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Multivariate evaluation of nutritional, techno-functional, and structural properties of wheat-mopane worm (*Gonimbrasia belina*) composite flours

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ABSTRACT

The rising global demand for sustainable, nutrient-dense protein sources has renewed focus on edible insects such as *Gonimbrasia belina* (mopane worm). This study investigated the impact of mopane worm powder (0 - 30% inclusion) on the nutritional, techno-functional, thermal, and structural properties of wheat-based composite flours. The protein content increased significantly ($p < 0.05$) from 16.4% in the control flour to 24.9% at a 30% substitution, confirming its potential as a high-quality protein alternative. Colour attributes revealed a decrease in lightness (L*) from 88.37 to 74.24 and an increase in redness (a*) from 0.56 to 1.50, reflecting a visible darkening with insect incorporation. Mopane worm powder exhibited the highest water-holding (2.5 g/g) and oil-holding capacity (2.7 g/g), surpassing that of wheat flour. Rapid Visco Analyzer (RVA) analysis revealed a marked reduction in peak viscosity (from 2050 cP to 980 cP), with final viscosity and setback values declining by 45% and 60%, respectively, indicating diminished starch retrogradation. Thermogravimetric analysis (TGA) demonstrated improved thermal stability, with mopane worm powder degrading at 285 °C compared to 250 °C for wheat. FT-IR spectra displayed intensified amide I (1650 cm^{-1}) and II (1540 cm^{-1}) bands, along with aliphatic and chitin-associated peaks, corroborating the enrichment of proteinaceous and lipid components. Principal Component Analysis and Hierarchical Cluster Analysis revealed clear sample clustering by inclusion level, with protein, colour, and techno-functional properties driving variance among the mopane-enriched composite flours. The incorporation of mopane worm powder significantly improved the nutritional profile, thermal stability, and structural matrix of wheat-based flours, underscoring its potential as a sustainable bio-ingredient for protein-energy malnutrition interventions within climate-resilient food systems.

1. Introduction

The African continent is home to an estimated 500 species of edible insects (Hlongwane et al., 2020), many of which hold untapped potential as sustainable protein sources and functional novel food ingredients. Despite their diversity and regional importance, the nutritional quality, structural properties, thermal behaviour, and techno-functional properties of these insects remain underexplored, particularly in the context of modern food processing and formulation systems (Mshayisa et al., 2021). Globally, edible insects are gaining traction as one of the most promising alternatives to conventional animal proteins. They are rich in high-quality protein, essential amino acids, and bioavailable micronutrients such as iron and zinc, while offering notable environmental benefits, including low greenhouse gas emissions, efficient feed conversion, and minimal land and water requirements (Van-Huis, 2013). Since 2010, the Food and Agriculture Organization (FAO) has actively promoted the use of insects as food and feed to support food security, sustainability, and livelihood diversification across multiple agro-ecological zones (Zielińska et al., 2018a; Bisconsin-Junior et al., 2025a).

In South Africa, the issue of food and nutrition insecurity remains acute, with high rates of stunting and micronutrient deficiencies persisting in vulnerable populations (Vorster, 2010). In this context, the valorisation of indigenous edible insects represents both a culturally aligned and scientifically viable strategy to enhance dietary quality. The mopane worm (*Gonimbrasia belina*), locally known as *mashonzha* (Venda), *amacimbi* (Ndebele), or *madora* (Shona), is among the most widely consumed and commercially significant insect species in Southern Africa (Kwiri et al., 2014; Hlongwane et al., 2021; Vanqa et al., 2022; Mashau et al., 2024). Harvested extensively in Limpopo,

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Mpumalanga, and parts of Zimbabwe, the mopane worm is more than a seasonal delicacy; it serves as a vital source of livelihood and nutrition (Baiyegunhi et al., 2016). Survey data indicate that over 94 % of households in mopane-rich regions regularly consume this insect, underlining its cultural acceptability and market potential (Siddiqui et al., 2024).

While the practice of entomophagy is well established in some rural areas of South Africa and to some extent in urban areas, the scientific exploration of mopane worms as a functional food ingredient, particularly in flour-based applications, remains scant. Existing literature on edible insect incorporation into food matrices has focused largely on species such as mealworms (*Tenebrio molitor*) (González et al., 2019; Zielińska et al., 2023; Xie et al., 2024), crickets (*Acheta domesticus*) (Gumul et al., 2023; Brena-Melendez et al., 2024; Sereda et al., 2024; Zafar et al., 2024) and black soldier fly (*Hermetia illucens*)(Montevecchi et al., 2021; Mshayisa et al., 2022), which have demonstrated favourable techno-functional properties, including water and oil absorption, foaming capacity, and emulsification when used in wheat-based formulations. These attributes have been pivotal in driving their adoption in bakery, meat analogue, and snack applications globally.

However, studies on *G. belina* (*Gonimbrasia belina*) have primarily emphasised proximate composition (Vanqa et al., 2022; Mashau et al., 2024), mineral content (Hlongwane et al., 2020), and basic nutritional attributes, with little attention paid to its behaviour in composite flour systems or its interaction with starch and gluten networks during processing. The mopane worm possesses a remarkable nutritional profile, containing up to 60 % protein on a dry matter basis, as well as substantial levels of unsaturated fatty acids, calcium, zinc, and iron (Vanqa et al., 2022). When milled into powder, this insect offers a strategic opportunity to enhance the nutritional and functional quality of wheat-based products through composite flour technology. Composite flour blends of wheat and non-traditional flours have gained traction for their role in food diversification, nutritional enrichment, and ingredient innovation (Chandra et al., 2015). Although mopane worm powder presents significant potential for application in food systems, its techno-functional, pasting and structural properties in wheat composite flour systems remain inadequately explored. There are considerable knowledge gaps regarding its impact on hydration dynamics, starch-protein interactions, and structure-function relationships, which are crucial for formulation optimisation, process performance prediction, and consumer acceptability.

Other edible insect species, such as mealworms and crickets have been shown to improve the textural and functional quality of processed foods. However, limited evidence exists on how mopane worm powder influences key functional indices such as water absorption capacity, emulsification activity, foaming capacity, and thermal pasting behaviour as measured by Rapid Visco Analyser (RVA). Furthermore, no published data currently address the structural changes in mopane worm-wheat composites as observed through Fourier-Transform Infrared (FT-IR) spectroscopy or how protein-rich insect flours impact the viscoelastic behaviour of starch-gluten systems. This presents a significant limitation in both academic understanding and industrial application of mopane worm powder in processed food development.

Recent reports by Vanqa et al. (2022) and Mashau et al. (2024) have confirmed the nutritional viability of mopane worms in food fortification. However, these studies have not investigated their integration into flour matrices or characterised their impact on functional and rheological parameters in depth. As a result, there remains a pressing need for empirical studies that address these functional gaps to enable the design of nutrient-rich, functional food products based on insect protein.

Therefore, the aim of this study was to evaluate the nutritional, pasting behaviour (via Rapid Visco Analyzer), thermal stability, structural fingerprinting (using FT-IR spectroscopy), and key techno-functional properties, including water and oil absorption, foaming capacity, and foam stability of wheat-mopane worm composite flours. This research seeks to bridge the knowledge gap in insect-based flour systems and provide a robust scientific foundation for the integration of mopane worm powder into mainstream food processing. The findings will contribute to the advancement of sustainable protein solutions and support the development of value-added insect-based ingredient products that can aid in addressing food and nutritional insecurity in Southern Africa.

2. Materials and methods

2.1. Preparation of edible insect composite flours

Dried mopane worm (*G. belina*) edible insects were procured from local vendors (Limpopo province, South Africa). These dried insects were milled (FRITSH Pulvrisette 19 Universal cutting mill, South Africa) with a rotor speed of 2 800 rpm and passed through a screen (P-19 sieve cassette, made of stainless steel, 0.75 mm trapezoidal perforation) with an aperture of 0.75 mm. The milled mopane powder was then sieved using an automatic sieve (Endecotts Octagon Digital Sieve Shaker, England) at an amplitude of 7 for 4 min per batch. Wheat-insect composite flours were prepared by blending wheat flour with mopane worm powder at substitution levels of 10 %, 20 %, and 30 % using a laboratory-grade planetary mixer to ensure homogeneity. The samples were designated as follows: WF = 100 % wheat flour; MW= 100 % mopane worm powder; WM10, WM20, and WM30 = composite flours containing 10 %, 20 %, and 30 % mopane powder, respectively. All samples were packed in airtight, food-grade containers and stored at ambient temperature in a dry, dark environment to prevent oxidative and microbial deterioration.

2.2. Proximate compositions of wheat-mopane composite flours

Proximate composition of the wheat-mopane composite flour was analysed according to the Association of Official Analytical Chemists (AOAC) (AOAC, 1995). The standard methods: moisture (method 925.10), crude protein (920.87), crude fat (932.06), and ash (923.03) were determined. Moisture was determined by vacuum oven drying at 105 °C for 3 hrs to constant weight, and crude fat was extracted using petroleum ether in a Soxhlet extractor. Ash content was measured after incineration at 550 °C for 5 hrs in a muffle furnace. The crude protein was quantified using the Dumas method on a TruSpec™ Leco CHN analyser (Leco Africa), following the calibration procedure of Mshayisa et al. (2022) and a nitrogen-to-protein conversion factor of 5.6 was applied. The sodium chloride was determined using the Volhard titration method. This method involved a back titration using silver nitrate and ammonium thiocyanate, with ferric ion as an indicator. Carbohydrates were calculated by difference, and the energy value was calculated using the formula detailed below:

$$Energy\left(\frac{\text{Kcal}}{100\text{g}}\right) = 4\ (\%\ \text{Carbohydrates} + \%\ \text{Protein}) + (9\ \text{x}\ \%\ \text{Fat})$$

2.3. Determination of colour

The colour of wheat-mopane flour was measured following the procedure adapted from Krystyjan et al. (2015), with minor modifications. Measurements were performed on the composite flours using a Konica Minolta CM-5 spectrophotometer (Konica Minolta Inc., Tokyo, Japan), calibrated to illuminant D65 and a 10° standard observer angle. Colour values were expressed in the CIELab colour space, where L* represents lightness (0 = black, 100 = white), a* indicates the green-red axis (negative values correspond to green, positive to red), and b* denotes the blue-yellow axis (negative values for blue, positive for yellow). The chroma (C*), hue (H)° and colour difference (ΔE) were calculated using the equations:

$$Chroma\ (C) = \sqrt{(a)^2 + (b)^2}$$

$$Hue\ (H^{\circ}) = \tan\left\{\frac{a}{b}\right\}$$

$$\Delta E = \sqrt{(L_0 - L_s)^2 + (a_0 - a_s)^2 + (b_0 - b_s)^2}$$

L_o, a_o and b_o refer to the control sample values of the reference wheat flour.

2.4. Determination of water activity and bulk density

The water activity (a_w) of wheat-mopane composite flour was determined following a slightly modified version of the method outlined by Vanqa et al. (2022). The SPRINT TH500 Novasina water activity meter (Zurich, Switzerland) was calibrated using saturated salt solutions at 53 %, 75 %, and 90 % relative humidity. For analysis, 5 g of the flour sample was placed in the instrument's sample chamber, followed by immediate sealing with the protection filter. After allowing 60 - 80 s for equilibrium, water activity values were recorded. The determination of bulk density was conducted according to the procedure described by Vanqa et al. (2022), with some modifications. First, five grams of the sample was transferred into a weighed measuring cylinder (50 mL) (W_1) and then compressed by tapping until the sample volume remained constant. The measuring cylinder was again weighed (W_2), the new volume (V_1) was noted, and the density (g/mL) was measured using the following formula:

$$Bulk\ Density = \frac{W_2 - W_1}{V_1}$$

2.5. Water Holding capacity and oil holding capacity

Water Holding Capacity (WHC) and Oil Holding Capacity (OHC) of wheat-mopane worm flours were determined following the protocols described by Mshayisa et al. (2022) and Vanqa et al. (2022), with slight modifications. Briefly, one g of each flour sample was mixed with 50 mL of MilliQ water for WHC assessment or 30 mL of sunflower oil for OHC measurement in a 50 mL centrifuge tube. The mixtures were vortexed for five minutes and incubated at ambient temperature for 60 min. Subsequently, samples were centrifuged (Beckman Coulter, Inc., Fullerton, CA) at 3220 *g* for 10 min at 20 °C. The supernatants were carefully decanted, and the tubes containing the pellets were weighed. WHC and OHC values were calculated using the weight difference and expressed as grams of water or oil held per gram of flour.

$$WHC\ or\ OHC\ \left(\frac{g}{g}powder\right) = \frac{M_2 - M_1}{M_0}$$

Where: M_2 represents the weight of the tube and the remaining pellet of composite flour (g); M_1 represents the weight of the tube and powder sample (g), and M_0 represents the weight of the powder sample, respectively.

2.6. Foam capacity and stability

The foaming properties of the edible insects composite flours were assessed following the method of Mshayisa and Van Wyk (2021), with slight modifications. Edible insect samples were rehydrated in Milli-Q water at 5 % (w/v) concentration, then centrifuged at 10 000 rpm for 15 min. Subsequently, 20 mL of the clear supernatant was homogenised using a high-shear homogeniser (Polytron PT 2500E) at 16,000 rpm for 3 min. The homogenised suspension was immediately transferred to a 50 mL graduated cylinder, and the total volume was recorded at time zero and again after 30 min. Foaming capacity and foam stability were calculated according to the following equations:

$$\text{Foaming Capacity (FC)} = \frac{V_a - V}{V} \times 100$$

$$\text{Foam Stability (FS)} = \frac{V_{30}}{V_a} \times 100$$

Where: V - volume before whipping (mL), V_a - volume after whipping (mL), V_{30} - volume after standing (mL).

2.7. Pasting properties and least gelation concentration

Pasting properties of wheat-mopane flour blends were evaluated using a Rapid Viscosity Analyzer (Perten Instruments, Tecmaster, Sweden). For each assay, 3 g of flour, adjusted for moisture content as described by Vanqa et al. (2024) and Xie et al. (2024), was accurately weighed into aluminium RVA canisters. Distilled water was added in proportion to the sample moisture, as determined by the RVA software. The pasting profile consisted of an initial holding period at 50 °C for 1 min, followed by heating to 95 °C for 2.5 min, and subsequent cooling to 50 °C. Key parameters extracted included pasting temperature (initiation of starch granule swelling), peak viscosity (maximum viscosity during heating), breakdown viscosity (difference between peak and minimum viscosity), final viscosity (viscosity at the end of cooling), and setback viscosity (increase in viscosity during cooling). The least gelation concentration (LGC) was determined following Bisconsin-Junior *et al.* (2025b). Composite flour blends were dispersed in distilled water across a concentration range of 4 - 7 % (w/w) and heated at 90 °C for 15 min in a water bath (Memmert, Lasec, Germany). After cooling to ambient temperature over 2 hours, gel formation was assessed by inverting the tubes and noting the minimum concentration at which the gel remained intact without flow or deformation.

2.8. Thermal properties

Thermogravimetric analysis (TGA) was performed to assess the thermal stability of wheat-mopane composite flours using a TGA-7 instrument (Perkin Elmer, Singapore), following the protocol described by Mshayisa et al. (2021), with minor modifications. Samples were heated from 30 °C to 650 °C at a controlled rate of 20 °C/min under a continuous flow of nitrogen gas at 50 mL/min to maintain an inert atmosphere throughout the analysis.

2.9. Fourier Transform Infrared Spectroscopy (FTIR) analysis

All samples were analysed using a Fourier Transform Infrared (FT-IR) spectrometer (Perkin Elmer, Singapore) equipped with a universal attenuated total reflectance (UATR) polarisation accessory, following the method described by Mshayisa *et al.* (2021). Prior to sample measurement, a background spectrum was collected. Powdered samples, prepared by grinding with a mortar, were placed directly onto the ATR crystal to ensure complete coverage. Spectra were acquired by co-adding 32 scans at a spectral resolution of 4 cm^{-1} across the range of 400 to 4000 cm^{-1}. The UATR crystal was thoroughly cleaned with acetone between samples to eliminate residual contamination.

2.10. Statistical analysis

All experiments were conducted in triplicate, and results are expressed as means ± standard deviation. Statistical significance between treatments was determined using multivariate analysis of variance (MANOVA) followed by Duncan's multiple range test ($p < 0.05$) for post hoc comparisons. Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were conducted to explore patterns and interrelationships among variables. All statistical analyses were performed using SPSS version 29.0 (SPSS Inc., Chicago, IL, USA).

3. Results and discussion

3.1. Impact of mopane worm powder on proximate composition

The proximate composition of wheat flour, mopane worm powder, and wheat-mopane composite flours is presented in Table 1. The results reveal clear differences in moisture content across the flour samples. Wheat flour (9.75 %) contained significantly ($p < 0.05$) higher moisture than mopane worm powder (5.70 %), while the composite blends (MW10-MW30) exhibited values between 9.62 % and 9.95 %, similar to wheat flour. These results suggest that although mopane worm powder itself is considerably drier, its incorporation into wheat flour does not significantly lower the moisture content of the blends beyond that of the wheat flour. This stability highlights the buffering effect of wheat flour, maintaining a relatively constant water content even at higher substitution levels. From a technological perspective, this implies that the substitution of mopane worm powder is unlikely to alter the storage stability or drying behaviour of composite flours, which is a desirable property for flour-based processing. This trend aligns with the observations reported by Mashau *et al.* (2024), who found that insect-enriched flours exhibited lower moisture values compared to pure cereal flours. The lower moisture content in mopane worm powder can be attributed to its higher protein and fat composition, which inherently contain less bound water compared to starch-rich wheat flour. Furthermore, the study by Kowalski *et al.* (2023) indicated that the moisture levels remained within acceptable ranges, suggesting that the incorporation of mealworm flour does not adversely affect the moisture stability of baked goods. These studies collectively support the notion that the inclusion of insect flour, such as mopane worm, does not compromise the moisture stability of flour-based products. Maintaining consistent moisture content is crucial, as it influences the shelf life and microbial stability of the final products. Therefore, the findings from this study align with existing literature, reinforcing the suitability of mopane worm powder as a functional ingredient in composite flours without negatively impacting moisture retention.

Ash content increased significantly ($p < 0.05$) with increasing levels of mopane worm powder substitution, rising from 0.5 % in the control wheat flour (WF) to 4.26 % in the 30 % composite flour (MW30). The 100 % mopane worm powder (MW) presents the highest ash content (13.76 ± 0.55), statistically significant ($p < 0.05$) from all composite flours (Table 1). This increase in ash content in the composite flours aligns with previous research, which demonstrates that insect flours are rich in minerals (Akande et al., 2020; Bas & El, 2022; Vanqa et al., 2022). The mineral enrichment observed in wheat-mopane worm composite flours highlights their potential to enhance micronutrient intake, a crucial factor for populations susceptible to mineral deficiencies. This supports the use of mopane worm powder as a functional ingredient to enhance the nutritional quality of staple cereal products. Employing advanced technologies such as Inductively Coupled Plasma (ICP) spectroscopy is necessary for an in-depth assessment of mineral content, thereby substantiating the micronutrient enhancement potential of mopane worm-enriched flours.

The protein content increased significantly ($p < 0.05$) with the level of mopane worm powder substitution, rising from 16.42 % ± to 1.04 % in the control wheat flour (WF) to 24.87 % ± to 2.68 % in the 30 % mopane worm composite flour (MW30). This observed enhancement aligns with the high intrinsic protein content of mopane worm flour, as reported by Mashau *et al.* (2024) at approximately 60.66 % on a dry basis. This value is substantially higher than that of wheat flour (11.35 %) and consistent with earlier reports indicating that edible insects often contain protein levels exceeding 50 % (Rumpold & Schlüter, 2013; Oliveira et al., 2024). These findings confirm that mopane worm powder can significantly enrich the protein content of cereal-based composites, thereby reinforcing its potential role in enhancing the nutrition of staple foods. Moreover, the protein quality and digestibility of mopane worm proteins require further investigation, especially considering the impact of chitin content and processing techniques on bioavailability (Oliveira et al., 2024; Mshayisa et al., 2025).

3.2. Physicochemical properties of wheat-mopane composite flours

Understanding both bulk density and water activity is crucial for assessing the quality and stability of food ingredients. Bulk density influences packaging, handling, and processing efficiency by affecting the volume, flow properties, and storage requirements of powdered materials. Water activity, on the other hand, governs microbial stability and shelf life by controlling the availability of free water necessary for microbial growth and chemical reactions (Ramashia et al., 2024). As illustrated in Fig. 1, significant differences ($p < 0.05$) in bulk density were observed among the samples. Wheat flour exhibited the highest bulk density (1.07 g/L), while mopane worm powder presented the lowest (0.78 g/L). The composite flours (MW10-MW30) displayed intermediate values (0.88 - 0.91), which were significantly ($p < 0.05$) lower than wheat flour but higher than mopane worm powder. These

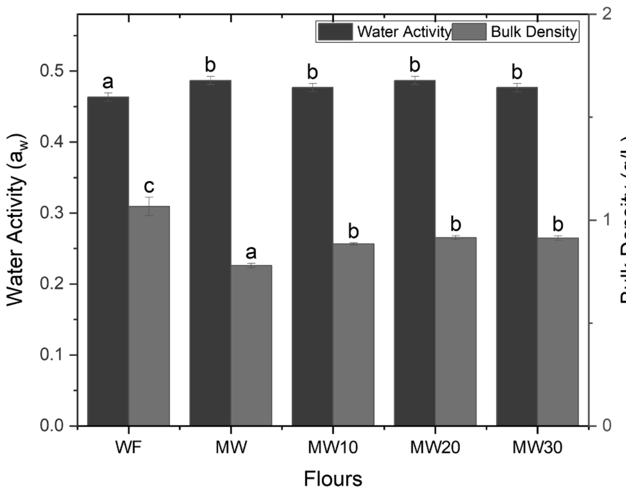


Fig 1. Water activity and bulk density of wheat-mopane composite flours. WF = Wheat flour; MW = Mopane worm powder; WM10-WM20 = Wheat flour with 10, 20 and 30 % mopane worm powder. Values are given as means ± SD from triplicate determinations. Different letters (a-e) indicate significant differences ($P < 0.05$).

Table 1
Proximate composition of wheat-mopane composite flours.

Flour Samples	Ash (%)	Moisture (%)	Crude Fat (%)	Crude Protein (%)	Carbohydrates (%)	Energy (Kcal/g)	Sodium(mg Na/100 g)
WF	0.52 ± 0.17[a]	9.75 ± 0.76[b]	0.80 ± 0.10[a]	16.42 ± 1.04[b]	72.52 ± 1.77[d]	362.92 ± 2.85[a]	135.74 ± 0.12[a]
MW	13.76 ± 0.05[e]	5.70 ± 0.02[a]	13.10 ± 1.75[c]	46.77 ± 0.06[d]	20.67 ± 1.72[a]	387.63 ± 0.84[b]	1816.93 ± 0.62[e]
MW10	1.39 ± 0.46[b]	9.95 ± 1.16[b]	2.92 ± 0.52[b]	11.10 ± 2.23[a]	74.61 ± 2.83[d]	369.23 ± 0.37[a]	586.10 ± 2.06[b]
MW20	2.87 ± 0.07[c]	9.66 ± 1.03[b]	2.51 ± 0.80[b]	18.98 ± 1.05[b]	65.98 ± 1.01[c]	362.40 ± 0.90[a]	839.03 ± 0.56[c]
MW30	4.26 ± 0.05[d]	9.62 ± 0.73[b]	3.83 ± 0.49[b]	24.87 ± 2.68[c]	57.24 ± 2.66[b]	363.70 ± 0.36[a]	1178.54 ± 0.37[d]

The data is expressed as mean ± standard deviation. The same superscripts in the same column indicate that the values are not significantly different (P >0.05). WF = Wheat flour; MW= Mopane worm powder; WM10 - WM30 = Wheat flour with 10, 20 and 30 % mopane worm powder.

results suggest that incorporation of mopane worm powder disrupts particle packing efficiency, most likely due to differences in particle size distribution, protein-lipid composition, and surface morphology compared with wheat flour. These results indicate a positive correlation between the proportion of mopane worm powder and the bulk density of the composite flour, suggesting that increasing the insect flour content leads to denser flour mixtures. For instance, Zielińska et al. (2018b) reported that insect flour incorporation tends to reduce bulk density due to the porous and fibrous nature of insect powders compared to dense cereal flours. This property impacts packaging, storage, and rehydration characteristics, with lower bulk density often correlating with enhanced porosity and potential for improved hydration behaviour (Hall et al., 2017). Water activity (a_w) values ranged from 0.45 in wheat flour to approximately 0.49 in the insect-enriched flours, with significant increases ($p < 0.05$) observed in all MW-containing samples compared to WF. This increase in water activity with insect flour substitution is consistent with findings by Carpentieri et al. (2024) and Kowalski *et al.* (2023), who attributed elevated water activity to the hygroscopic nature of insect proteins and chitin. While the water activity levels remain below the threshold for most microbial growth (< 0.6), the slight increase may influence shelf life and necessitate consideration in product formulation and storage. Overall, the bulk density and water activity data reinforce the functional impact of mopane worm powder inclusion on physical and preservation-related properties of composite flours, with implications for product design and quality control.

3.3. Colour attributes of wheat-mopane composite flours

The colourimetric analysis of wheat flour (WF), mopane worm powder (MW), and their composite blends (MW10, MW20, MW30) revealed statistically significant differences ($p < 0.05$) in all measured CIELab parameters (Table 2). Wheat flour exhibited the highest lightness (L*) value of 88.37 ± 0.00, significantly greater than 100% mopane worm powder at 53.89 ± 0.02, reflecting the stark contrast between the pale wheat and the darker insect flour. The composite blends exhibited a dose-dependent and statistically significant ($p < 0.05$) decrease in L* values with increasing mopane worm powder content, as shown by 81.55 ± 0.04, 77.56 ± 0.04, and 74.24 ± 0.03 for 10 %, 20 %, and 30 % substitution, respectively ($p < 0.05$). This confirms a darkening effect attributed to the incorporation of mopane worm powder. Composite flours displayed incremental increases in redness proportional to mopane content, with values of 0.87 ± 0.01, 1.25 ± 0.01, and 1.50 ± 0.01 for MW10, MW20, and MW30, respectively ($p < 0.05$). This trend suggests that even low levels of mopane worm powder substantially influence the hue of the composite flour. The yellow-blue coordinate (b*) differed significantly ($p < 0.05$) among samples, with mopane powder exhibiting the highest yellowness (21.10 ± 0.03) compared to wheat flour (10.30 ± 0.01). Composite blends demonstrated intermediate b* values that increased with mopane substitution but remained significantly lower than pure mopane flour, indicating a dilution effect of yellow pigmentation in the composites.

The total colour difference (ΔE) values also increased significantly ($p < 0.05$) with mopane worm flour addition, from negligible in wheat flour to 36.18 ± 0.14 in pure mopane flour. Composite flours showed ΔE values of 5.51 ± 2.27, 10.93 ± 0.04, and 14.37 ± 0.02 for MW10, MW20, and MW30, respectively, confirming perceptible and dose-dependent deviations from the control colour. The observed significant increase in hue angle with mopane worm flour incorporation, shifting from 10.32° ± 0.01 in wheat flour to 21.44° ±0.03 in pure mopane powder, reflects a clear tonal transition towards warmer, yellow-brown hues. This trend is consistent with findings reported by Zielińska *et al.* (2021), who documented similar hue angle increases in wheat flours enriched with cricket and mealworm powders. These shifts were attributed to the natural pigment composition of insect flours, including melanins and protein-bound chromophore.

Regarding chroma, the decrease from 86.87 in wheat flour to 79.74 in mopane powder highlights a reduction in colour saturation or vividness in pure insect powder, while composite blends maintained intermediate chroma values (83 to 85), indicating partial retention of colour intensity (Table 2). The maintenance of chroma in composite flours suggests synergistic interactions between wheat starch and insect proteins that mitigate excessive dulling of colour, preserving visual appeal. These consistent findings across diverse insect species and food matrices underscore the critical role of insect flour pigmentation in

Table 2
Colour attributes and pH of wheat-mopane composite flours.

Attributes	WF	MW	MW10	MW20	MW30
L*	88.37 ± 0.00[e]	53.89 ± 0.02[a]	81.55 ± 0.04[d]	77.56 ± 0.04[c]	74.24 ± 0.03[b]
a*	0.56 ± 0.00[a]	3.82 ± 0.01[e]	0.87 ± 0.01[b]	1.25 ± 0.01[c]	1.50 ± 0.01[d]
b*	10.30 ± 0.01[a]	21.10 ± 0.03[e]	10.63 ± 0.03[b]	11.78 ± 0.02[c]	12.76 ± 0.03[d]
ΔE	-	36.18 ± 0.14[d]	5.51 ± 0.27[a]	10.93 ± 0.04[b]	14.37 ± 0.02[c]
Hue angle	10.32 ± 0.01[a]	21.44 ± 0.03[e]	10.67 ± 0.03[b]	11.85 ± 0.02[c]	12.85 ± 0.03[d]
Chroma	86.87 ± 0.01[e]	79.74 ± 0.01[a]	85.30 ± 0.03[d]	83.95 ± 0.04[c]	83.29 ± 0.04[b]
pH	5.99 ± 0.01[a]	6.03 ± 0.01[bc]	6.00 ± 0.01[bc]	6.04 ± 0.01[c]	6.04 ± 0.01[c]

The data is expressed as mean ± standard deviation. The same superscripts in the same row indicate that the values are not significantly different (p > 0.05). WF = Wheat flour; MW = mopane worm powder; WM10 - WM30 = Wheat flour with 10, 20 and 30% mopane worm powder.

modifying product appearance. The shifts in hue and chroma not only reflect compositional differences but also serve as indicators of potential changes in sensory perception, influencing consumer acceptance. Understanding these colour dynamics is essential for tailoring insect powder inclusion rates and processing conditions to optimise both nutritional benefits and aesthetic quality.

3.4. Techno-functional properties

The water holding capacity (WHC) and oil holding capacity (OHC) of wheat-mopane worm composite flours are shown in Fig. 2A. The WHC of 100 % mopane worm powder (MW) was significantly higher (2.5 g/g) than that of wheat flour (1.82 g/g) and composite blends (MW10, MW20, MW30), which ranged between 1.60 and 1.82 g/g. Statistical analysis indicated the composite flours' WHC did not differ significantly from WF but were significantly lower than MW ($p < 0.05$). The high WHC of 100 % Mopane worm powder aligns with reports on other insect powders, which exhibit strong hydration properties due to their complex protein and polysaccharide matrix, including chitin and other dietary fibres (Vanqa et al., 2022). These results are consistent with findings by Carpentieri *et al.* (2024), who reported that 100 % *Tenebrio molitor* flour exhibited a markedly higher WHC (3.39 g/g) compared to durum wheat semolina (1.7 g/g). Consistent with the mopane worm results reported in this study, Carpentieri et al. (2024) observed that composite flours

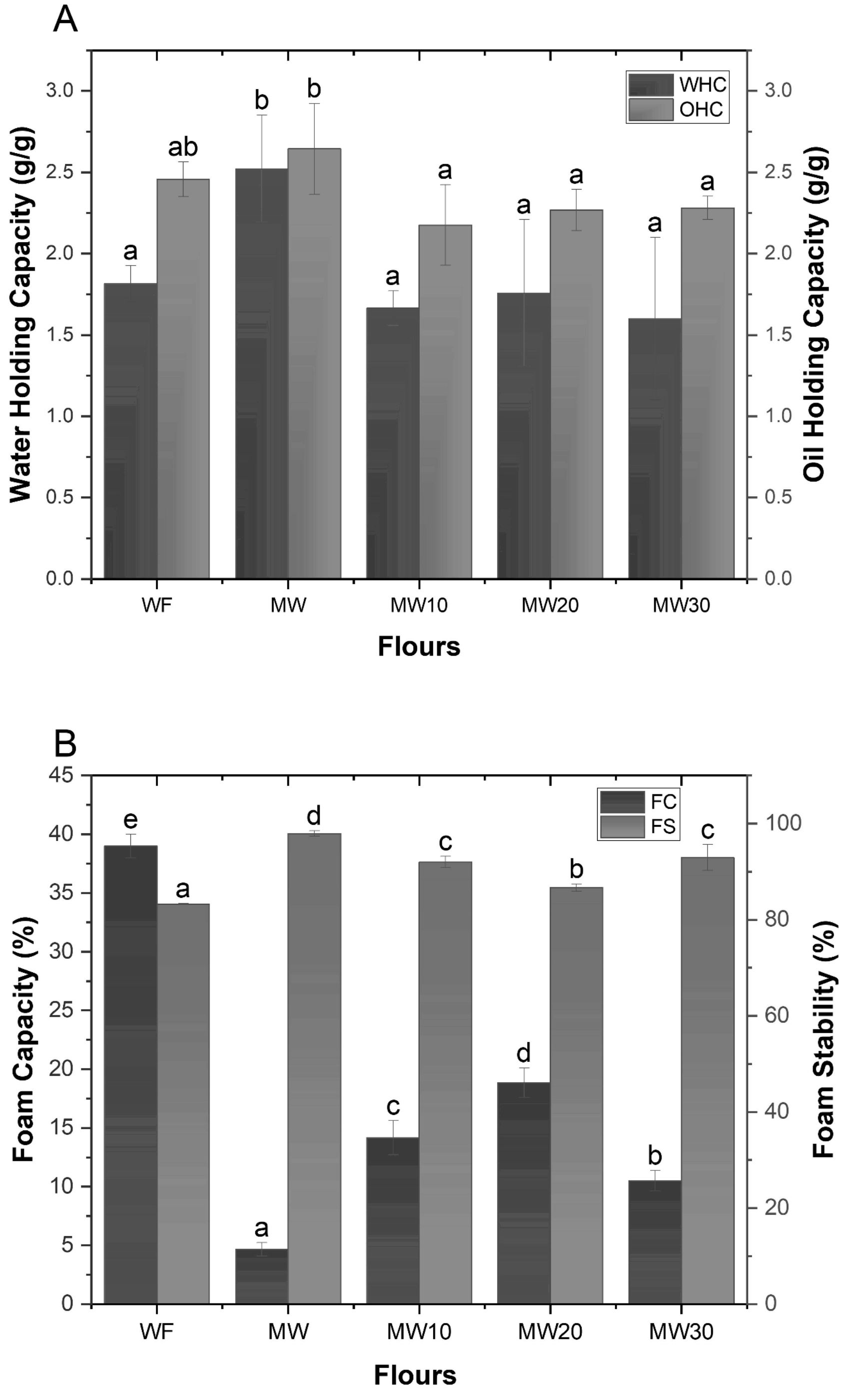


Fig. 2. A) Water and Oil Holding capacity, B) foaming capacity and stability of wheat-mopane composite flours. WF =Wheat flour; WM10-WM20 = Flour with 10, 20 and 30 % mopane worm flour. Values are given as means ± SD from triplicate determinations. Different letters (a-e) indicate significant differences ($P < 0.05$).

with incremental insect substitution (5–30 %) showed WHC values that, while elevated relative to the control, remained significantly lower than the pure insect flour.

Analogous to findings reported for WHC, the oil holding capacity (OHC) of mopane worm flour (2.64 g/g) was significantly elevated compared to composite flours and the control sample, which exhibited OHC values in the approximate range of 2.2–2.4 g/g. The composite flours exhibited relatively uniform OHC values ranging from approximately 2.2 to 2.4 g/g, which were not statistically different from each other or from the wheat flour control. This pattern suggests that the mopane worm powder possesses a superior lipid-binding capacity, but dilution with wheat flour attenuates this functional attribute in the composites. Comparatively, studies on other edible insects reveal a range of OHC values generally consistent with these findings. For instance, *Tenebrio molitor* (mealworm) flour has demonstrated OHC values between 2.3 and 3.0 g/g (Kwiri et al., 2014; Zielińska et al., 2018b; Carpentieri et al., 2024), aligning closely with the OHC of mopane worm powder. Similarly, cricket (*Acheta domesticus*) powders have been reported to contain OHC in the range of 1.8 to 2.7 g/g (Bas & El, 2022). These studies collectively demonstrate that insect flours exhibit substantial oil-binding capacities, which is attributed to their unique protein structures and associated lipid fractions. Functionally, the high OHC of mopane worm powder is significant for food formulations that require improved fat retention, flavour stability, and mouthfeel, such as in bakery, snack, and meat analogue products. The moderated OHC observed in the composite flours indicates an intermediate lipid-binding potential compared to wheat flour and 100% mopane worm powder. This suggests that the blends may offer functional advantages in terms of fat retention and stability, although further studies, particularly on sensory attributes, would be required to confirm these effects in finished products. To our knowledge, this study is among the first to systematically evaluate mopane worm powder within composite flours as a functional ingredient, extending current work on edible insects beyond nutritional profiling into techno-functional characterisation. Given the mopane worm's cultural and nutritional importance in Southern Africa, these findings contribute to both the scientific literature and the valorisation of indigenous protein sources. By examining and comparing the water and oil holding capacities of pure and composite mopane worm powders with wheat flour, the study enhances our understanding of their functional potential in food systems. This contribution fills an important void in the literature, as most studies have focused on commonly researched species, such as mealworm, cricket, and black soldier fly larvae. As illustrated in Fig. 2B, the foaming capacity (FC) and foaming stability (FS) of the wheat-mopane composite flours showed distinct trends with increasing levels of mopane worm powder. Wheat flour exhibited the highest foaming capacity (40 %), which significantly declined with increasing insect flour inclusion, reaching the lowest value at 30 % MW substitution (MW30). This decline in FC can be attributed to the reduced availability of surface-active gluten proteins, which are key contributors to foam formation in wheat-based systems. Conversely, foaming stability was markedly enhanced in all samples containing mopane powder, with values exceeding 85 % even at the lowest inclusion level (MW10). Mopane worm powder displayed the highest FS (100 %) despite its poor foaming capacity, suggesting that the insect proteins, although less efficient at initial foam formation, contribute to forming more resilient and stable interfacial films. These results align with previous findings on insect flours, such as those of *Acheta domesticus* and *Tenebrio molitor*, where high hydrophobicity and molecular compactness hinder foaming capacity but promote long-term stability (Maiyo et al., 2022; Zielińska et al., 2023). Collectively, these results underscore the functional complementarity of cereal and insect proteins in tailoring aerated food systems.

3.5. Pasting properties and gelation properties

The pasting behaviour of starch-based systems is a critical determinant of their functional and textural performance in processed foods. In this study, mopane worm powder was found to significantly alter the pasting profiles of wheat flour blends, with strong implications for product formulation and nutritional quality (Fig. 3). As the inclusion of mopane worm powder increased from 0 % to 30 %, the peak viscosity (PV) declined markedly, confirming a starch dilution effect. The control wheat flour (WF) exhibited a PV of 1923.5 cP, whereas the 30 % mopane worm composite (MW30) decreased to 853 cP, representing a reduction of more than 55 %. This trend aligns with findings by Carpentieri *et al.* (2024) and Xie *et al.* (2022), who reported similar declines in peak and final viscosity upon incorporating edible insect flours. The reduction in breakdown and setback viscosities with increasing mopane worm powder indicates greater paste stability and reduced retrogradation. These observations are consistent with studies on *Tenebrio molitor* and *Macrotermes subhylanus*, where insect protein interfered with starch re-association, resulting in softer gels and improved storage stability (Aboge et al., 2022; Vanqa et al., 2024). Such properties are particularly beneficial for applications requiring freeze-thaw stability or extended shelf life. The near-flat RVA curve observed for 100 % mopane worm powder reflects the complete absence of starch-driven gelatinisation and retrogradation phenomena that typify cereal flours. This absence is expected, as mopane worm powder is an animal-derived ingredient composed primarily of proteins, lipids, and chitin rather than starch. Consequently, it lacks the amylose and amylopectin fractions responsible for viscosity development during heating and cooling. The resulting flat RVA profile therefore indicates that viscosity changes in mopane-based blends arise predominantly from protein denaturation and aggregation, rather than starch gelatinisation, underscoring its potential to influence the functional behaviour of composite flours through protein-mediated mechanisms, rather than starch-mediated ones. Similar to results by Aleman *et al.* (2022), the high protein and lipid content of insect flours can drive alternate gelation or emulsification pathways. These systems are less reliant on starch viscosity and instead offer opportunities for low-glycemic or high-protein formulations tailored to functional or clinical nutrition. From a formulation standpoint, blends with 10–20 % MW strike a practical balance between improved nutrition and manageable viscosity. Beyond this range, additional hydrocolloids or pregelatinised starches may be required to restore processability, particularly in dough- or batter-based systems. As

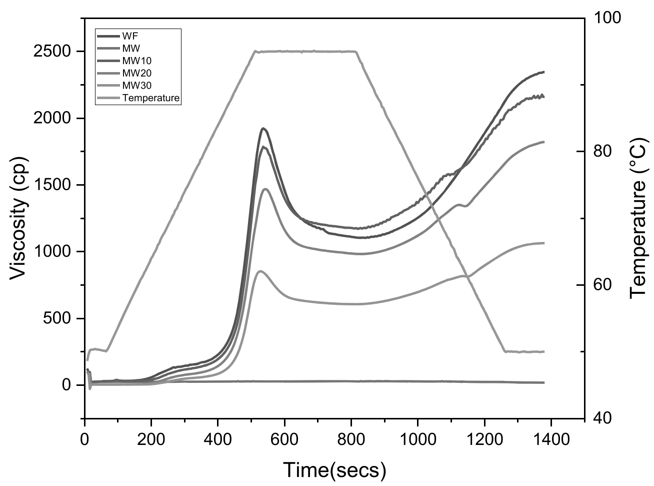


Fig 3. Pasting properties of wheat-mopane worm composite flours. The graph illustrates changes in peak viscosity, breakdown, setback, and final viscosity across increasing mopane worm concentrations, highlighting the impact on gelatinization and retrogradation behaviour. WF =Wheat flour; WM10-WM20 = Flour with 10, 20 and 30 % mopane worm flour.

depicted in Table 3, the results of the least gelation concentration reveal that 100 % mopane worm powder lacks gel-forming ability across all tested concentrations, in stark contrast to the wheat control and wheat-mopane composite flours, which exhibited dose-dependent gelation. These findings support the RVA observations, where 100 % mopane powder showed a flat viscosity curve, confirming the absence of starch-based gelatinisation. While mopane worm powder on its own does not support gel formation, its synergistic use with wheat flour, where starch acts as the primary gelling agent, enables the development of high-protein formulations with acceptable textural and structural properties.

3.6. Thermal properties

The thermogravimetric analysis (TGA) presented in Fig. 4 illustrates the thermal decomposition behaviour of wheat flour (WF), mopane worm powder (MW), and wheat-mopane worm composite flours at inclusion levels of 10 % (MW10), 20 % (MW20), and 30 % (MW30). All samples exhibited a characteristic multi-stage degradation pattern. The initial mass loss observed below 150 °C across all samples can be attributed to the release of free water and loosely bound water associated with hydrophilic sites of proteins and polysaccharides, as reported in similar TGA studies of protein- and carbohydrate-rich food matrices. The main degradation region, occurring between 250 °C and 400 °C, corresponds to the thermal decomposition of proteins, lipids, and polysaccharides, including the denaturation and pyrolysis of

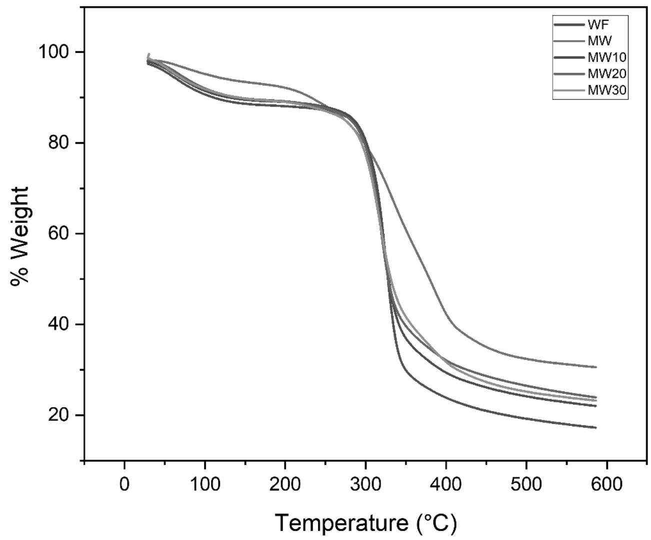
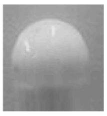
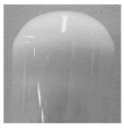
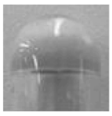
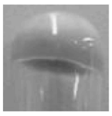
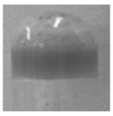
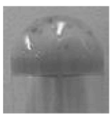
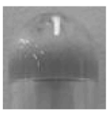
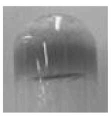


Fig 4. TGA thermograms of wheat-mopane composite flours. WF =Wheat flour; WM10-WM20 = Flour with 10, 20 and 30 % mopane worm flour.

Table 3
Least gelation concentration of wheat-mopane composite flours at different concentrations (4 - 7 % w/v).

Sample	4%	5%	6%	7%
WF				
MW	⊗	⊗	⊗	⊗
MW10				
MW20				
MW30				

WF =Wheat flour; WM10-WM20 = Flour with 10, 20 and 30% mopane worm flour. Photographs embedded in the table cells qualitatively illustrate the presence or absence of gel formation at each concentration.

macromolecular chains. The thermal profile of the pure mopane worm powder showed delayed and broader degradation peaks compared to WF. This indicates a more thermally stable matrix, which can be ascribed to the high protein and lipid content in mopane worms. In contrast, WF, predominantly composed of starch and gluten proteins, exhibited an earlier onset and sharper weight loss transition, suggesting a lower resistance to thermal degradation. Interestingly, as the level of mopane worm powder increased from 10 % to 30 %, the composite flour profiles progressively adopted thermal characteristics resembling those of the pure insect flour, indicating a strong compositional influence on thermal behaviour. This highlights the potential of incorporating edible insects into traditional cereal-based flour to modulate its thermal properties. Our results align with earlier findings by Fernández-Sánchez et al. (2025), who demonstrated thermal stability in *Sphenarium rugosum* flour, with decomposition temperatures exceeding 300 °C, characteristic of proteinaceous matrices. Similarly, Bogusz *et al.* (2024) reported enhanced thermal stability in yellow mealworm flours processed via pulsed electric fields, further supporting the correlation between protein content and delayed degradation. However, while those studies focused on insect flours in isolation, our work makes a unique contribution by assessing thermal transitions in binary flour systems that comprise both insect and cereal components. This study is among the first to report TGA thermal profiles of wheat-mopane worm composite flours, thus offering novel insights into the structural and compositional effects of insect flour enrichment on thermal behaviour. The observed shift in degradation patterns with increasing insect flour inclusion highlights the impact of entomophagy-based ingredients on thermal resilience, a trait that is advantageous in food processing operations such as baking, extrusion, and drying. The higher residual weight observed in MW and MW30 samples beyond 450 °C may also be attributed to the presence of thermally stable mineral and chitinous components, a finding consistent with the evolved gas profiles observed by Masite et al. (2022) via TGA-FT-IR. The thermal stability imparted by mopane worm powder suggests its potential as a functional fortifying ingredient in wheat-based formulations. These findings lay the groundwork for further investigations into the kinetics of thermal degradation, energy requirements during processing, and the impact of these thermal characteristics on nutritional bioavailability and product shelf stability.

3.7. Structural properties

Assessing wheat-mopane composite flours using Fourier-transform infrared (FT-IR) spectroscopy is essential for elucidating the molecular interactions, compositional shifts, and structural integrity of functional groups that underpin the nutritional and techno-functional behaviour of

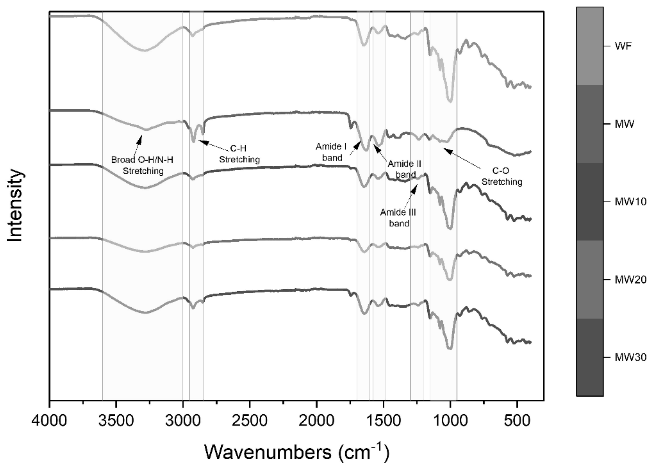


Fig 5. FT-IR spectra of wheat-mopane composite flours. WF =Wheat flour; WM10-WM20 = Flour with 10, 20 and 30 % mopane worm flour.

insect-enriched food systems. Fig. 5 illustrates the FT-IR spectra of wheat-mopane worm composite flours containing varying levels of mopane worm fpowder (MW10, MW20, MW30), alongside the control samples of pure wheat flour (WF) and 100% mopane worm flour (MW). Across all samples, characteristic absorption bands were observed in the regions corresponding to major biochemical components. The broad and intense bands around 3200 - 3400 cm^{-1}, attributable to O—H and N—H stretching vibrations, were more prominent in mopane worm powder and its enriched composites, reflecting the higher protein and moisture-associated hydrogen bonding typically observed in insect-based flours (Mshayisa et al., 2021; Ruggeri et al., 2023). The increasing intensity of these bands with higher MW inclusion confirms the protein-dominant nature of mopane worms compared to starch-rich wheat flour.

The absorption bands in the region 2850 - 2950 cm^{-1}, corresponding to C—H symmetric and asymmetric stretching in aliphatic chains, indicate the presence of lipid components. The peaks were more pronounced in mopane worm powder and in composites with higher substitution levels (e.g., MW30), reflecting the substantial lipid content of insect flours, which is known to remain significant unless defatting procedures are applied (Bogusz et al., 2024). The diminishing lipid-associated peaks in lower inclusion blends further support the compositional dilution of lipid-rich components by starchy wheat flour.

Importantly, the amide I (1650 cm^{-1}) and amide II (1540 cm^{-1}) bands, arising from $C = O$ stretching and N—H bending of peptide linkages, were clearly intensified in the mopane worm powder and high-inclusion composite flours. This observation confirms the dominance of insect-derived proteins and is consistent with previous findings in *Acheta domesticus* and *Tenebrio molitor* flour systems (Fernández-Sánchez et al., 2025). The gradual emergence of these amide bands as mopane inclusion increases suggests a structural transition in the protein matrix, which could affect techno-functional behaviours such as emulsification and foaming. Spectral bands in the fingerprint region (900 - 1200 cm^{-1}), particularly around 1020 - 1080 cm^{-1}, correspond to C—O and C—O-C stretching vibrations from carbohydrates and chitin polysaccharides. The presence of these bands in all samples, but particularly in mopane worm powder, highlights the persistence of chitinous exoskeletal components in the insect flour. These peaks decrease in intensity in wheat-dominant blends (e.g., WF and MW10), consistent with dilution of insect-derived structural polysaccharides.

Overall, the spectra exhibit a clear compositional gradient, ranging from starch-dominated (WF) to protein-dominated (MW) structures, with intermediate profiles for the composite flours. The spectral transitions observed validate the successful incorporation of mopane worm flour and provide a biochemical basis for understanding changes in nutritional and functional properties.

This study contributes to the growing, yet limited, body of literature on the structural fingerprinting of insect-enriched cereal composites. While prior research has established FT-IR profiles of insect flours and proteins in isolation, this work is among the first to systematically characterise gradient composite matrices and reveal the molecular transformations induced by functional ingredient substitution. The findings also establish FT-IR as a rapid, non-destructive tool for monitoring the compositional integrity and authenticity of insect-fortified food systems.

4. Elucidation of variable interdependencies in wheat-mopane worm composites through principal component and cluster analyses

Multivariate data analysis (MVA) techniques such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) are powerful tools for exploring complex datasets, particularly those involving compositional, techno-functional, and physicochemical attributes. In this study, PCA and HCA were employed to elucidate the interrelationships among variables and to differentiate sample groups arising from the partial substitution of wheat flour (WF) with mopane worm (MW) powder. These methods facilitated enhanced pattern recognition and enabled a more holistic interpretation of data structure, far surpassing the explanatory capacity of univariate analyses.

The PCA biplot (Fig. 6) captured 84.1 % of the total variance, with PC1 (72.9 %) and PC2 (11.2 %) accounting for the major sources of variation. A clear separation along PC1 was observed, with 100 % MW and the 30 % inclusion blend (MW30) positioned positively, while WF and low-level blends (MW10) clustered negatively. The most influential variables along PC1 were crude protein, crude fat, sodium, and energy, all of which were strongly associated with MW and MW30, reflecting the elevated nutrient density conferred by insect inclusion. In contrast, carbohydrates, moisture content, hue angle, and water activity (a_w) loaded negatively and aligned with the wheat flour control, indicative of the dilution effect from insect powder substitution.

Techno-functional attributes, such as foam capacity and water and oil holding capacities, which are loaded predominantly along PC2, contribute to the differentiation of intermediate blends (MW10 and MW20). Additionally, the co-location of b*, chroma, and ΔE* vectors in the positive quadrant highlights the significant chromatic changes introduced by MW, potentially attributable to pigment-rich cuticular components and Maillard browning during drying. These findings confirm that the incorporation of mopane worm powder significantly transforms both the compositional and functional architecture of the flour matrix. PCA thus served as a critical tool to reveal the nutritional divergence and functional versatility introduced by the inclusion of insect flour.

The hierarchical cluster analysis (Fig. 7) further corroborated the PCA results. Three primary variable clusters were identified. The first comprised ash, crude protein, energy, fat, and ΔE, forming a nutrient-dense group closely linked to the inclusion of MW. The second cluster grouped oil holding capacity, sodium, moisture, and carbohydrates, reflecting variables responsive to hydration and solute retention properties. A third, more distinct cluster included L*, hue angle, a_w, and foam capacity, variables indicative of visual quality and interfacial behaviour. This clustering pattern underscores two dominant functional domains within the dataset: one centred on nutrient enrichment and colour modification, and another on matrix hydration and surface-active properties. Notably, foam stability and bulk density clustered independently, suggesting that these traits are mechanistically distinct and potentially governed by structural reorganisation rather than compositional change.

To the best of our knowledge, this is the first study to integrate both PCA and HCA for a comprehensive assessment of the nutritional, techno-functional, and physicochemical attributes of wheat-mopane worm composite flours. The combined application of these multivariate techniques offers a novel analytical framework for edible insect fortification research and demonstrates how insect-derived ingredients can systematically restructure cereal matrices across multiple functional domains. This contributes significantly to advancing sustainable ingredient innovation and data-driven formulation strategies in the design of functional foods.

5. Conclusions

This study shows that partial substitution of wheat flour with mopane worm powder markedly enhances protein content while modifying colour, pasting behaviour, structural properties, and thermal stability. Importantly, multivariate analyses (PCA and HCA) demonstrated clear discrimination of samples according to mopane inclusion level, identifying protein, colour, and techno-functional traits as the major drivers of variability. These findings underscore the potential of mopane worm powder not only as a culturally significant, nutrient-rich ingredient, but also as a structuring agent capable of systematically reshaping cereal matrices. Taken together, the results provide a foundation for developing protein-enriched, insect-based food products and highlight multivariate analysis as a powerful framework for evaluating ingredient innovation. Future research should focus on evaluating the digestibility and bioavailability of mopane worm proteins, particularly in consideration of the role of chitin in nutrient absorption. Application trials in real food systems, such as bread, pasta, and extruded snacks, are crucial for validating functional performance. Meanwhile, sensory studies are necessary to assess consumer acceptance of the visual and textural changes. Additionally, optimising processing methods and assessing shelf-life stability will support the development of safe, high-

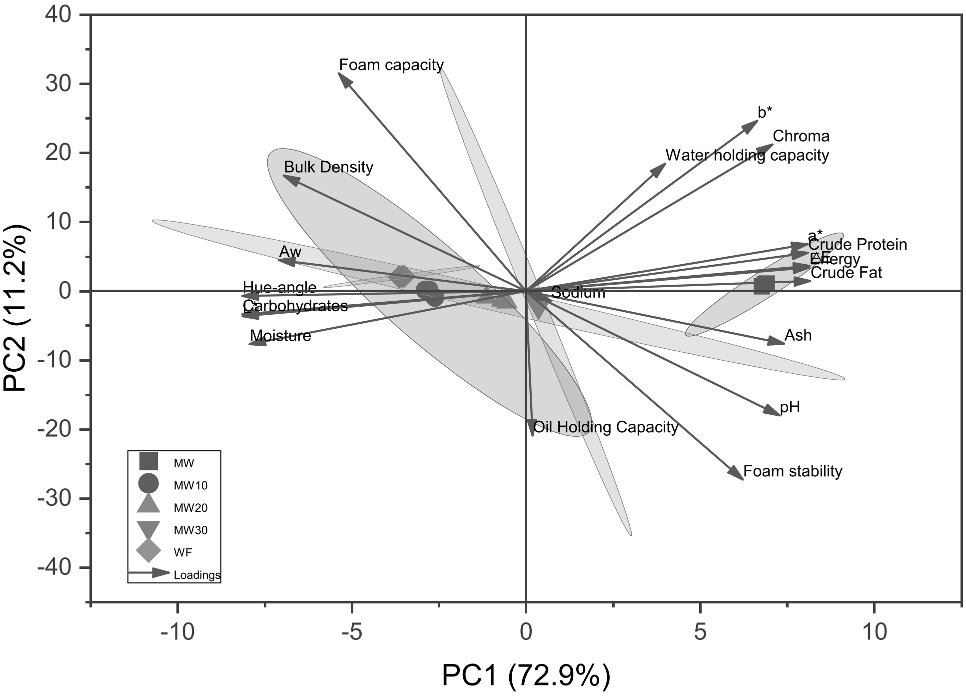


Fig 6. PCA biplot showing the distribution of composite flours based on nutritional, physicochemical and Technofunctional attributes. PC1 and PC2 explain 72.9 % and 11.2 % of total variance, respectively.

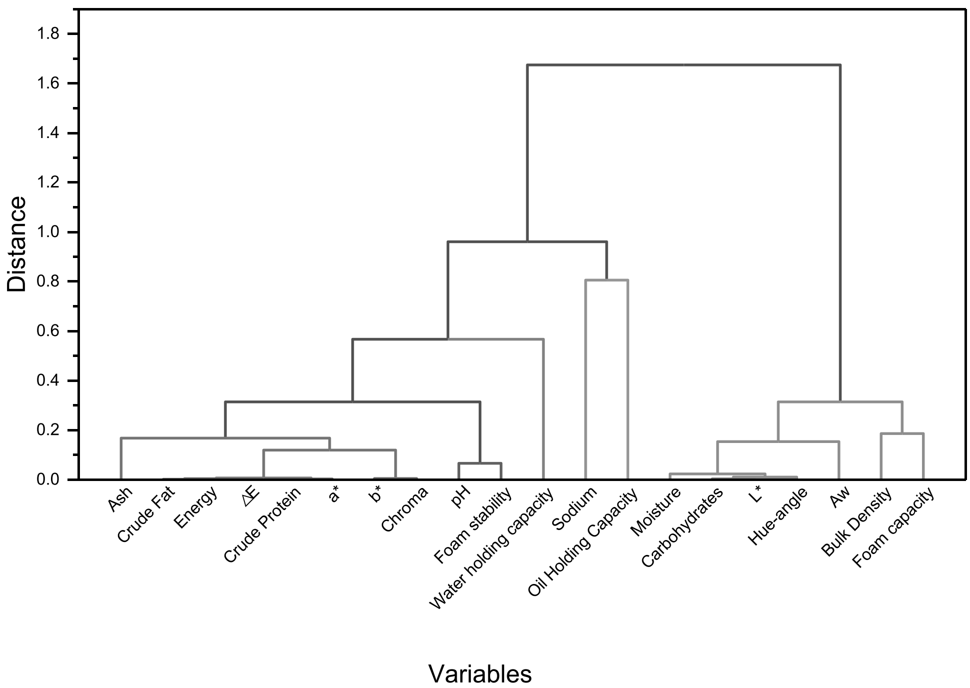


Fig 7. Dendrogram showing hierarchical clustering of variables based on compositional, functional, and colour attributes of composite flours.

quality products and their integration into the market.

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Ethical statement

This study did not involve human participants or live animals. All experimental procedures were conducted in accordance with institutional guidelines for research on non-living biological materials. The mopane worms (*Gonimbrasia belina*) used in this study were harvested post-mortem and handled following food-grade safety and hygiene standards. No ethical approval was required.

CRediT authorship contribution statement

Vusi Vincent Mshayisa: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Thembisile Adilaite Nkosi:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Nande Dlelanga:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Keneilwe Shantel Matladi:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Lamla Mayekiso:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization.

Declaration of competing 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.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

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