrates, and minimal land and water requirements position them as an attractive option to diversify global protein production [4]. In parallel, the food industry is increasingly incorporating reformulation strategies aimed at sustainability, including the development of hybrid products that combine traditional meat matrices with high-performance alternative ingredients. Additionally, approaches for partial replacement of animal fat using functional components capable of enhancing water-holding capacity and emulsifying stability are being explored, contributing to improved nutritional profiles in the final product. Among these innovations, insect powders have demonstrated notable technological and nutritional potential [5], driving growing interest as functional ingredients in processed meat products [6].

Among the most widely studied species – also authorized for consumption and commercialization under current European regulations [7] – *Acheta domesticus* and *Tenebrio molitor* stand out due to their high protein content (50–60 %), favorable lipid profile rich in monounsaturated and polyunsaturated fatty acids (oleic and linoleic acids) [8], significant levels of minerals (Mg, Zn, and P as well as low Na content), and dietary fiber derived from chitin [9]. Moreover, this EU regulation already includes whole insects (*A. domesticus* and *T. molitor*) within the “novel foods” definition. Obtaining their powders allows for a more versatile integration into food matrices and facilitates their incorporation into emulsified meat products [3, 10]. In such systems, insect powders can act not only as protein sources but also as functional agents capable of influencing water retention, emulsion stability, and textural properties [6].

Frankfurter-type sausages provide an appropriate model to evaluate the technological behavior of these alternative ingredients. Nevertheless, the partial replacement of meat with insect powders may affect critical parameters such as color, pH, texture, proximate composition, mineral content, and sensory attributes [11, 12]. The magnitude and direction of these effects depend on several factors, including insect species, replacement level, the amount of insect powder added, and the intrinsic characteristics of the meat matrix—which explains the variability reported in the scientific literature [13-14].

Despite the growing number of studies available, significant knowledge gaps remain regarding the effects of *A. domesticus* and *T. molitor* powders on the physicochemical, technological, nutritional, and sensory properties of emulsified meat products. Furthermore, consumer acceptance continues to be a major challenge, particularly in regions where insect consumption is not culturally established and entomophobia prevails [15].

Therefore, the aim of the present study was to evaluate the effect of incorporating *Acheta domesticus* and *Tenebrio molitor* powders into frankfurter formulations as a partial meat replacement,

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

assessing their impact on chemical composition, emulsion stability, physicochemical properties, color, texture, and sensory acceptance. This work seeks to provide robust evidence on the technological feasibility and potential of these insect powders as functional ingredients in processed meat products, contributing to the development of sustainable and nutritionally valuable alternatives.

## MATERIALS AND METHODS

### *Raw materials*

*Acheta domesticus* (WAD: whole *A. domesticus*, dried and milled) and *Tenebrio molitor* (WTM: whole *T. molitor*, dried and milled) powders were supplied by Insectum (Valencia, Spain). Both insect powders were previously characterized by Rodríguez-Párraga *et al.* [5]. Regarding proximal composition, WAD showed 57.3 % protein, 21.5 % fat, 4.9 % dietary fiber, 4.4 % moisture and 2.3 % ash; WTM showed 50.0% protein, 30.8 % fat, 3.3 % dietary fiber, 6.0 % moisture and 2.1 % ash. Meat ingredients [beef lean meat (from shoulder) and pork backfat], were purchased from a local butcher shop (Murcia, Spain), transferred to the Food Pilot Plant at the Miguel Hernández University (CIAGRO-UMH, Orihuela, Alicante, Spain), and stored under refrigeration ((4±2) °C) until use. Additives and spices were purchased from a local supplier (Suministros River S.L.U., Alicante, Spain).

### *Frankfurt-type sausages formulation and manufacturing*

A traditional Frankfurt-type sausage formulation containing 65 % beef lean meat and 35 % pork backfat was used as control (CT). The insect-inclusive formulations were produced by replacing 7.5 % and 15 % of beef meat with each insect powder (WAD and WTM) and were designated 7.5WAD, 15WAD, 7.5WTM, and 15WTM, respectively. The meat ingredients and insect powders alone accounted for 100 % of the base matrix; the quantities of additives and spices were expressed relative to the total meat content: 20 % water (ice form *m/m*), 2.5 % sodium chloride (*m/m*), 300 mg/kg sodium tripolyphosphate, 150 mg/kg sodium nitrite, 0.5 g/kg powder smoke and spices (a mixture of white pepper, nutmeg and oregano).

The Frankfurt-type sausages were prepared in the Food Pilot Plant (CIAGRO-UMH) following the process reported by Fernández-López *et al.* [16]. Each component was weighed separately, and lean meat was first ground in a cutter (1094-Homogeneizer, Tekator, Höganäs, Sweden) to a particle size of approximately 1 cm. Crushed ice and salt were then added to promote protein solubilization and maintain low batter temperature, thereby minimizing heat-induced smearing. Subsequently, the rest of additives and spices were incorporated, followed by the diced backfat. After homogenization (2 min, temperature below 12 °C), a cohesive and uniform batter was obtained. Following preparation,

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

the meat emulsion was transferred into 20 mm diameter pre-hydrated cellulose casings (Fibran-Pack, Fibran, Girona, Spain) using a piston-driven stuffer (EM-12, Mainca, Granollers, Spain). Care was taken to eliminate air gaps by applying maximum filling pressure, with links manually tied every 20–22 cm. The samples underwent thermal processing in a water bath (85–90 °C) until an internal core temperature of 72 °C was confirmed via probe thermometry. Post-cooking, sausages were rapidly cooled in an ice bath for 10 min. After manual casing removal, the products were vacuum-sealed in high-barrier low-density polyethylene bags (W.K. Thomas Spain S.L., Rubí, Spain), characterized by an oxygen permeability <math><5 \text{ cm}^3/\text{m}^2 \text{ per } 24 \text{ h}</math> at 23 °C/50 % RH and water vapor permeability of 1.1 g/m<sup>2</sup> per 24 h. Samples were maintained at 4 °C until further testing. This entire experimental procedure was performed in triplicate across three separate production days.

#### *Meat emulsion stability*

A mass of 10 g of meat emulsion (raw) was first centrifuged (Model 2652, Nahita, Alicante, Spain; 1253×g, 1 min), subsequently heated in a water bath (70 °C, 30 min), and centrifuged once more (1253×g, 3 min). The supernatant was discarded and the remaining pellet was weighed. Emulsion stability was assessed by calculating the total expressible fluid (TEF/%) ; Eq. 1) according to Hughes *et al.* [17]:

$$\text{TEF} = \left( \frac{m(\text{tube+sample}) - (m(\text{tube+pellet}))}{m(\text{sample})} \right) \cdot 100 \quad /1/$$

Three measurements were conducted for each formulation in every batch ( $N=3$ ).

#### *Proximate composition*

Moisture (AOAC method 950.46; oven air-drying) [18], ash (AOAC method 920.153 method; muffle furnace) [18], protein (AOAC method 981.10; Kjeldahl analysis) [18], total dietary fiber (TDF) (AOAC method 991.43; enzymatic-gravimetric procedure) [18] and fat content (AOAC method 991.36; Soxhlet extraction) [18] were determined following official methods. Three measurements for each batch per treatment were performed ( $N=3$ ).

#### *Fatty acid profile*

Total lipids were extracted according to AOAC [18] and converted into FAMES via methylation for chromatographic analysis. An Agilent HP 6890 gas chromatograph (Hewlett Packard Agilent, Santa Clara, USA), fitted with a Suprewax-280 capillary column (Tecknokroma, Barcelona, Spain), was utilized for separation and quantification, following the operational parameters of Rodríguez-

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

Párraga *et al.* [3]. For fatty acid identification, retention times were matched against a 37-component FAME standard (Supelco Inc., Darmstadt, Germany), with tridecanoic acid (C13:0) acting as the internal standard. Results, integrated via Station GC software, were expressed as g/100 g of fat and calculated from the mean of triplicate analyses. To evaluate the nutritional profile, various indices (AI, TI, h/H, and SFA/UFA and n-6/n-3 ratios) were calculated based on the fatty acid data [19].

#### *Mineral profile*

The mineral profile of Frankfurt-type sausage samples was determined in triplicate using inductively coupled plasma mass spectrometry (ICP-MS) on a Shimadzu MS-2030 instrument (Shimadzu, Kyoto, Japan) following the procedure described by Rodríguez-Párraga *et al.* [5]. For sample preparation, 200 mg of dehydrated material was digested with 8 mL of concentrated HNO<sub>3</sub> (69 %) and 2 mL of H<sub>2</sub>O<sub>2</sub> in a microwave digestion unit (MARS™ One, CEM Corporation). Instrument calibration was carried out using appropriately diluted multi-element standard solutions. ICP-MS operating parameters included a carrier gas flow of 0.70 L/min, plasma gas flow of 9.0 L/min, auxiliary gas flow of 1.10 L/min, and radio frequency power set at 1.2 kW with a 7.0 V power filter. Three measurements for each batch per treatment were performed ( $N=3$ ).

#### *pH and water activity*

Water activity ( $a_w$ ) was determined at 25 °C using a NOVASINA TH200 digital hygrometer (Novasina; Axair Ltd., Pfaeffikon, Switzerland). Measurements were performed in triplicate for each sample ( $N=3$ ).

Sample pH was determined using a Hach 5233 puncture electrode (Hach-Lange S.L.U., Vézenaz, Switzerland) integrated with a SensION™+pH 3 meter (Model 510, Crison Instruments S.A., Barcelona, Spain) featuring automatic temperature compensation. Prior to each measurement session, the system was standardized with buffer solutions at pH=4.01 and 7.00. To ensure representative data, three readings were taken per sample by inserting the electrode into different locations, with the final value derived from the mean of these replicates.

#### *Color properties*

Color measurements of the Frankfurt-type sausages were obtained using a Minolta CM-700 spectrophotometer (Minolta Camera Co., Osaka, Japan) configured with a 10° standard observer, D<sub>65</sub> illuminant, and apertures of 11 mm for illumination and 8 mm for measurement. The instrument was calibrated according to the manufacturer's specifications prior to analysis. Color was recorded in the CIELAB space, reporting lightness ( $L^*$ ), redness ( $a^*$ ), and yellowness ( $b^*$ ). From these

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

coordinates, chroma ( $C^*$ ), hue angle ( $H^*$ ), and total color differences ( $\Delta E^*$ ) relative to the control sausage were calculated (Eqs. 2, 3, and 4, respectively), following the American Meat Science Association recommendations [20].

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad /2/$$

$$H^* = \arctan\left(\frac{b^*}{a^*}\right) \quad /3/$$

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad /4/$$

Spectral reflectance data were collected at 10 nm intervals withing the 360–740 nm wavelength range.

To provide a representative profile, nine measurements were performed per sample by analyzing three different locations on the surface of three 2 cm slices.

#### *Textural properties*

The textural characteristics of the Frankfurt-type samples were evaluated via Texture Profile Analysis (TPA) using a TA-XT2i analyzer (Stable Micro Systems, Surrey, UK). Test specimens, prepared as 1 cm<sup>3</sup> cubes, underwent a double-compression cycle to 75 % of their original height at a steady crosshead speed of 1 mm/s. Measurements were conducted at ambient temperature. From the obtained force–deformation curves, the parameters of hardness (N), springiness (mm), cohesiveness, and chewiness (N·mm) were calculated. Six determinations were conducted per sample.

#### *Residual nitrite level*

Residual nitrite content (mg NaNO<sub>2</sub>/kg sample) was determined following the ISO/DIS 2918.26 guidelines [21]. These measurements were performed in triplicate for each batch per treatment ( $N=3$ ).

#### *Sensory analysis*

A consumer-based sensory trial was performed at the CIAGRO-UMH Sensory Analysis Laboratory (Orihuela, Spain). The panel comprised 50 untrained volunteers (54 % female and 46 % male), recruited from the university's student body and faculty. Participants were selected based on their regular consumption of meat products (at least once a week) and their interest in participating. Inclusion criteria required individuals free from food allergies or any physiological conditions that could

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

impair sensory perception, Before the sessions, all volunteers provided written informed consent. To prevent sensory fatigue, mineral water and unsalted crackers were provided for palate cleansing between samples. Using a 9-point hedonic scale, ranging from 1 ('dislike extremely') to 9 ('like extremely'), participants assessed several attributes including overall appearance, color, hardness, juiciness, general taste, overall flavor, and overall acceptability, using a 9-point hedonic scale (1=dislike extremely; 9=like extremely).

### *Statistical analysis*

Data were subjected to one-way analysis of variance (ANOVA), and mean differences were assessed using Tukey's post hoc test at a 95 % confidence level ( $p < 0.05$ ). Principal Component Analysis (PCA) was employed to reduce data dimensionality and explore the interrelationships among the chemical, techno-functional, and sensory properties of the different formulations. A biplot representation was subsequently generated to map the spatial distribution of the samples while simultaneously visualizing the contribution of each original variable to the underlying principal components. The experimental data were analyzed using SPSS for Windows v. 29 [22]. Results are reported as mean values  $\pm$  standard deviations.

## **RESULTS AND DISCUSSION**

### *Effects of insect powders on emulsion stability*

Emulsion stability is a key technological property of meat batters, as it reflects the ability of the protein matrix to immobilize both water and fat prior to thermal processing, thereby preventing phase separation during handling and cooking. This property is influenced by multiple factors, including protein content, type and functionality; fat composition; ionic strength; processing conditions; and the presence of additives or non-meat ingredients [23,24]. At the molecular level, interfacial stabilization relies on protein–protein interactions and the amphiphilic nature of proteins, while the formation of a continuous gel network contributes to the physical entrapment of water and lipid droplets. Additional structural elements, such as lipid-protein interactions and the degree of lipid unsaturation, can further modulate emulsion stability, as these interactions favor the maintenance and integrity of the sausages [6].

Emulsion stability was evaluated in the raw meat batter prior to stuffing, as the percentage of Total Expressible Fluid (TEF). The results are shown in **Fig. 1**, where higher TEF values indicate lower emulsion stability. Formulations containing 15 % insect powder (15WAD and 15WTM) exhibited significantly lower TEF values compared to the control, with reductions exceeding 70 %. Lower

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

inclusion levels (7.5WAD and 7.5WTM) also showed significant reductions (above 44 %) compared to the control ( $p < 0.05$ ), indicating a marked improvement in emulsion stability. When insect powders were incorporated at 7.5 % (7.5 WAD and 7.5WTM), the improvement was only statistically significant ( $p < 0.05$ ) for the WTM formulation. While myofibrillar proteins from meat are the primary contributors to emulsion formation and stabilization, non-meat proteins can also participate in the development and stabilization of meat emulsions depending on their concentration, solubility, and functional properties [11]. The interaction between meat and non-meat ingredients when lean meat is replaced by insect powders appears to enhance this functionality.

In this regard, the incorporation of insect powders exerted a stabilizing effect on the meat emulsion that was dependent on both the inclusion level and the insect species. Beyond the partial replacement of meat proteins, emulsion stability could be influenced by the protein content and techno-functional properties of the insect powders, particularly their emulsifying activity (EA) [25]. The higher EA reported for WTM compared to WAD [5] likely contributed to the superior stability observed in those formulations (Fig. 1). Additionally, the amphiphilic nature of insect proteins may enhance their ability to adsorb at the oil–water interface, contributing to improved emulsion stability. Overall, the results suggest that a 15 % inclusion level represents an optimal threshold for improving emulsion stability in frankfurter-type meat batters, particularly when using WTM, highlighting the potential of insect powders as functional ingredients in hybrid meat emulsions.

#### *Effect of insect powders on chemical composition of Frankfurt-like sausages*

The incorporation of insect powders into frankfurter-type sausages resulted in significant changes in proximate composition across all formulations, with the exception of ash content, which did not differ significantly among treatments ( $p > 0.05$ ) (Table 1).

Regarding moisture content, all insect powder–enriched formulations showed lower values compared to the CT ( $p < 0.05$ ). The lowest moisture levels ( $p < 0.05$ ) were observed in sausages with the highest replacement levels (15WTM and 15WAD), regardless of the insect species. This reduction in moisture can be directly attributed to the partial replacement of lean meat (which has a high intrinsic water content) with insect powders, which are characterized by substantially lower moisture levels. Similar moisture reductions have been reported in previous studies involving the incorporation of insect-based ingredients into meat products [3,5,6,26].

Protein content was significantly affected by the addition of insect powders, except for the 7.5WTM formulation, which showed protein content similar to the CT ( $p > 0.05$ ). Given that beef lean meat typically contains 20–30 g of protein/100 g [25], its replacement with insect powders was

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

expected to result in sausages with higher protein content. As shown in Table 1, protein content increased proportionally with the level of insect powder incorporation; sausages containing 15 % insect powder reached higher values than those with 7.5 %. In this case, the species of insect also influenced the final protein content: sausages formulated with WAD (7.5WAD and 15WAD) exhibited higher protein levels than their WTM counterparts. This difference is explained by the higher protein concentration of WAD (57.3 g protein/100 g) compared to WTM (50.0 g protein/100 g) [5]. In this context, the partial replacement of lean meat with insect powder represents a substitution of traditional animal protein with a sustainable alternative, the nutritional impact of which depends on both the inclusion level and the specific powder composition.

These findings are consistent with previous works by Wook *et al.* [27], who evaluated frankfurter-type sausages formulated with *T. molitor* and silkworm pupae (*Bombyx mori*) powders. In their study, insect-enriched sausages showed higher protein contents than the control, with values ranging from approximately 26 to 31 g/100 g, depending on the processing method applied to the insect powder. Notably, defatted and hydrolyzed insect powders led to even greater increases in protein content without significantly affecting moisture and ash levels, highlighting how processing influences the nutritional quality of insect-based ingredients [3].

Similarly, Cavalheiro *et al.* [6] reported protein contents of up to 17.8 % in frankfurter-type sausages formulated with cricket powder, values that are comparable to those obtained in the present study, particularly for formulations containing *A. domesticus* powder.

Nevertheless, the changes in the proximal composition of insect-enriched meat products are closely associated with the formulation approach; insect powders can be utilized either for fortification purposes or as substitutes for lean meat or fat fractions [28].

Regarding fat content, only sausages with WTM (7.5WTM and 15WTM) exhibited higher values ( $p < 0.05$ ) than both the CT and those with WAD (7.5WAD and 15WAD), the latter showing similar fat content ( $p > 0.05$ ). These differences can be attributed to the high intrinsic fat content of WTM (30.8 g/100 g) compared to WAD (21.5 g/100 g) and beef lean meat (approx. 15–20 g/100 g) [5,29].

Given that the TDF content in sausages is derived solely from the added insect powder, the differences observed among formulations are likely due to both the inclusion level and the insect species. Since the TDF content in WAD was higher than in WTM (4.9 g/100 g vs 3.3 g/100 g) [5], the sausages with the highest amount of WAD (15WAD) presented the highest TDF content ( $p < 0.05$ ). However, the TDF content in all insect-based sausages remained below 1 %, suggesting it may not be of significant nutritional importance in this specific matrix.

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

Residual nitrite determination is a critical parameter for chemical safety assessment, as nitrites are intentionally added as curing agents to inhibit the growth of pathogenic microorganisms, including *Clostridium botulinum*, and to stabilize the characteristic pink color of cured meat products [30]. Frankfurters with added with powder exhibited higher residual nitrite values than control sausages ( $p < 0.05$ ) (Table 1). Formulations with WTM showed higher values than those with WAD ( $p < 0.05$ ), with no significant differences found between inclusion level within the same species ( $p > 0.05$ ). Although insects do not inherently contain high levels of nitrites, they can indirectly influence residual nitrite content in processed meat products by introducing nitrates or microbiological factors that promote nitrate-to-nitrite conversion during curing [31]. The mineral profile of edible insects, including nitrate precursors, varies substantially with species, developmental stage, and feeding substrate, indicating that insects may carry measurable levels of nitrate into food products. The overall composition and processing dynamics of the product can change when insects or insect-derived ingredients are added to meat products, which in turn may influence the amount of nitrite that remains in the final product after curing. According to Commission Regulation (EU) 2023/2108 [32], which amends Regulations (EC) No 1333/2008 and (EU) No 231/2012, the maximum residual nitrite level permitted in heat-treated meat products is 90 mg/kg. The residual nitrite values obtained in the present study were well below this regulatory limit (Table 1), thereby ensuring product safety and minimizing potential health risks associated with excessive nitrite intake, such as the formation of carcinogenic N-nitrosamines [30].

Regarding the mineral profile of Frankfurt-type sausages (Table 1), the partial replacement of lean meat with insect powders significantly influenced the mineral composition in a species- and dose-dependent manner. According to Regulation (EC) No. 1169/2011 [33], a food may be considered a source of a given mineral when it provides at least 15 % of the Nutrient Reference Value (NRV) per 100 g of product. In this context, all formulations, including the CT, could be considered a source of iron and potassium, which is consistent with the intrinsic contribution of muscle tissue [29].

Notably, the incorporation of WTM led to a marked increase in Mg and Mn contents, particularly at the 15 % substitution level (15WTM), reaching concentrations compatible with nutritional relevance according to current European criteria. Similarly, formulations containing WAD exhibited higher Ca and Mn contents ( $p < 0.05$ ), with the 15 % inclusion level (15WAD) providing the highest values. These differences reflect not only the intrinsic mineral composition of the insect species [5] but also the reformulation effect associated with lean meat substitution, which alters the relative contribution of muscle tissue to the overall mineral profile [29]. Lean meat is known to contain

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

higher concentrations of Fe, Zn, Mg, and P than adipose tissue, whereas sodium is mainly derived from added salt rather than from raw materials [34].

However, despite some significant increases observed, only specific formulations achieved mineral levels that meet the thresholds required to be considered nutritionally relevant under current European regulations. This highlights the importance of both insect species selection and inclusion level when designing hybrid meat products aimed at improving mineral composition. Overall, the observed mineral modulation results from the combined effect of lean meat replacement and the distinct mineral profiles of the insect powders, would support their potential use as functional ingredients within a regulatory-compliant framework.

**Table 2** summarizes the fatty acid profile and the nutritional quality indices of the control and the reformulated Frankfurt-type sausages. In all formulations, the UFA fraction predominated over the SFA fraction, and the MUFA fraction predominated over the PUFA fraction. Specifically, the primary UFA was oleic acid (C18:1 cis), accounting for more than 40% of the total. The main SFAs were palmitic (C16:0) and stearic (C18:0) acids, while the predominant PUFA was linoleic acid (C18:2). Together, these four fatty acids represented 92-93 % of the total fatty acid content in the sausages. The partial replacement of lean meat with WTM and WAD led to slight but significant variations in the content of all fatty acids ( $p < 0.05$ ). The highest concentrations of C16:0 and C18:0 were found in the CT, followed by WAD- and WTM-enriched sausages ( $p < 0.05$ ), with these variations also being significantly influenced ( $p < 0.05$ ) by the inclusion level. This trend aligns with the reported lipid profiles of WTP and WAD [5] or even with *T. molitor* and *A. domesticus* oils, where palmitic acid is the primary SFA and stearic acid content remains low [35]. Oleic acid was identified as the main fatty acid in both insect species, consistent with previous studies on their respective oils [3,35].

The incorporation of insect powders (WTM and WAD) reduced the SFA content by up to 7 % and increased PUFA content by up to 21 % compared to the CT. The 15WTM formulation exhibited the most pronounced changes ( $p < 0.05$ ), leading to an overall improvement in lipid nutritional indices. However, none of the reformulated sausages fulfilled the requirements for official nutrition claims related to saturated fat reduction under Regulation (EC) No 1924/2006 [36].

The nutritional profile of the lipid fraction was assessed using two prevalent indices: the n-6/n-3 and PUFA/SFA ratios. Regarding the latter, the inclusion of insect flour (both WTM and WAD) led to a significant increase in the PUFA/SFA ratio ( $p < 0.05$ ) relative to the control (CT). The most pronounced elevation was recorded in the 15WTM formulation, which reached a peak value of 0.35. This improvement can be attributed to the combined effect of a reduction in the SFA fraction and a concomitant increase in the PUFA fraction resulting from the partial replacement of beef meat with

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

insect powders. Despite this increase, the values of the PUFA/SFA ratio did not exceed 0.4 (not even in 15WTM), which is the threshold established by Wood *et al.* [37] for considering these fats nutritionally desirable, given that higher values are associated with more favorable health outcomes. The reformulation of frankfurters with insect powders also failed to meet established health recommendations regarding the n6/n3 ratio, as all sausages exhibited values higher than 4. Since the typical Western diet is already characterized by a high intake of n6 fatty acids and a low intake of n3 fatty acids, a pattern associated with an increased risk of inflammatory and cardiovascular diseases, low n6/n3 ratios, ideally between 1 and 4, are recommended [38]. The high prevalence of n6 fatty acids (9.90-12.17 g/100 g fat) compared to n3 fatty acids (0.90-1.04 g/100 g fat) in Frankfurt-type sausages (both control and reformulated) explains why these values remain elevated. Additionally, the lipid profiles of WAD and WTM contribute to these results because linoleic acid (C18:2, n6) is the predominant PUFA in both insect powders, representing more than 95% of this fraction [5]. Beyond the PUFA/SFA and n6/n3 ratios, the nutritional quality of the lipid fraction was further assessed using complementary indices related to the cardiovascular risk: the atherogenic index (AI), the thrombogenic index (TI) and the hypocholesterolemic/hypercholesterolemic ratio (h/H). These indices provide a more integrative evaluation of the health impact of fatty acid composition than individual fatty acids alone [24,39]. Lower AI and TI values indicate a lower cardiovascular risk, while a higher h/H ratio suggests a better hypocholesterolemic profile. Frankfurt-like sausages formulated with WAD (7.5WAD and 15WAD) showed improvements in all three indices compared to the CT (lower AI and TI, and higher h/H;  $p < 0.05$ ). In contrast, for WTM-sausages, this improvement was only significant for the TI index, with the AI and h/H ratio remained at values similar to the CT ( $p > 0.05$ ; Table 2). These differences between WTM and WAD formulations are likely related to the total fat content and the specific fatty acid profile of each insect species. The modifications that both insect species induce in the fatty acid profile of Frankfurt-type sausages (depending on the replacement level) are, in some cases, not intensive enough to trigger drastic shifts in these nutritional ratios. Nevertheless, these results are in full agreement with our previous characterization of WTM and WAD samples [5] which demonstrated that WAD possesses a superior profile for these three indices compared to WTM (evidenced by lower AI and TI values and higher h/H ratios).

Overall, although none of the formulations reached the PUFA/SFA and n6/n3 thresholds generally considered optimal for health, the consistent modulation of all lipid quality indices highlights the potential of insect powders as effective ingredients for improving the nutritional quality of hybrid meat products. These effects were found to be both species- and concentration-dependent. Regarding the species, the use of WAD as a partial lean meat replacement yielded greater

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

improvements in these indices than WTM. In terms of concentration, the most significant nutritional enhancements were achieved at the highest inclusion level (15 %).

#### *Effect of insect powders on techno-functional properties of Frankfurt-like sausages*

Regarding pH, significant differences were observed among the samples, with the exception of formulations 7.5WAD and 15WAD, which did not differ significantly from each other ( $p > 0.05$ ; **Table 3**). Compared to the CT, the pH values increased ( $p < 0.05$ ) with the incorporation of WTM and WAD, ranging from 6.02 (CT) to 6.28 (15WTM). In all formulations, including both control and reformulated sausages, pH values fell within the typical range reported for cooked sausages (5.8–6.5). This range is regarded as optimal from a technological perspective, as it supports proper protein functionality and emulsion stability, while also contributing positively to sensory attributes such as flavor and color stability [16]. Similar pH values have been previously reported in cooked sausages added with insect powders (6.05–6.37) [3, 11].

The partial replacement of beef lean meat by insect powders did not alter the water activity values of the resulting Frankfurt-type sausages ( $p > 0.05$ ; **Table 3**). The values remained within the typical range for cooked, emulsified meat products (0.95–0.98), contributing to their texture and juiciness, while requiring strict hygienic and storage conditions [40].

Color is a critical quality attribute in meat product reformulation, as it serves as the primary visual cue for consumer perception of freshness, quality, and overall acceptance. **Table 3** shows the color properties of control and reformulated Frankfurt-type sausages. The addition of insect powders decreased  $L^*$  and  $a^*$  values ( $p < 0.05$ ).  $L^*$  values decreased progressively as the concentration of both WTM and WAD increased ( $p < 0.05$ ), without differences between both insect powders ( $p > 0.05$ ). The inclusion of edible insect flours in meat product reformulations typically results in a significant reduction of  $L^*$  values, leading to a darker appearance in the final product. This decrease has been primarily attributed to the inherent pigmentation of insect exoskeletons, particularly the presence of melanin, as well as the high concentration of Fe and various minerals found in insect species like *T. molitor* or *A. domesticus* [26]. The thermal processing of sausages likely promoted Maillard reactions between insect-derived proteins and carbohydrates, which, along with the Strecker degradation generate dark-colored compounds, such as high-molecular-mass melanoidins [41]. These reactions, intensified at advanced stages, largely explain the post-cooking darkening observed in formulations with higher insect powder inclusion (15WTM and 15WAD). Additionally, the presence of chitin, although it is not a pigment, may indirectly contribute to visual darkening by affecting light scattering and surface reflectance [14]. Regarding redness ( $a^*$ ), the incorporation of insect powders led to a

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

reduction compared to the CT ( $p < 0.05$ ), an effect that was more pronounced in WAD-sausages. For WTM-sausages, this reduction was concentration-dependent ( $p < 0.05$ ). This trend, also reported by Cavalheiro *et al.* [6], is primarily attributed to a dilution effect on the myoglobin concentration within the meat batter, combined with the introduction of intrinsic brownish pigments from the insects [12]. This reduction in redness values has also been reported by García-Segovia *et al.* [42] in sausages added with *T. molitor* powder. For yellowness ( $b^*$ ), significant increases compared to the CT ( $p < 0.05$ ) were only observed in formulations containing WTM (7.5WTM and 15WTM). This increase has been linked to carotenoid-related compounds and the high lipid content inherent to *T. molitor* [12], explaining why these changes were more evident in WTM-sausages.

In relation to psychophysical magnitudes, 15WAD was the only formulation to show a significantly lower chroma ( $C^*$ ) compared to the CT ( $p < 0.05$ ), indicating a less saturated color. However, all insect-added sausages exhibited higher hue angle ( $H^*$ ) values than the CT ( $p < 0.05$ ), with the highest values found in WTM-sausages.

The combined behavior of color coordinates resulted in total color differences ( $\Delta E^*$ ) compared to the CT (Table 3) that were dependent on the concentration of insect powder added ( $p < 0.05$ ) rather than the insect species ( $p > 0.05$ ). Consequently, the 15WTM and 15WAD samples showed higher  $\Delta E^*$  values ( $p < 0.05$ ) than the 7.5 % formulations. The replacement of lean meat by WAD and WTM induced noticeable changes in the color of the reformulated sausages, even at the lowest inclusion levels (7.5 %), reaching  $\Delta E^*$  values  $> 3.0$  [20].

Fig. 2 presents the reflectance spectra of all Frankfurt-type sausages. The shape of the reflectance spectrum of the CT was consistent with that typically reported for thermally treated cured meat products [20]. While the addition of insect powders did not alter the typical shape of the spectrum, it significantly varied the percentage of reflectance. Regardless of insect species, sausages formulated with insect powders exhibited lower reflectance values ( $p < 0.05$ ) than the CT across almost all wavelengths (360–740 nm). Interestingly, sausages containing 7.5 % insect powder (7.5WAD and 7.5WTM) showed isosbestic points across wavelengths ranging from 460 to 600 nm, corresponding to the blue, green and yellow color ranges. However, at a 15 % inclusion level (15WTM and 15WAD), the number of isosbestic wavelengths decreased, remaining mainly within the 360–450 nm range (violet color range). The area of the spectrum where the separation between samples was best visualized corresponds to the orange and red color range (640–740 nm), which correlates with the previously discussed decrease in the  $a^*$  coordinate.

The texture of cooked meat products is primarily governed by the formation of a stable protein-water-fat matrix during thermal processing; therefore, the fat-to-lean ratio and moisture content

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

significantly affect textural parameters. In the context of reformulation, the incorporation of non-meat ingredients, such as alternative proteins from insects, alters the water-holding capacity and the continuous phase of the emulsion, thereby modifying the final product's texture [43]. Additionally, heat distribution within the meat emulsion can become uneven when insect powder is incorporated, further impacting the final texture of hybrid meat products.

The texture profile of Frankfurt-type sausages is presented in **Table 3**. Elasticity did not show significant differences among the various formulations ( $p>0.05$ ), suggesting that the flexible nature of the protein network was maintained despite the incorporation of insect powders. Conversely, hardness, gumminess, cohesiveness and chewiness were significantly affected ( $p<0.05$ ) by the addition of insect powders. Hardness, gumminess and chewiness followed a consistent trend: the incorporation of insect powders at the lowest concentration (7.5 %) decreased these values compared to those of the CT, whereas at the highest concentration (15 %), these textural parameters increased again, reaching values similar to those of the CT ( $p>0.05$ ). However, the behavior of cohesiveness was distinct; a significant reduction was only observed in sausages with the highest amount of insect powder (15WTM and 15WAD), regardless of the insect species.

The replacement of meat proteins with insect flours typically induces significant modifications in the textural profile of cooked sausages, often resulting in increased hardness and reduced cohesiveness [3,11,43]. These changes have been primarily attributed to the presence of chitin, a structural polysaccharide in the insect exoskeleton that acts as a non-functional filler. Chitin can interfere with the formation of a continuous myofibrillar protein network and alter the lipid-protein and protein-protein interactions between meat and non-meat ingredients [6,23]. Additionally, the replacement of lean meat by high-solid-content powders decreases the overall moisture content in the reformulated sausages (**Table 1**), which generally results in a harder structure [43]. Furthermore, insect flours often exhibit lower gel-forming capacity compared to myofibrillar muscle proteins, which can weaken the matrix's ability to entrap water and fat effectively. Consequently, the resulting meat-insect hybrid products may exhibit varying textural properties depending not only on the inclusion level but also on the insect species, the specific processing techniques used to pre-treat the insect biomass, and the method of application.

#### *Effect of insect powders on the sensory properties of Frankfurt-like sausages*

The results of the hedonic sensory evaluation of control and reformulated Frankfurter-type sausages are summarized in **Table 3**. The incorporation of insect powders significantly affected all evaluated sensory attributes ( $p<0.05$ ), with a general trend toward lower scores as the inclusion level

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

increased from 7.5 % to 15 %. The control sausage received the highest ratings across all categories, ranging from 7.07 for overall acceptability to 7.43 for general taste. Among the reformulated samples, the 7.5WAD and 7.5WTM formulations showed the highest scores, with no significant differences from the CT in attributes such as hardness and overall flavor ( $p > 0.05$ ). Similar results were reported by Kim *et al.* [11] and Cavaleiro *et al.* [6], who observed that low inclusion levels of *T. molitor* and *A. domesticus* (up to 10 %) do not negatively impact the sensory perception of cooked sausages, whereas higher concentrations tend to decrease scores. Appearance and color scores decreased significantly ( $p < 0.05$ ) in the 15 % formulations, particularly in 15WAD, which received the lowest scores. This negative perception by the panellists correlates with the objective color instrumental measurements previously discussed, where 15WAD exhibited the lowest lightness and redness values. The darker and less red appearance caused by the high concentration of insect powders likely deviated from the traditional "pinkish" expectations for Frankfurter-type sausages, impacting consumer preference. This "darkening effect" is a common challenge in insect-meat hybrids; for instance, Cruz-López *et al.* [26] highlighted that consumers often associate the brownish hue of insect-added products with a lack of freshness or a non-traditional formulation. Regarding texture, the juiciness and hardness scores also showed a concentration-dependent decline. Formulation 15WAD was perceived as significantly less juicy than the CT ( $p < 0.05$ ). This result may be linked to the lower moisture content and the interference of chitin with the myofibrillar protein network, which, as observed in the TPA analysis, can lead to a more heterogeneous or less cohesive matrix. As noted by Acosta-Estrada *et al.* [43], the inclusion of high-fiber insect powders can alter the mouthfeel of emulsified products, increasing crumbliness. Finally, overall acceptability followed a similar pattern; while 7.5 % inclusion levels (especially 7.5WAD) remained within the "like slightly" range, the 15 % formulations, particularly 15WAD, were closer to the neutral point of the scale. These findings suggest that while 7.5 % replacement is well-tolerated, higher concentrations of insect powder may require further flavor or color masking strategies to enhance consumer appeal.

### *Principal components analysis*

Principal component analysis (PCA) was applied to explore the relationships among compositional, nutritional, technological, and sensory variables in Frankfurt-type sausages formulated with insect powders. The spatial distribution of the 5 formulations in the two-dimensional space defined by the first two principal components is displayed in Fig. 3. The first two principal components explained 68.33 % of the total variance, with PC1 accounting for 42.05 % and PC2 for 26.28 %.

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

PC1 clearly discriminated the CT from those formulated with insect flours (7.5WTM, 15WTM, 7.5WAD, and 15WAD), indicating a strong effect of insect inclusion on the overall product matrix. Control samples were located on the positive side of PC1 and were mainly associated with higher moisture content, elasticity, cohesiveness, lower emulsion stability and overall sensory attributes such as flavor and general taste. These samples were also related to certain saturated fatty acids, reflecting the typical structural and compositional characteristics of conventional meat emulsions. In contrast, sausages formulated with insect powders were shifted towards the negative side of PC1, suggesting that the incorporation of insect-derived ingredients substantially modified the physicochemical and technological properties of the product.

PC2 further differentiated the insect-containing sausages according to both the insect species and the level of inclusion. Sausages formulated with *T. molitor* powder (7.5WTM and 15WTM) and *A. domesticus* powder (7.5WAD and 15WAD) showed a clear separation along this axis, reflecting differences in protein content, mineral composition (e.g. Ca, Na, Fe), texture-related parameters (hardness, chewiness, gumminess), and lipid profile. Samples with higher inclusion levels (15 %) were generally located farther from the origin than those with 7.5 %, indicating a concentration-dependent effect of insect powder addition on product characteristics.

Overall, the PCA results demonstrate that the incorporation of *T. molitor* and *A. domesticus* powders significantly influences the technological, nutritional, and quality-related attributes of Frankfurt-like sausages. These effects are gradual and strongly dependent on both insect species and inclusion level, supporting the technological feasibility of insect-based reformulation while highlighting the need for formulation optimization to control texture and residual nitrite content.

## CONCLUSIONS

The partial replacement of beef lean meat with *Acheta domesticus* (WAD) and *Tenebrio molitor* (WTM) powders proves to be a successful strategy for developing hybrid meat products that align with sustainability and health trends. Beyond simple protein fortification, these insect ingredients act as effective techno-functional agents, significantly enhancing the physical stability of meat emulsions.

From a nutritional perspective, the inclusion of insect powders successfully transforms a traditional meat product into a denser source of essential minerals and unsaturated fats, with WAD showing a superior potential.

Finally, the 7.5 % substitution level is identified as the optimal threshold; it maximizes nutritional and technological benefits while preserving the sensory profile and color characteristic of

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

Frankfurter-type sausages. These findings provide the meat industry with a scientifically validated framework for the transition toward more sustainable and functional hybrid products, demonstrating that edible insects are not just fillers but valuable ingredients for food innovation.

## ACKNOWLEDGEMENT

During the preparation of this work, the authors used Google-Gemini/OPENAI to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

## FUNDING

Funding for this research was provided by the UMH-FAPESP through the International Research Project between UMH (Spain) and Sao Paulo State (Brazil) "Looking for new sources of ingredients in the development of sustainable meat products". Additional support was received through the Ibero-American Programme for Science and Technology for Development (CYTED), specifically via the *Red AIProsos* 125RT0165.

## ETHICS APPROVAL

The study was approved by the Responsible Research Office at Miguel Hernández University (OIR-Reg. 231,129,141,204; Ref. PRL.RTA.JFL.JRP.23, UMH, Elche, Alicante, Spain). During the sensory analysis and prior to testing, participants were informed about the product characteristics and the procedure, and written informed consent was obtained.

## CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## AUTHORS' CONTRIBUTION

J. Rodríguez-Párraga contributed to methodology, formal analysis, writing original draft and editing. R. Lucas-González contributed to data curation, conceptualization, supervision and writing review and editing. C. Botella-Martínez contributed to methodology and validation. M. Viuda-Martos contributed to conceptualization, resources, validation, writing review and editing. F. Borrás-Rocher contributed to formal analysis, validation, writing review and editing, J. Á. Pérez-Alvarez contributed

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

to conceptualization, resources, validation, writing review and editing. J. Fernández-López contributed to conceptualization, data curation, supervision, writing review and editing.

### ORCID ID

J. Rodríguez-Párraga <https://orcid.org/0009-0004-6417-2327>

R. Lucas-González <https://orcid.org/0000-0003-0309-7031>

C. Botella-Martínez <https://orcid.org/0000-0002-1546-9093>

M. Viuda-Martos <https://orcid.org/0000-0001-9801-3819>

F. Borrás-Rocher <https://orcid.org/0000-0002-5519-4573>

J.A. Pérez-Alvarez <https://orcid.org/0000-0002-1143-5646>

J. Fernández-López <https://orcid.org/0000-0002-4771-8437>

### REFERENCES

1. United Nations. World population prospects 2024. Summary of results. New York, NY, USA: United Nations; 2024.
2. Lu MX, Zhu C, Smetana S, Zhao M, Zhang H, Zhang F, *et al.* Minerals in edible insects: review of content and potential for sustainable sourcing. *Food Sci Hum Wellness*. 2023;1-18.  
<https://doi.org/10.26599/FSHW.2022.9250005>
3. Rodríguez-Párraga J, Lucas-González R, Viuda-Martos M, Muñoz-Bas C, Barba FJ, Pérez-Alvarez JA, *et al.* Exploring the suitability of *Tenebrio molitor* powder (whole and defatted by supercritical CO<sub>2</sub>) as a partial fat replacement in bologna-type sausages. *Meat Sci*. 2025;228:109890 .  
<https://doi.org/10.1016/j.meatsci.2025.109890>
4. Davalos-Vazquez A, Mojica L, Sánchez-Velázquez OA, Castillo-Herrera G, Urías-Silva JE, Dayen A. *et al.* Techno-functional properties and structural characteristics of cricket protein concentrates affected by pre-treatments and ultrafiltration/diafiltration processes. *Food Chem*. 2024;461:140908.  
<https://doi.org/10.1016/j.foodchem.2024.140908>
5. Rodríguez-Párraga J, Lucas-González R, Botella-Martínez C, Viuda-Martos M, Lorenzo JM, Borrás-Rocher F, *et al.* Unlocking the potential of insect powders for the development of sustainable and nutritious foods: Nutritional and techno-functional properties. *Future Foods*. 2025;12:100838.  
<https://doi.org/10.1016/j.fufo.2025.100838>

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

6. Cavalheiro CP, Ruiz-Capillas C, Herrero AM, Pintado T, Cruz TMP, da Silva MCA. Cricket (*Acheta domestica*) flour as meat replacer in frankfurters: Nutritional, technological, structural, and sensory characteristics. *Innov Food Sci Emerg Technol.* 2023;83:103245.  
<https://doi.org/10.1016/j.ifset.2022.103245>
7. European Union. Regulation (EU) 2015/2283 of the European Parliament and of the Council of 25 November 2015 on novel foods. *OJEU* 2015; 11/12/2015.
8. Álvarez PJ, Mateo J, Giráldez J. Harina de grillo *Acheta domestica*: composición lipídica y posibilidades sobre su modificación por medio de la dieta. *Bistua Rev Fac Cienc Basicas.* 2021;18(2):38-43.  
<https://doi.org/10.24054/01204211.v2.n2.2020.841>
9. Stull VJ, Weir TL. Chitin and omega-3 fatty acids in edible insects have underexplored benefits for the gut microbiome and human health. *Nat Food.* 2023;4(4):283-7.  
<https://doi.org/10.1038/s43016-023-00728-7>
10. Villaseñor VM, Enriquez-Vara JN, Urías-Silva JE, Mojica L. Edible insects: Techno-functional properties food and feed applications and biological potential. *Food Rev Int.* 2022;38 (Suppl. 1):866-92.  
<https://doi.org/10.1080/87559129.2021.1890116>
11. Kim H, Setyabrata D, Lee Y, Jones OG, Kim YHB. Effect of house cricket (*Acheta domestica*) flour addition on physicochemical and textural properties of meat emulsion under various formulations. *J Food Sci.* 2017;82(12):2787-93.  
<https://doi.org/10.1111/1750-3841.13960>
12. Choi YS, Kim TK, Choi HD, Park JD, Sung JM, Jeon KH, *et al.* Optimization of replacing pork meat with yellow worm (*Tenebrio molitor* L.) for frankfurters. *Korean J Food Sci Anim Resour.* 2017;37(5):617-25.  
<https://doi.org/10.5851/kosfa.2017.37.5.617>
13. Brena-Melendez A, Garcia-Amezquita LE, Liceaga A, Pascacio-Villafán C, Tejada-Ortigoza V. Novel food ingredients: Evaluation of commercial processing conditions on nutritional and technological properties of edible cricket (*Acheta domestica*) and its derived parts. *Innov Food Sci Emerg Technol.* 2024;92:103589.  
<https://doi.org/10.1016/j.ifset.2024.103589>
14. Omuse ER, Tonnang HEZ, Yusuf AA, Machekano H, Egonyu JP, Kimathi E, *et al.* The global atlas of edible insects: analysis of diversity and commonality contributing to food systems and sustainability. *Sci Rep.* 2024;14(1):5045.

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

<https://doi.org/10.1038/s41598-024-55603-7>

15. Meyer-Rochow VB. Entomophagy and its impact on world cultures: the need for a multidisciplinary approach. *Forest Insects as Food: Humans Bite Back*. Proceedings of the workshop on Asia-Pacific resources and their potential for development; 2008 February 19-21, Thailand, 2010;6(2):23-36. Available from:  
<https://www.cabidigitallibrary.org/doi/full/10.5555/20103207741>
16. Fernández-López J, Lucas-González R, Viuda-Martos M, Sayas-Barberá E, Navarro C, Haros CH, *et al.* Chia (*Salvia hispanica* L.) products as ingredients for reformulating frankfurters: Effects on quality properties and shelf-life. *Meat Sci.* 2019;156:139-45.  
<https://doi.org/10.1016/j.meatsci.2019.05.028>
17. Hughes E, Cofrades S, Troy DJ. Effects of fat level, oat fibre and carrageenan on frankfurters formulated with 5, 12 and 30% fat. *Meat Sci.* 1997;45(3):273-81.  
[https://doi.org/10.1016/S0309-1740\(96\)00109-X](https://doi.org/10.1016/S0309-1740(96)00109-X)
18. AOAC Official methods of analysis. 18th ed. Rockville, MD, USA: AOAC International; 2010.
19. Chen J, Liu H. Nutritional indices for assessing fatty acids: A mini-review. *Int J Mol Sci.* 2020;21(16):5695.  
<https://doi.org/10.3390/ijms21165695>
20. King DA, Hunt MC, Barbut S, Claus JR, Cornforth DP, Joseph P, *et al.* American Meat Science Association guidelines for meat color measurement. *Meat Muscle Biol.* 2023;6(4).  
<https://doi.org/10.22175/mmb.12473>
21. ISO 2918:1975. Meat and meat products: Determination of nitrite content. Geneva, Switzerland: International Organization for Standardization (ISO); 1975.
22. IBM Corp. IBM SPSS Statistics for Windows v. 29; 2023. Available from <https://www.ibm.com/products/spss-statistics>
23. Paradiso VM, Giarnetti M, Summo C, Pasqualone A, Minervini F, Caponio F. Production and characterization of emulsion filled gels based on inulin and extra virgin olive oil. *Food Hydrocoll.* 2015;45:30-40.  
<https://doi.org/10.1016/j.foodhyd.2014.10.027>
24. Botella-Martínez C, Viuda-Martos M, Pérez-Álvarez JA, Fernández-López J. Total and partial fat replacement by gelled emulsion (hemp oil and buckwheat flour) and its impact on the chemical, technological and sensory properties of frankfurters. *Foods.* 2021;10(8):1681.  
<https://doi.org/10.3390/foods10081681>

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

25. Vlahova-Vangelova D, Balev D, Kolev N, Dragoev S. Possibilities for partial replacement of pork meat in cooked sausages by mealworm flour. *Carpath J Food Sci Technol*. 2023;5-14. <https://doi.org/10.34302/crpjfst/2023.15.4.1>.
26. Cruz-López SO, Escalona-Buendía HB, Martínez-Arellano I, Domínguez-Soberanes J, Álvarez-Cisneros YM. Physicochemical and techno-functional characterization of soluble proteins extracted by ultrasound from the cricket *Acheta domestica*. *Heliyon*. 2024;10(23):e40718. <https://doi.org/10.1016/j.heliyon.2024.e40718>.
27. Kim HW, Setyabrata D, Lee YJ, Jones OG, Kim YHB. Pre-treated mealworm larvae and silkworm pupae as a novel protein ingredient in emulsion sausages. *Innov Food Sci Emerg Technol*. 2016;38:116-23. <https://doi.org/10.1016/j.ifset.2016.09.023>
28. Rocchetti G, Leni G, Rebecchi A, Dordoni R, Giuberti G, Lucini L. The distinctive effect of different insect powders as meat extenders in beef burgers subjected to cooking and in vitro gastrointestinal digestion. *Food Chem*. 2024;442:138422. <https://doi.org/10.1016/j.foodchem.2024.138422>
29. USDA. Department of Agriculture, Agricultural Research Service. Food Data Central. Available from: <https://fdc.nal.usda.gov/>. Accessed January 23, 2026.
30. Zhou F, Xie Y, Wang Y, Zhang H, Wang J, Liao X, *et al*. An overview of the formation mechanisms of endogenous and exogenous N-nitrosamines in human diets. *J Environ Sci*. 2025;158: 527-41. <https://doi.org/10.1016/j.jes.2025.02.016>
31. Jankauskienė A, Aleknavicius D, Andrulevičutė V, Mockus E, Bartkienė E, Jukniene I, *et al*. Nutritional composition and safety parameters of mealworms (*Tenebrio molitor*) reared on substrates derived from by-products. *Appl Sci*. 2024;14(7):2744. <https://doi.org/10.3390/app14072744>
32. European Union. Commission Regulation (EU) 2023/2108 of 6 October 2023 amending Annex II to Regulation (EC) No 1333/2008 of the European Parliament and of the Council and the Annex to Commission Regulation (EU) No 231/2012 as regards food additives nitrites (E 249-250) and nitrates (E 251-252). *OJEU* 2023;9/10/2023.
33. European Union. Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011 on the provision of food information to consumers. *OJEU* 2011;22/11/2011.
34. Hernández Rico FD. Carne y productos cárnicos como alimentos funcionales; 2022. Universidad Nacional Autónoma de México, México.

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

35. Martínez-Pineda M, Juan T, Antoniewska-Krzeska A, Vercet A, Abenoza M, Yagüe-Ruiz C, *et al.* Exploring the potential of yellow mealworm (*Tenebrio molitor*) oil as a nutraceutical ingredient. *Foods*. 2024;13(23):3867.  
<https://doi.org/10.3390/foods13233867>
36. European Union. Regulation (EC) No 1924/2006 of the European Parliament and of the Council of 20 December 2006 on nutrition and health claims made on foods. *OJEU* 2006;30/12/2006.
37. Wood JD, Enser M, Fisher AV, Nute GR, Sheard PR, Richardson RI, *et al.* Fat deposition, fatty acid composition and meat quality: A review. *Meat Sci*. 2008;78(4):343-58.  
<https://doi.org/10.1016/j.meatsci.2007.07.019>
38. Yang Y, Xia Y, Zhang B, Li D, Yan J, Yang J, *et al.* Effects of different n-6/n-3 polyunsaturated fatty acids ratios on lipid metabolism in patients with hyperlipidemia: a randomized controlled clinical trial. *Front Nutr*. 2023;10.  
<https://doi.org/10.3389/fnut.2023.1166702>
39. Souza Paglarini C, de Figueiredo-Furtado G, Honorio AR, Mokarzel L, da Silva Vidal VA, Badan-Ribeiro AP, *et al.* Functional emulsion gels as pork back fat replacers in Bologna sausage. *Food Struct*. 2019;20:100105.  
<https://doi.org/10.1016/j.foostr.2019.100105>
40. Feiner G. *Meat products handbook: Practical science and technology*. Oxford, UK: Woodhead Publishing; 2006.
41. Silva Barbosa Correia B, Drud-Heydary Nielsen S, Jorkowski J, Arildsen Jakobsen LM, Zacherl C, Bertram HC. Maillard reaction products and metabolite profile of plant-based meat burgers compared with traditional meat burgers and cooking-induced alterations. *Food Chem*. 2024;445:138705.  
<https://doi.org/10.1016/j.foodchem.2024.138705>
42. García-Segovia P, Igual M, Noguerol AT, Martínez-Monzó J. Use of insects and pea powder as alternative protein and mineral sources in extruded snacks. *Eur Food Res Technol*. 2020;246(4):703-12.  
<https://doi.org/10.1007/s00217-020-03441-y>
43. Acosta-Estrada BA, Reyes A, Rosell CM, Rodrigo D, Ibarra-Herrera CC. Benefits and challenges in the incorporation of insects in food products. *Front Nutr*. 2021;8.  
<https://doi.org/10.3389/fnut.2021.687712>

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

**Table 1.** Effect of partial replacement of lean meat with *Acheta domesticus* and *Tenebrio molitor* powders on proximal composition, residual nitrite level and mineral profile of Frankfurt-type sausages

Composition	Sample				
	CT	7.5WTM	15WTM	7.5WAD	15WAD
	w/(g/100 g)				
Moisture	(70.93±0.29) <sup>a</sup>	(66.76±0.02) <sup>b</sup>	(64.93±0.55) <sup>c</sup>	(67.63±0.47) <sup>b</sup>	(65.57±0.31) <sup>c</sup>
Ash	(1.82±0.07) <sup>a</sup>	(1.91±0.15) <sup>a</sup>	(1.86±0.14) <sup>a</sup>	(1.95±0.23) <sup>a</sup>	(1.71±0.65) <sup>a</sup>
Fat	(9.24±0.43) <sup>b</sup>	(10.23±0.44) <sup>a</sup>	(10.10±0.39) <sup>a</sup>	(8.41±0.52) <sup>b</sup>	(8.13±1.09) <sup>b</sup>
Protein	(16.15±0.10) <sup>c</sup>	(16.38±0.09) <sup>c</sup>	(17.31±0.23) <sup>b</sup>	(17.79±0.25) <sup>b</sup>	(19.19±0.37) <sup>a</sup>
TDF	n.d.	(0.20±0.01) <sup>d</sup>	(0.45±0.03) <sup>b</sup>	(0.33±0.03) <sup>c</sup>	(0.70±0.02) <sup>a</sup>
w(residual nitrite)/(mg/kg)	(26.47±0.75) <sup>c</sup>	(35.06±0.4) <sup>a</sup>	(37.89±2.82) <sup>a</sup>	(31.02±0.75) <sup>b</sup>	(32.01±0.52) <sup>b</sup>
	w/(mg/100 g)				
Ca	(107.82±29.61) <sup>bc</sup>	(79.09±4.31) <sup>c</sup>	(89.03±2.75) <sup>bc</sup>	(120.53±14.96) <sup>b</sup>	(175.44±5.50) <sup>a</sup>
Cu	(0.56±0.22) <sup>b</sup>	(0.90±0.11) <sup>ab</sup>	(1.27±0.02) <sup>a</sup>	(0.53±0.04) <sup>b</sup>	(0.85±0.23) <sup>b</sup>
Fe	(8.98±3.12) <sup>a</sup>	(7.48±0.21) <sup>a</sup>	(8.32±0.61) <sup>a</sup>	(7.57±1.26) <sup>a</sup>	(7.43±0.94) <sup>a</sup>
K	(1048.35±10.65) <sup>ab</sup>	(977.22±11.53) <sup>bc</sup>	(951.70±7.55) <sup>c</sup>	(1063.52±38.86) <sup>a</sup>	(1040.69±40.08) <sup>ab</sup>
Mg	(87.84±30.34) <sup>b</sup>	(123.21±1.93) <sup>b</sup>	(164.03±1.19) <sup>a</sup>	(87.54±4.12) <sup>b</sup>	(95.80±4.44) <sup>b</sup>
Mn	(0.35±0.12) <sup>d</sup>	(0.47±0.01) <sup>d</sup>	(0.63±0.01) <sup>c</sup>	(0.99±0.04) <sup>b</sup>	(1.60±0.02) <sup>a</sup>
Na	(420.83±25.16) <sup>b</sup>	(232.91±13.16) <sup>c</sup>	(235.80±8.62) <sup>c</sup>	(396.73±51.05) <sup>b</sup>	(551.38±22.58) <sup>a</sup>
P	(0.10±0.01) <sup>b</sup>	(0.19±0.02) <sup>a</sup>	(0.26±0.01) <sup>a</sup>	Trace	Trace
Zn	(7.52±1.03) <sup>a</sup>	(2.51±0.25) <sup>b</sup>	(2.02±0.16) <sup>b</sup>	(3.93±0.64) <sup>b</sup>	(2.82±0.99) <sup>b</sup>

<sup>a-c</sup>For each parameter, values followed by the same letter are not significantly different according to Tukey's HSD post-hoc test ( $p>0.05$ ). Data are presented as mean value±standard deviation. n.d.=not detected, CT=control frankfurters with conventional formulation, 7.5WTM=frankfurters with 7.5 % beef lean meat substitution by *Tenebrio molitor* powder, 15WTM=frankfurters with 15 % beef lean meat substitution by *Tenebrio molitor* powder, 7.5WAD=frankfurters with 7.5 % beef lean meat substitution by *Acheta domesticus* powder, 15WAD=frankfurters with 15 % beef lean meat substitution by *Acheta domesticus* powder, TDF=total dietary fiber

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

**Table 2.** Effect of partial replacement of lean beef meat with *Acheta domesticus* and *Tenebrio molitor* powders on fatty acid profile (g/100 g fat) and nutritional quality indices of Frankfurt-type sausages

Lipid profile and indices	Sample				
	CT	7.5WTM	15WTM	7.5WAD	15WAD
C10:0	(0.10±0.01) <sup>a</sup>	(0.08±0.01) <sup>b</sup>	(0.07±0.01) <sup>c</sup>	(0.08±0.01) <sup>b</sup>	(0.08±0.01) <sup>b</sup>
C12:0	(0.10±0.01) <sup>c</sup>	(0.10±0.01) <sup>b</sup>	(0.10±0.01) <sup>a</sup>	(0.09±0.01) <sup>c</sup>	(0.08±0.01) <sup>d</sup>
C14:0	(1.55±0.02) <sup>c</sup>	(1.65±0.01) <sup>b</sup>	(1.75±0.01) <sup>a</sup>	(1.49±0.01) <sup>d</sup>	(1.43±0.04) <sup>e</sup>
C14:1	(0.10±0.01) <sup>a</sup>	(0.07±0.01) <sup>c</sup>	(0.06±0.01) <sup>d</sup>	(0.08±0.01) <sup>b</sup>	(0.08±0.01) <sup>b</sup>
C15:0	(0.11±0.01) <sup>a</sup>	(0.09±0.01) <sup>b</sup>	(0.08±0.01) <sup>c</sup>	(0.08±0.01) <sup>bc</sup>	(0.08±0.01) <sup>bc</sup>
C16:0	(24.30±0.37) <sup>a</sup>	(23.74±0.01) <sup>c</sup>	(23.00±0.18) <sup>d</sup>	(23.86±0.04) <sup>bc</sup>	(24.16±0.19) <sup>ab</sup>
C16:1	(2.22±0.06) <sup>a</sup>	(2.27±0.01) <sup>a</sup>	(2.22±0.02) <sup>a</sup>	(2.24±0.04) <sup>a</sup>	(2.15±0.03) <sup>b</sup>
C17:0	(0.42±0.01) <sup>a</sup>	(0.37±0.01) <sup>b</sup>	(0.34±0.01) <sup>d</sup>	(0.36±0.01) <sup>c</sup>	(0.35±0.01) <sup>c</sup>
C17:1	(0.39±0.01) <sup>a</sup>	(0.35±0.01) <sup>b</sup>	(0.33±0.01) <sup>c</sup>	(0.36±0.01) <sup>b</sup>	(0.34±0.01) <sup>c</sup>
C18:0	(13.91±0.18) <sup>a</sup>	(12.92±0.01) <sup>b</sup>	(12.15±0.36) <sup>c</sup>	(13.14±0.23) <sup>b</sup>	(13.72±0.17) <sup>a</sup>
C18:1 cis	(44.67±0.67) <sup>b</sup>	(45.19±0.02) <sup>ab</sup>	(45.41±0.32) <sup>a</sup>	(45.00±0.24) <sup>ab</sup>	(43.61±0.19) <sup>c</sup>
C18:2 (n6)	(9.69±0.04) <sup>d</sup>	(10.66±0.03) <sup>c</sup>	(11.96±0.23) <sup>a</sup>	(10.61±0.05) <sup>c</sup>	(11.22±0.17) <sup>b</sup>
C18:2 (n3)	(0.06±0.01) <sup>ab</sup>	(0.06±0.01) <sup>ab</sup>	(0.07±0.01) <sup>a</sup>	(0.07±0.01) <sup>a</sup>	(0.06±0.01) <sup>b</sup>
C18:3 (n3)	(0.43±0.01) <sup>b</sup>	(0.47±0.03) <sup>a</sup>	(0.50±0.02) <sup>a</sup>	(0.48±0.01) <sup>a</sup>	(0.49±0.01) <sup>a</sup>
C18:3 (n6)	(0.21±0.01) <sup>b</sup>	(0.20±0.01) <sup>b</sup>	(0.20±0.01) <sup>b</sup>	(0.20±0.01) <sup>b</sup>	(0.22±0.01) <sup>a</sup>
C20:0	(0.70±0.01) <sup>b</sup>	(0.78±0.01) <sup>a</sup>	(0.72±0.05) <sup>ab</sup>	(0.75±0.07) <sup>ab</sup>	(0.78±0.01) <sup>a</sup>
C20:1	(0.40±0.01) <sup>a</sup>	(0.38±0.01) <sup>b</sup>	(0.38±0.01) <sup>b</sup>	(0.39±0.01) <sup>ab</sup>	(0.39±0.01) <sup>ab</sup>
C20:2	(0.15±0.01) <sup>a</sup>	(0.13±0.01) <sup>b</sup>	(0.13±0.01) <sup>b</sup>	(0.15±0.01) <sup>a</sup>	(0.15±0.01) <sup>a</sup>
C20:3	(0.40±0.02) <sup>b</sup>	(0.37±0.01) <sup>b</sup>	(0.40±0.01) <sup>b</sup>	(0.48±0.02) <sup>a</sup>	(0.48±0.02) <sup>a</sup>
C23:0	(0.11±0.01) <sup>b</sup>	(0.11±0.01) <sup>b</sup>	(0.12±0.01) <sup>ab</sup>	(0.11±0.01) <sup>ab</sup>	(0.12±0.01) <sup>a</sup>
SFA	(41.27±0.42) <sup>a</sup>	(39.82±0.01) <sup>b</sup>	(38.33±0.41) <sup>c</sup>	(39.96±0.12) <sup>b</sup>	(40.80±0.30) <sup>b</sup>
UFA	(58.73±0.42) <sup>c</sup>	(60.18±0.01) <sup>b</sup>	(61.67±0.41) <sup>a</sup>	(60.04±0.12) <sup>b</sup>	(59.20±0.30) <sup>c</sup>
MUFA	(47.78±0.42) <sup>a</sup>	(48.28±0.03) <sup>a</sup>	(48.40±0.24) <sup>a</sup>	(48.06±0.19) <sup>a</sup>	(46.57±0.16) <sup>b</sup>
PUFA	(10.96±0.01) <sup>d</sup>	(11.90±0.04) <sup>c</sup>	(13.27±0.17) <sup>a</sup>	(11.98±0.07) <sup>c</sup>	(12.63±0.14) <sup>b</sup>
PUFA/SFA	(0.27±0.01) <sup>c</sup>	(0.30±0.01) <sup>b</sup>	(0.35±0.01) <sup>a</sup>	(0.30±0.01) <sup>b</sup>	(0.31±0.01) <sup>b</sup>
n6/n3	(11.01±0.27) <sup>c</sup>	(12.04±0.20) <sup>b</sup>	(12.58±0.04) <sup>a</sup>	(10.58±0.16) <sup>c</sup>	(11.01±0.09) <sup>c</sup>
AI	(0.15±0.01) <sup>a</sup>	(0.15±0.01) <sup>a</sup>	(0.15±0.01) <sup>a</sup>	(0.14±0.01) <sup>b</sup>	(0.13±0.01) <sup>c</sup>
TI	(1.26±0.02) <sup>a</sup>	(1.18±0.01) <sup>b</sup>	(1.11±0.02) <sup>c</sup>	(1.18±0.01) <sup>b</sup>	(1.12±0.02) <sup>c</sup>
h/H	(14.76±0.37) <sup>b</sup>	(14.53±0.02) <sup>b</sup>	(14.75±0.03) <sup>b</sup>	(15.28±0.11) <sup>a</sup>	(15.71±0.12) <sup>a</sup>
n6	(9.90±0.03) <sup>d</sup>	(10.87±0.02) <sup>c</sup>	(12.17±0.16) <sup>a</sup>	(10.81±0.05) <sup>c</sup>	(11.44±0.12) <sup>b</sup>
n3	(0.90±0.02) <sup>c</sup>	(0.90±0.02) <sup>c</sup>	(0.97±0.01) <sup>b</sup>	(1.02±0.02) <sup>a</sup>	(1.04±0.02) <sup>a</sup>

<sup>a-c</sup>For each parameter, values followed by the same letter are not significantly different according to Tukey's HSD post-hoc test ( $p>0.05$ ). Data are presented as mean value±standard deviation. AI=atherogenic index, TI=thrombogenic index, h/H=hypocholesterolemic/hypercholesterolemic ratio, CT=control frankfurters with conventional formulation, 7.5WTM=frankfurters with 7.5 % beef lean meat substitution by *Tenebrio molitor* powder, 15WTM=frankfurters with 15 % beef lean meat substitution by *Tenebrio molitor* powder, 7.5WAD=frankfurters with 7.5 % beef lean meat substitution by *Acheta domesticus* powder, 15WAD=frankfurters with 15 % beef lean meat substitution by *Acheta domesticus* powder

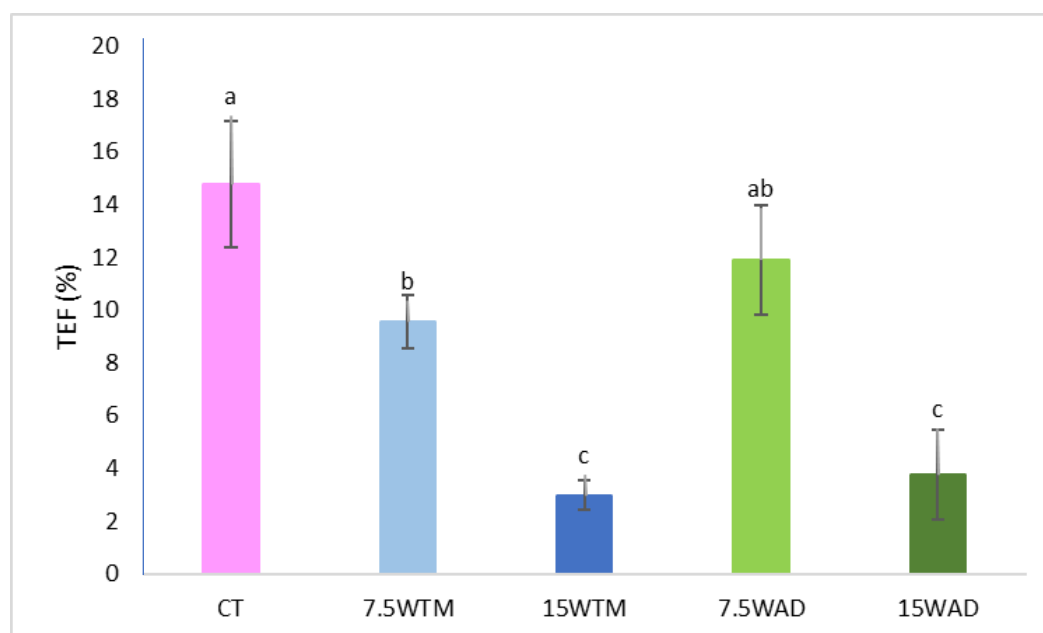
Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.

**Table 3.** Effect of partial replacement of lean meat with *Acheta domesticus* and *Tenebrio molitor* powders on techno-functional (pH,  $a_w$ , color, texture) and sensory properties of Frankfurt-type sausages

Parameter	Sample				
	CT	7.5WTM	15WTM	7.5WAD	15WAD
pH	(6.02±0.03) <sup>d</sup>	(6.10±0.02) <sup>c</sup>	(6.28±0.02) <sup>a</sup>	(6.15±0.02) <sup>b</sup>	(6.16±0.01) <sup>b</sup>
$a_w$	(0.959±0.01) <sup>a</sup>	(0.957±0.01) <sup>a</sup>	(0.956±0.01) <sup>a</sup>	(0.957±0.01) <sup>a</sup>	(0.959±0.02) <sup>a</sup>
Color properties					
$L^*$	(58.45±2.16) <sup>a</sup>	(55.27±3.09) <sup>b</sup>	(54.37±1.71) <sup>c</sup>	(55.69±1.39) <sup>b</sup>	(51.70±1.13) <sup>c</sup>
$a^*$	(7.34±0.56) <sup>a</sup>	(6.32±0.49) <sup>b</sup>	(5.82±0.83) <sup>c</sup>	(5.40±0.40) <sup>c</sup>	(85.60±0.24) <sup>c</sup>
$b^*$	(8.38±0.23) <sup>b</sup>	(10.21±0.75) <sup>a</sup>	(10.17±1.28) <sup>a</sup>	(8.56±0.56) <sup>ab</sup>	(8.38±0.38) <sup>b</sup>
$C^*$	(11.16±0.28) <sup>ab</sup>	(12.03±0.66) <sup>a</sup>	(11.72±1.46) <sup>a</sup>	(10.12±0.62) <sup>bc</sup>	(9.79±0.38) <sup>c</sup>
$h^*$	(48.84±2.82) <sup>c</sup>	(58.18±2.93) <sup>ab</sup>	(60.26±2.13) <sup>a</sup>	(57.76±1.75) <sup>b</sup>	(58.86±1.41) <sup>ab</sup>
$\Delta E^*$	nd	(3.20±1.15) <sup>b</sup>	(7.83±1.07) <sup>a</sup>	(3.62±0.79) <sup>b</sup>	(6.54±1.91) <sup>a</sup>
Textural parameters					
Hardness/N	(104.20±15.77) <sup>a</sup>	(78.98±8.39) <sup>b</sup>	(94.21±13.96) <sup>ab</sup>	(97.04±18.15) <sup>ab</sup>	(107.78±15.85) <sup>a</sup>
Cohesiveness	(0.77±0.03) <sup>a</sup>	(0.77±0.02) <sup>a</sup>	(0.72±0.02) <sup>b</sup>	(0.77±0.03) <sup>a</sup>	(0.74±0.03) <sup>b</sup>
Gumminess	(79.77±10.95) <sup>a</sup>	(60.89±5.15) <sup>b</sup>	(67.62±8.28) <sup>ab</sup>	(74.52±11.49) <sup>a</sup>	(79.35±9.80) <sup>a</sup>
Elasticity/mm	(0.33±0.03) <sup>a</sup>	(0.30±0.03) <sup>a</sup>	(0.31±0.04) <sup>a</sup>	(0.29±0.04) <sup>a</sup>	(0.31±0.04) <sup>a</sup>
Chewiness/(N·m m)	(26.38±5.79) <sup>a</sup>	(18.42±2.65) <sup>b</sup>	(21.01±3.94) <sup>ab</sup>	(21.84±6.74) <sup>ab</sup>	(24.53±5.12) <sup>a</sup>
Sensory properties					
Appearance	(7.20±1.66) <sup>a</sup>	(6.13±2.08) <sup>ab</sup>	(5.27±2.10) <sup>bc</sup>	(6.33±1.72) <sup>ab</sup>	(4.50±2.29) <sup>c</sup>
Color	(7.37±1.85) <sup>a</sup>	(6.17±2.00) <sup>ab</sup>	(5.47±2.45) <sup>bc</sup>	(5.57±1.99) <sup>bc</sup>	(4.10±1.99) <sup>c</sup>
Hardness	(7.10±1.83) <sup>a</sup>	(6.07±1.71) <sup>ab</sup>	(6.10±1.70) <sup>ab</sup>	(6.50±1.48) <sup>ab</sup>	(5.37±2.27) <sup>b</sup>
Juiciness	(7.23±1.41) <sup>a</sup>	(6.40±2.08) <sup>a</sup>	(5.90±1.92) <sup>ab</sup>	(6.30±1.93) <sup>a</sup>	(4.70±2.21) <sup>b</sup>
General taste	(7.43±1.56) <sup>a</sup>	(6.53±1.75) <sup>ab</sup>	(5.53±2.06) <sup>b</sup>	(6.50±1.59) <sup>ab</sup>	(5.37±2.18) <sup>b</sup>
Overall flavor	(7.10±1.37) <sup>a</sup>	(6.53±1.71) <sup>a</sup>	(5.83±1.90) <sup>ab</sup>	(6.23±1.87) <sup>ab</sup>	(5.13±2.09) <sup>c</sup>
Overall acceptability	(7.07±1.44) <sup>a</sup>	(6.27±1.48) <sup>ab</sup>	(5.57±2.17) <sup>bc</sup>	(6.30±1.53) <sup>ab</sup>	(5.03±1.97) <sup>c</sup>

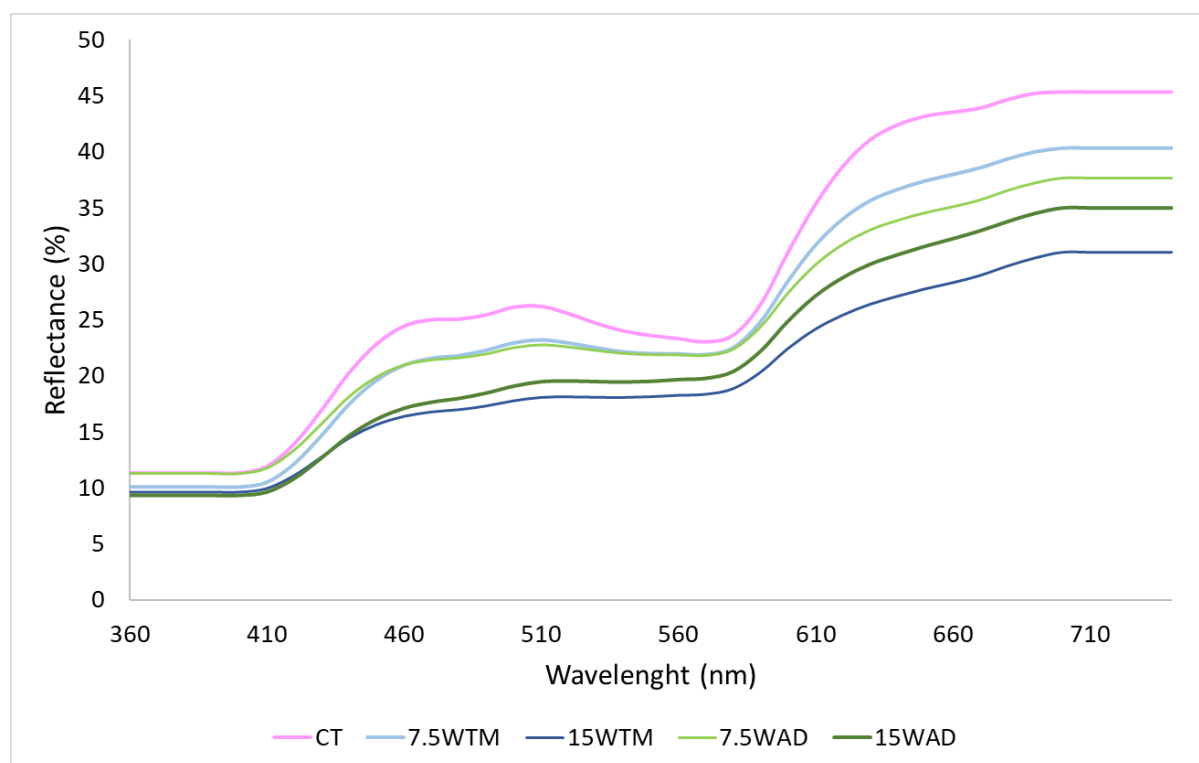
<sup>a-c</sup>For each parameter, values followed by the same letter are not significantly different according to Tukey's HSD post-hoc test ( $p>0.05$ ). Data are presented as mean value±standard deviation. CT=control frankfurters with conventional formulation, 7.5WTM=frankfurters with 7.5 % beef lean meat substitution by *Tenebrio molitor* powder, 15WTM=frankfurters with 15 % beef lean meat substitution by *Tenebrio molitor* powder, 7.5WAD=frankfurters with 7.5 % beef lean meat substitution by *Acheta domesticus* powder, 15WAD=frankfurters with 15 % beef lean meat substitution by *Acheta domesticus* powder,  $a_w$ =water activity

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.



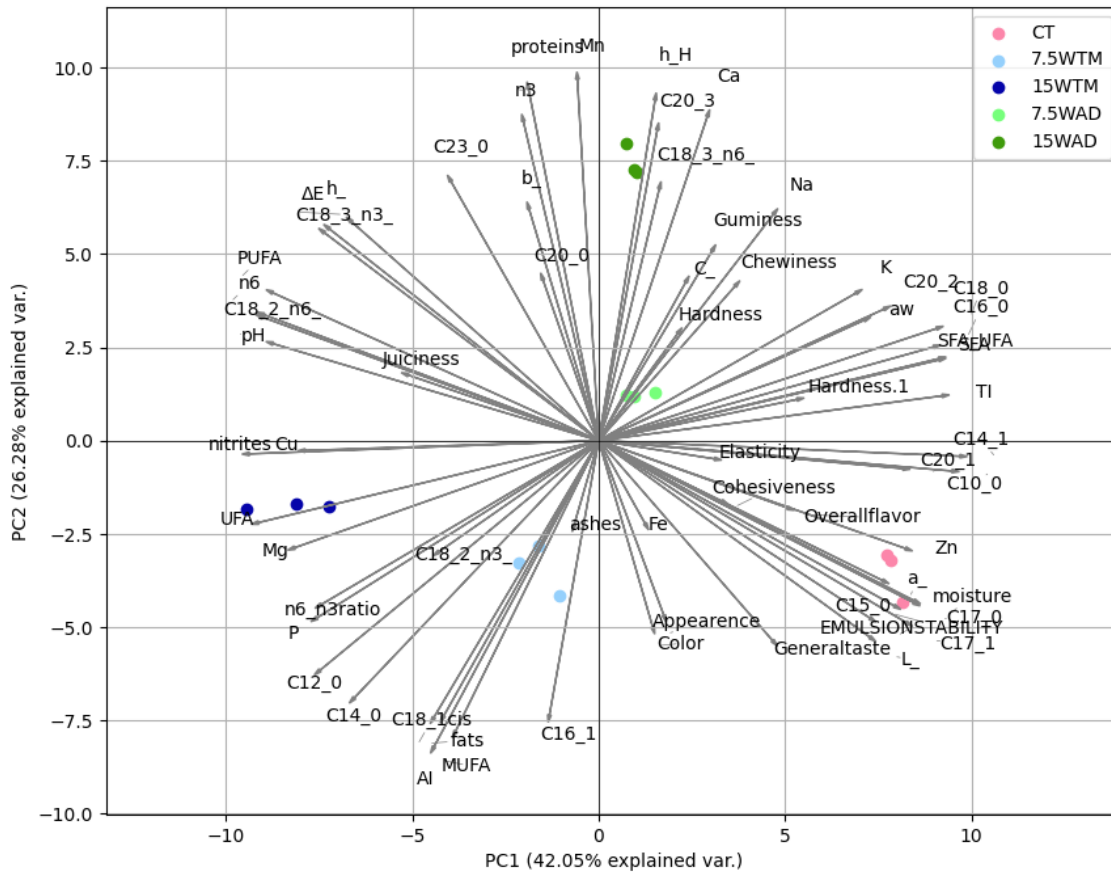
**Fig. 1.** Effect of partial replacement of lean beef meat with *Acheta domesticus* and *Tenebrio molitor* powders on emulsion stability of Frankfurt-type sausages. Results are expressed as the percentage of total expressible fluid (TEF/%). Data are presented as mean value $\pm$ standard deviation. Different letters indicate statistically significant differences as determined by Tukey's HSD post-hoc test ( $p < 0.05$ ). CT=control frankfurters with conventional formulation, 7.5WTM=frankfurters with 7.5 % beef lean meat substitution by *Tenebrio molitor* powder, 15WTM=frankfurters with 15 % beef lean meat substitution by *Tenebrio molitor* powder, 7.5WAD=frankfurters with 7.5 % beef lean meat substitution by *Acheta domesticus* powder, 15WAD=frankfurters with 15 % beef lean meat substitution by *Acheta domesticus* powder

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.



**Fig. 2.** Reflectance spectra between 360 and 740 nm of Frankfurt-like sausages (control and with insect powders added). CT=control frankfurters with conventional formulation, 7.5WTM=frankfurters with 7.5 % beef lean meat substitution by *Tenebrio molitor* powder, 15WTM=frankfurters with 15 % beef lean meat substitution by *Tenebrio molitor* powder, 7.5WAD=frankfurters with 7.5 % beef lean meat substitution by *Acheta domesticus* powder, 15WAD=frankfurters with 15 % beef lean meat substitution by *Acheta domesticus* powder

Please note that this is an unedited version of the manuscript that has been accepted for publication. This version will undergo copyediting and typesetting before its final form for publication. We are providing this version as a service to our readers. The published version will differ from this one as a result of linguistic and technical corrections and layout editing.



**Fig. 3.** Principal component analysis (PCA) biplot and component loadings (evaluated parameters). CT=control frankfurters with conventional formulation, 7.5WTM=frankfurters with 7.5 % beef lean meat substitution by *Tenebrio molitor* powder, 15WTM=frankfurters with 15 % beef lean meat substitution by *Tenebrio molitor* powder, 7.5WAD=frankfurters with 7.5 % beef lean meat substitution by *Acheta domesticus* powder, 15WAD=frankfurters with 15 % beef lean meat substitution by *Acheta domesticus* powder