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ENHANCING CEREAL FLOURS WITH EDIBLE INSECTS: FUNCTIONAL AND RHEOLOGICAL INSIGHTS FOR SUSTAINABLE FOOD SOLUTIONS

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ABSTRACT

This study aims to evaluate the potential of incorporating edible insects *Macrotermes subhyalinus* and *Cirina butyrospermi* into sprouted maize and millet flours to create sustainable and nutritionally enhanced food products. The methodology involved examining the functional and rheological impacts of various insect incorporation rates (20 %, 22.5 %, 25 %) on 16 flour formulations, measuring properties such as water absorption capacity (WAC) and oil absorption capacity (OAC), and conducting a sensory evaluation of the finished products. The results show that *Macrotermes subhyalinus* decreases the WAC of both cereals due to its low WAC (41.74 ± 4.14 %), while *Cirina butyrospermi* increases the OAC, particularly in the MaCB20 (121.23 ± 12.38) and MaCB25 (120.36 ± 5.46) formulations. All insect-enriched flours have high dispersibility (> 90 %), except MaMS25. The MaCB25 formulation, with a TOPSIS score of 0.687, is recommended for applications in beverages and bakery products. The sensory evaluation of the biscuits revealed acceptable quality (score : 5.18). In conclusion, insect-enriched flours are a viable and high-quality alternative for the food industry, contributing to sustainability and nutritional improvement.

Keywords : *functional properties, rheological properties, sustainability in the food industry, sensory evaluation.*

RÉSUMÉ

Valoriser les farines de céréales avec des insectes comestibles : éclairages fonctionnels et rhéologiques pour des solutions alimentaires durables

Cette étude a pour objectif d'évaluer le potentiel d'incorporation des insectes comestibles *Macrotermes subhyalinus* et *Cirina butyrospermi* dans des farines de maïs et de mil germés pour créer des produits alimentaires durables et nutritionnellement améliorés. La méthodologie a consisté à examiner les impacts fonctionnels et rhéologiques de divers taux d'incorporation d'insectes (20 %, 22,5 %, 25 %) sur 16 formulations de farine, en mesurant des propriétés comme la capacité d'absorption d'eau (CAE) et la capacité d'absorption d'huile (CAH), et en réalisant une évaluation sensorielle des produits finis. Les résultats montrent que *Macrotermes subhyalinus* diminue la CAE des deux céréales en raison de sa faible CAE (41,74 ± 4,14 %), tandis que *Cirina butyrospermi* augmente la CAH, particulièrement dans les formulations MaCB20 (121,23 ± 12,38) et MaCB25 (120,36 ± 5,46). Toutes les farines enrichies en insectes ont une haute dispersibilité (> 90 %), sauf MaMS25. La formulation MaCB25, avec un score TOPSIS de 0,687, est recommandée pour des applications dans les boissons et produits de boulangerie. L'évaluation sensorielle des biscuits a révélé une qualité acceptable (score : 5,18). En conclusion, les farines enrichies avec des insectes sont une alternative viable et de haute qualité pour l'industrie alimentaire, contribuant à la durabilité et à l'amélioration nutritionnelle.

Mots-clés : *propriétés fonctionnelles, propriétés rhéologiques, durabilité dans l'industrie alimentaire, évaluation sensorielle.*

I - INTRODUCTION

The quest for food security emerges as a critical challenge on the global stage, magnified by projections estimating the world's population to approach 9 billion by 2050 [1]. This anticipated demographic expansion signals an urgent need for a 70 % increase in food production to satisfy the escalating demand, presenting a formidable challenge that necessitates innovative strategies, particularly in the developing world [2]. Nations such as Côte d'Ivoire are emblematic of the struggle against malnutrition, a plight disproportionately affecting vulnerable groups such as children and pregnant women [3]. Compounded by socio-economic and environmental hurdles, these issues underscore the complexity of scaling food production to meet future demands. The FAO underscores the necessity for food systems to not only scale up to meet this burgeoning demand but also to navigate the vicissitudes of climate change, water scarcity, and soil degradation [4]. In response, the pivot toward sustainable and nutritious food sources has catalyzed research and innovation within the agricultural and food science sectors [5]. This paradigm shift encompasses the exploration of advanced agricultural practices and the formulation of food products leveraging underutilized natural resources. Among these, edible insects emerge as a cornerstone, heralded for their high nutritional value-rich in proteins, lipids, vitamins, and minerals-and environmental sustainability [1]. In Côte d'Ivoire, for instance, over 11 insect species, including *Macrotermes subhyalinus* and *Cirina butyrospermi*, are integral to local diets and cultural practices [6]. Insect farming articulates a minimal ecological footprint, heralding a path towards more sustainable food systems [7]. Concurrently, the valorization of germinated cereals like corn and millet, known for their enhanced digestibility and reduced risk of chronic diseases, underscores the nutritional merits of processing techniques that amplify bioavailable nutrients while mitigating anti-nutritional factors [8-10]. This study introduces an avant-garde concept: the synergy of insect and germinated cereal flours to create composite blends. These blends aim to harness the nutritional, environmental, and functional benefits of both components, potentially revolutionizing food industry standards. Functional properties-critical for food product formulation—such as water and oil absorption capacities, foam stability, and emulsion activity, come to the forefront of this innovation [11, 12]. Yet, the incorporation of novel ingredients into food products demands rigorous evaluation to preserve functional and sensory qualities [13]. This investigation employs Multi-Criteria Decision Making (MCDM) techniques, specifically the TOPSIS method, to judiciously select the optimal flour formulation. The goal is to unveil composite blends that amalgamate the virtues of germinated cereals and edible insects, offering a blueprint for nutritious, functional, and sensorially appealing food solutions.

II - MATERIAL AND METHODS

II-1. Biological material

This research utilized germinated seeds of corn and millet. These seeds underwent germination under controlled conditions to achieve optimal growth. Additionally, two insect species, *Macrotermes subhyalinus* and *Cirina butyrospermi*, were reared under precise environmental control to standardize temperature, humidity, and nutritional parameters. Rigorous sampling methods were employed to ensure minimal disturbance and accurate representation of the biological material.

II-2. Production of flours from germinated cereals (Corn and Millet)

Flour production followed the protocol established by [3]. Corn and millet seeds were first soaked in water for 24 hours to initiate germination. Post-soaking, the seeds were rinsed, spread on cloth-covered trays, and left to air-dry at ambient conditions for three days. The germinated seeds were then oven-dried at 50 °C for an additional three days. The dried grains were degerminated manually before being pulverized using a Moulinex BLENFORCE1 600W blender. The ground material was sieved through a 500 µm mesh to obtain a fine flour, which was subsequently stored in airtight containers at -20 °C to preserve sample integrity pending analysis.

II-3. Production of insect powder

Insect powders were prepared as per the guidelines set forth by [3]. *Macrotermes subhyalinus* and *Cirina butyrospermi* were separately pulverized using the same model of blender, and the powders were stored in distinct containers to prevent cross-contamination.

II-4. Enrichment of local flours

Flour enrichment was carried out following [14]. Insect powders from *Macrotermes subhyalinus* (MS) and *Cirina butyrospermi* (CB) were integrated into the corn and millet flours in varying proportions (20 %, 22.5 %, and 25 %), as detailed in ***Table 1***.

Table 1 : *Enrichment of Composite Flours with Macrotermes subhyalinus (MS) and Cirina butyrospermi (CB) Powders in Corn and Millet Flours*

Flour Code	Composition
MaMS20	Corn flour (80 %) + *Macrotermes subhyalinus* powder (20 %)
MaMS22.5	Corn flour (77.5 %) + *Macrotermes subhyalinus* powder (22.5 %)
MaMS25	Corn flour (75 %) + *Macrotermes subhyalinus* powder (25 %)
MiMS20	Millet flour (80 %) + *Macrotermes subhyalinus* powder (20 %)
MiMS22.5	Millet flour (77.5 %) + *Macrotermes subhyalinus* powder (22.5 %)
MiMS25	Millet flour (75 %) + *Macrotermes subhyalinus* powder (25 %)
MaCB20	Corn flour (80 %) + *Cirina butyrospermi* powder (20 %)
MaCB22.5	Corn flour (77.5 %) + *Cirina butyrospermi* powder (22.5 %)
MaCB25	Corn flour (75 %) + *Cirina butyrospermi* powder (25 %)
MiCB20	Millet flour (80 %) + *Cirina butyrospermi* powder (20 %)
MiCB22.5	Millet flour (77.5 %) + *Cirina butyrospermi* powder (22.5 %)
MiCB25	Millet flour (75 %) + *Cirina butyrospermi* powder (25 %)

II-5. Functional parameters analysis of the formulated flours

Functional properties of the formulated flours were quantitatively assessed employing standardized methodologies, primarily utilizing centrifugation techniques [3]. The water absorption capacity (WAC) was measured through a procedure delineated by [15], leveraging centrifugation to ascertain the flours' hydration capabilities. Oil absorption capacity (OAC) was determined following the method prescribed by [16], which evaluates the flours' affinity for oil. Additionally, emulsifying activity (EA), emulsion stability (ES), foaming capacity (FC), and foam stability (FS) were comprehensively assessed according to protocols by [17]. Bulk density, an indicator of flour compaction, was precisely measured following the approach described by [18]. This methodological rigor ensures the reliability and consistency of functional property measurements across the study.

II-6. Rheological parameters analysis

Rheological characteristics of the flours were analyzed to gauge their behavior under various conditions. The swelling index, indicative of the flour's capacity to absorb water and swell, was evaluated as per the guidelines of [19]. The time required for the flour to become fully wet, denoted as wetting ability, was assessed following the method established by [20]. Flour dispersibility, reflecting the ease with which the flour disperses in a liquid medium, was quantified according to the procedure outlined by [21]. The hydrophilic-lipophilic balance, a measure of the flour's affinity towards water and oil, was calculated based on the ratio of WAC to OAC as defined by [22]. These analyses provide insight into the flours' suitability for various food applications, based on their hydration, dispersion, and swelling properties.

II-7. Determination of TOPSIS Score (MCDM) for ranking the flours

The ranking of the formulated flours was conducted using the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), a recognized Multi-Criteria Decision Making (MCDM) technique [23, 24]. MCDM facilitates the identification of the most favorable alternative among a set of options characterized by conflicting criteria. The process commenced with the construction of a decision matrix, wherein each row represented a flour variant and each column a criterion (e.g., WAC, OAC), incorporating average values for these parameters. This matrix underwent normalization using the Min-Max method to ensure comparability of values. A uniform weighting was applied across the normalized matrix, treating each criterion equally in the decision-making process. The identification of positive and negative ideal solutions, representing optimal and least desirable criterion values, respectively, enabled the calculation of Euclidean distances for each flour type. TOPSIS scores were derived from these distances, indicating each flour's relative performance against the ideal solution. A higher TOPSIS score signifies a closer approximation to the ideal, facilitating a ranked evaluation of flours based on their cumulative performance across assessed criteria [24, 25].

II-8. Sensory Acceptability Evaluation of the Produced Biscuits

II-8-1. Biscuit Preparation

Insect-enriched biscuits were crafted following the protocols of [26] and De [27], with slight modifications. Selection of flours for biscuit production was guided by prior analyses determining the most suitable blends based on functional and rheological properties. For the experimental batches, 50 % of the standard wheat flour was replaced with varying proportions of the chosen enriched cereal (corn or millet) and insect flour blends. The formulation included 3g of sugar, 1.7mL of vanilla essence, 0.8mL of salt, 20mL of milk, and 0.7mL of baking powder, mixed thoroughly with the flour blend. To this mixture, 13g of butter was added, and the dough was kneaded for two minutes until firm. The dough was then rolled, shaped, and baked at 150°C for 20 minutes in a preheated oven.

II-8-2. Sensory Analysis

A sensory panel of 60 volunteers, comprising young girls and boys as well as adult women and men, was assembled based on availability. Coded samples of the biscuits were distributed to the panelists in a randomized sequence. Participants were asked to rate their sensory experiences across multiple attributes—appearance, aroma, taste, aftertaste, flavor, crunchiness, and texture—using a 9-point hedonic scale. This scale ranged from 9 (extremely pleasant) to 1 (extremely unpleasant), allowing for a comprehensive assessment of sensory acceptability [28 - 29].

II-9. Statistical Data Analysis

Data collection was conducted using Excel, with further analysis performed in R software version 4.2.0 [30]. An analysis of variance (ANOVA) was employed to evaluate the differences between sample means and to discern any statistically significant distinctions among the biscuit variants tested.

III - RESULTS AND DISCUSSION

III-1. Functional properties of formulated flours

The functional properties of formulated flours are critical, reflecting the complex synergy between the composition, structural attributes, and physicochemical characteristics of proteins, along with other essential food components. These properties, foundational to the formulation process, include Water Absorption Capacity (WAC), Oil Absorption Capacity (OAC), Emulsifying Activity (EA), Emulsion Stability (ES), Foaming Capacity (FC), Foam Stability (FS), and Bulk Density (BD), as outlined in *Table 2*. The quantification and characterization of these parameters are vital for understanding their influence on the textural, nutritional, and sensory attributes of food products. This examination aims to elucidate the direct correlation between these functional properties and their impact on the overall quality and performance of food products, facilitating the optimization of product formulations. The analysis robustly demonstrates that the functional properties of *Cirina butyrospermi* predominantly surpass those of *Macrotermes subhyalinus* with the sole exception of bulk density. Additionally, it is revealed that the functional attributes of cereals are significantly altered by the incorporation of these insect species, with variations directly correlated to both the type and rate of insect and cereal incorporation.

Specifically, the incorporation of *Macrotermes subhyalinus* into the cereal matrices results in a notable reduction in Water Absorption Capacity (WAC) a phenomenon not observed with the addition of *Cirina butyrospermi*. This reduction can be attributed to the inherently lower WAC observed in *Macrotermes subhyalinus*, quantified at 41.74 ± 4.14 %. As suggested by [31], the variance in WAC may be due to differences in chemical composition, particularly lipid content, which inversely impacts WAC. Flours with enhanced WAC such as MiCB22.5 (111.66 ± 5.21 %) present potential applications in the production of various food items including but not limited to charcuterie, pasta, melted cheese, and bakery goods, leveraging their superior moisture retention. Furthermore, findings highlight the critical role of Oil Absorption Capacity (OAC) in assessing the synergy between proteins and lipids within food formulations. Contrary to WAC, a significant elevation in OAC is observed in flour samples MaCB20 (121.23 ± 12.38) and MaCB25 (120.36 ± 5.46), aligning with the findings of [3], who reported even higher OAC values, up to 170.958 ± 19.37, in corn flour enriched with Oryctes owariensis. The pronounced OAC in these formulations underscores their utility as premium ingredients within the food industry, particularly for enhancing food texture and sensory characteristics. Moreover, the high OAC is instrumental in food preservation, serving as a barrier against oxidative rancidity, thereby facilitating product longevity and maintaining nutritional integrity. The study presents findings on bulk density, revealing a notable decrease upon the incorporation of *Macrotermes subhyalinus* and *Cirina butyrospermi* species, with the most significant reduction observed in MaMS22.5 (0.70 ± 0.07 g/ml). These observed densities fall below those documented by [32] for composite flours of taro and wheat, ranging between 0.82 and 0.85 g/mL. Such variation suggests a distinct interaction between the added insect species and the flour matrix, highlighting the specificity of their integration effects. The implications of these findings are considerable, especially in terms of storage, transportation, and marketing logistics for the produced flours. The lower densities suggest potential for significantly reducing packaging material volumes, thereby optimizing distribution processes. Additionally, flours with densities under 1 g/ml, as found in this study, are advantageous for creating weaning foods and high-energy content foods, aligning with recommendations from previous research. [33] emphasizes the importance of optimizing foaming power and foam stability for enhancing the texture, consistency, and visual appeal of food products. This research observes a substantial increase in the foaming power of millet flour upon the addition of these species, enhancing from 1.26 ± 0.22 % to 1.93 ± 0.20 % for MiCB22.5 and 1.85 ± 0.12 % for MiMS22.5.

This enhancement in foaming power indicates an improved incorporation of air bubbles, which is advantageous for various food applications. This observation supports the theory posited by [34], which correlates successful foaming capability with the presence of flexible protein molecules that reduce surface tension. Conversely, a diminished foaming ability is linked to the resistance of highly structured globular proteins to surface denaturation. Foam stability exhibited significant variability, reflecting the diverse nature of the formulations studied. These variations provide valuable insights for tailoring the texture and structure of final food products. Although emulsifying activity showed no significant changes, notable decreases in emulsion stability were observed in certain formulations, affecting their potential use in cakes, desserts, and dressings. This aspect underscores the critical role of protein properties in the quality of food formulations, as noted by [35]. This research offers significant insights into the functional properties of formulated flours, opening avenues for varied applications in the food industry. The findings underscore the importance of understanding protein properties to enhance the quality of formulated food products, particularly highlighting their utility in specialized areas such as pastry and sauce production.

Table 2 : *Functional properties of the different samples*

Flours	EA	ES	WAC	OAC	BD	FC	FS
CB100	62.48±13.27**a**	59.44±2.23bcd	99.77±0.83d	127.86±12.29b	0.74±0.00ab	1.07±0.10bc	21.02±0.08a
MS100	48.12±11.30a	11.66±1.66a	41.74±4.14a	76.41±21.02a	1.00±0.00c	0.21±0.00a	18.14±3.52a
Ma100	39.20±9.77a	87.39±3.20d	100.43±4.51d	97.65±14.11ab	0.75±0.00ab	1.67±0.15deg	14.52±0.41ab
MaCB20	46.66±10.53a	21.85±1.63a	103.04±5.31d	121.23±12.38b	0.74 ±0.00ab	1.32±0.06bef	62.62±6.99e
MaCB22.5	54.25±13.22a	45.95±19.30ac	105.88±3.06d	110.4±14.10ab	0.74±0.00ab	1.27±0.24be	37.90±2.14c
MaCB25	53.54±1.19a	82.41±7.36d	105.20±5.68d	120.36±5.46b	0.76±0.02ab	1.06±0.11b	73.80±5.40e
MaMS20	56.45±7.23a	77.90±16.17cd	83.83±1.59bc	89.12±19.23ab	0.74±0.00ab	1.53±0.15beg	39.68±5.49c
MaMS22.5	58.73±3.42a	85.82±5.17d	80.02±4.62bc	92.18±21.58ab	0.70±0.07a	1.63±0.19deg	38.98±6.70c
MaMS25	54.05±2.99a	83.32±13.21d	73.87±2.76b	93.63±7.82ab	0.74±0.00ab	1.60±0.02cdeg	29.04±0.82bc
Mi100	52.30 ±4.53a	58.52±10.73bcd	105.97±5.70d	131.46±11.99b	0.79±0.00b	1.26±0.22bd	36.66±5.77c
MiCB20	51.33±5.26a	66.11±11.34cd	108.34±3.92d	89.60±17.11ab	0.77±0.02b	1.68±0.11deg	41.07±3.09c
MiCB22.5	45.28±6.24a	27.89±5.15ab	111.66±5.21d	100.59±4.69ab	0.77±0.02b	1.93±0.20g	43.91±0.91cd
MiCB25	53.48±8.22a	13.55±2.69a	108.05±2.14d	91.82±19.08ab	0.75±0.00ab	1.64±0.04deg	43.33±0.82c
MiMS20	61.36±1.96a	74.87±9.80cd	79.29±6.23bc	99.47±12.25ab	0.74±0.00ab	1.70±0.12deg	60.71±3.09e
MiMS22.5	61.77±13.69a	77.71±19.56cd	83.18±2.00bc	88.41±8.74ab	0.74±0.00ab	1.85±0.12fg	60.18±4.00de
MiMS25	64.41±7.32a	64.64±10.74cd	86.74±4.73c	91.01±14.17ab	0.75±0.00ab	1.80±0.41cg	64.81±16.03e

Values with different alphabetical letters in the same column are statistically different ($p < 0.05$). MS: Macrotermes subhyalinus; CB: Cirina butyrospermi; Ma: Corn; Mi: Millet; MaMS20: corn flour (80 %) and Macrotermes subhyalinus (20 %); MaMS22.5: corn flour (77.5 %) and Macrotermes subhyalinus (22.5 %); MaMS25: corn flour (75 %) and Macrotermes subhyalinus (25 %); MiMS20: millet flour (80 %) and Macrotermes subhyalinus (20 %); MiMS22.5: millet flour (77.5 %) and Macrotermes subhyalinus (22.5 %); MiMS25: millet flour (75 %) and Macrotermes subhyalinus (25 %); MaCB20: corn flour (80 %) and Cirina butyrospermi (20 %); MaCB22.5: corn flour (77.5%) and Cirina butyrospermi (22.5 %); MaCB25: corn flour (75 %) and Cirina butyrospermi (25%); MiCB20: millet flour (80 %) and Cirina butyrospermi (20 %); MiCB22.5: millet flour (77.5 %) and Cirina butyrospermi (22.5 %); MiCB25: millet flour (75 %) and Cirina butyrospermi (25 %). WAC: Water Absorption Capacity, OAC : Oil Absorption Capacity, EA: Emulsifying Activity, ES: Emulsion Stability, FC: Foaming Capacity, FS : Foam Stability, and BD: Bulk Density.

III-2. Rheological properties of formulated flours

The rheological properties of enriched flours were assessed to ascertain their influence on food product quality and texture. ***Table 3*** displays significant variations across several rheological parameters. All enriched flour samples demonstrated a dispersibility index exceeding 90 %, indicating a robust capacity for dispersion in water. However, the MaMS25 sample exhibited a slight reduction to 87.22 ± 0.96 %. Notably, flours enriched with larvae from

Rhynchophorus phoenicis and *Oryctes owariensis* showcased an enhanced dispersibility, significantly surpassing those reported for traditional taro and wheat flours (66 - 73 %) [32]. This superior dispersibility is advantageous for forming a fine and consistent paste [36] Wettability trends revealed a decline, particularly in samples enriched with *Macrotermes subhyalinus*, as observed in MaMS22.5 (24.33 ± 2.08 min) and MiMS25 (23.00 ± 2.64 min). This reduction may be attributed to alterations in the chemical composition of the flours, especially an increase in lipid content, which could inhibit water penetration due to the presence of fats on particle surfaces [32]. Despite this decrease in wettability, the formulated flours are not deemed rapidly soluble in water, with a flour considered wettable if its wettability time is under 60 seconds and very wettable if less than 30 seconds [37]. The hydrophilic/lipophilic ratio (HLB) analysis through ANOVA revealed a decrease with the addition of insect powders to corn flour, shifting from 1.04 ± 0.12 for Ma100 to 0.79 ± 0.09 for MaMS25. In contrast, the addition of millet powder, particularly with *Cirina butyrospermi* species, resulted in an HLB increase.

These findings suggest a greater oil over water preference in these flours, except for a few samples where HLB > 1, indicating variations in polysaccharides and protein content could explain these disparities [37]. Swelling indices for the enriched samples remained consistent, with slight increases observed in MaCB20 (0.89 ± 0.00), MaMS20 (0.90 ± 0.01), and MiCB20 (0.90 ± 0.02). However, these values are lower than those reported for bean flours (1.80-1.84 mL) and Ghanaian cowpea (2.65-2.68 mL), suggesting the nature of the starch species and high fiber contents in these samples may contribute to a decreased ability to swell [38]. This suggests a reduced capacity for volumetric expansion when water is absorbed [39] In conclusion, the rheological analysis of the enriched flours unveils specific properties, offering intriguing characteristics for certain food applications. The noted decrease in wettability, alongside high dispersibility, variations in HLB, and moderate swelling index, suggest their potential suitability for specific food systems that require these distinct rheological characteristics.

Table 3 : *Rheological parameters of formulated flours*

Flour	Dispersibility	Wettability	Swelling index	Hydrophilic/lipophilic balance
CB100	90,55±0,50b	11,66±1,52a	0,91±0,00ab	0,78±0,06ab
MS100	97,11±0,38d	12,00±1,00a	0,94±0,03b	0,58±0,19a
Ma100	90,77±0,83b	14,33±2,51ab	0,86±0,00a	1,04±0,12bc
MaCB20	96,88±0,38d	15,00±1,00ab	0,89±0,00ab	0,85±0,10ac
MaCB22.5	90,55±0,96b	17,00±1,00abcd	0,87±0,01a	0,96±0,11ac
MaCB25	96,88±0,38d	22,00±2,00def	0,86±0,01a	0,87±0,05ac
MaMS20	93,88±0,96c	21,66±2,88cef	0,90±0,01ab	0,97±0,21ac
MaMS22.5	96,66±0,00d	24,33±2,08f	0,88±0,00a	0,89±0,18ac
MaMS25	87,22±0,96a	21,66±2,88cf	0,87±0,02a	0,79±0,09ac
Mi100	97,88±1,53d	15,33±1,52ab	0,87±0,01a	0,81±0,10ac
MiCB20	93,33±0,00c	15,66±1,15ab	0,90±0,02ab	1,24±0,27c
MiCB22.5	93,05±0,48c	14,66±1,52ab	0,88±0,03a	1,11±0,00bc
MiCB25	96,88±0,19d	19,00±1,73bf	0,88±0,00ab	1,21±0,26bc
MiMS20	97,00±0,33d	16,33±0,57abc	0,87± 0,02a	0,80±0,04ac
MiMS22.5	92,22±0,96bc	18,66±1,52be	0,85±0,03ab	0,94±0,06ac
MiMS25	97,66±0,33d	23,00±2,64cf	0,89 ±0,03a	0,96±0,12ac

Values with different alphabetical letters in the same column are statistically different ($p < 0.05$). MS: *Macrotermes subhyalinus*; CB : *Cirina butyrospermi*; Ma : Corn; Mi : Millet; MaMS20 : corn flour (80 %) and *Macrotermes subhyalinus* (20 %); MaMS22.5 : corn flour (77.5 %) and *Macrotermes subhyalinus* (22.5 %); MaMS25 : corn flour (75 %) and *Macrotermes subhyalinus* (25 %); MiMS20 : millet flour (80 %) and *Macrotermes subhyalinus* (20 %); MiMS22.5 : millet flour (77.5 %) and *Macrotermes subhyalinus* (22.5 %); MiMS25 : millet flour (75 %) and *Macrotermes subhyalinus* (25 %); MaCB20: corn flour (80 %) and *Cirina butyrospermi* (20 %) ; MaCB22.5 : corn flour (77.5 %) and *Cirina butyrospermi* (22.5 %); MaCB25 : corn flour (75 %) and *Cirina butyrospermi* (25 %) ; MiCB20 : millet flour (80 %) and *Cirina butyrospermi* (20 %) ; MiCB22.5 : millet flour (77.5 %) and *Cirina butyrospermi* (22.5 %) ; MiCB25 : millet flour (75 %) and *Cirina butyrospermi* (25 %).

III-3. Correlation between the analyzed flour parameters

The analysis of linear correlation coefficients among the assessed flour parameters unveils significant relationships ***(Figure 1)***. Notably, a robust positive correlation exists between the hydrophilic/lipophilic ratio (HLB) and Water Absorption Capacity (WAC), as well as with foaming power, both with correlation coefficients (r) of 0.68. This relationship is particularly salient within the domain of surfactants, where a heightened HLB is known to enhance the foaming power of surfactants, thereby augmenting the stability and efficacy of foams across various applications [40 - 42]. Additionally, the investigation reveals a positive correlation between the swelling index and bulk density (r = 0.65). The swelling index, indicative of a flour's ability to absorb and retain water, is positively associated with characteristics such as density and hydration capacity, as documented by some researchers [43, 44]. Conversely, significant negative correlations were identified between certain parameters, specifically between foaming power and bulk density (r = -0.78), as well as with the swelling index (r = -0.62). These observations can be attributed to the composition of the formulated flours; ingredients rich in protein content are known to enhance foaming power while simultaneously inhibiting swelling due to their limited capacity for water absorption [45].

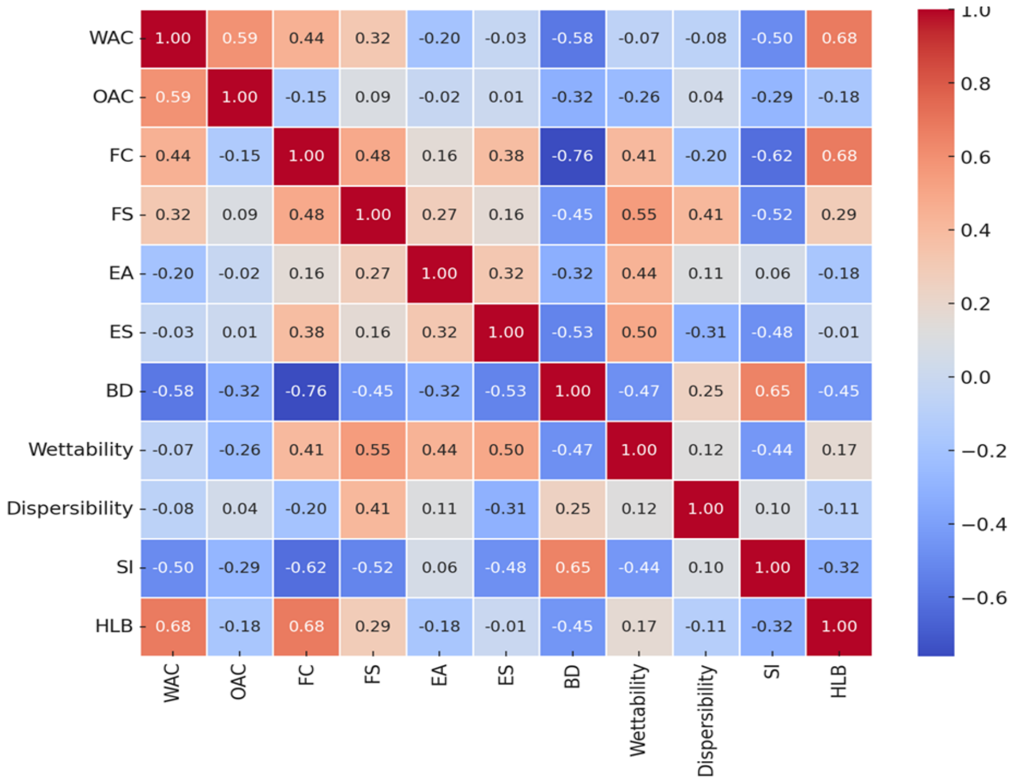

Figure 1 : *Linear Correlation Matrix among Analyzed Parameters*

WAC : Water Absorption Capacity, OAC : Oil Absorption Capacity, EA : Emulsifying Activity, ES : Emulsion Stability, FC : Foaming Capacity, FS : Foam Stability, and BD : Bulk Density, SI : Swelling index, HLB : Hydrophilic/lipophilic balance.

III-4. Classification of flours according to MCDM Score and specific food Application

The evaluation scores, as depicted in *Figure 2*, serve as a composite indicator of each flour type's aggregate performance across all tested parameters, with higher scores indicating superior overall performance. Within this framework, the MaCB25 flour emerges as the leading contender, achieving the highest normalized score of 0.687. This score positions MaCB25 as the flour with the most advantageous functional and rheological profile, a distinction underscored by previous research [24, 25]. While MaCB25 flour distinguishes itself in terms of quality, the selection of the optimal flour formulation ultimately hinges on the specific requirements of the intended food application. An exhaustive analysis of the normalized scores for the functional properties of MaCB25 flour, tailored to various food categories ***(Figure 3)***, elucidates the wide-ranging potential applications of MaCB25, thus presenting it as a versatile option for food industry professionals aiming to enhance the functional quality of their products. Notably, the "Beverages" category achieves the highest score (1.93), underscoring the particular suitability of MaCB25 flour for beverage formulations. This aptness is attributed to its exceptional dispersibility (96.88±0.38), optimal hydrophilic-lipophilic balance (HLB : 0.87 ± 0.05), and notable water absorption capacity (WAC : 105.20 ± 5.68 %) [43 - 46].

Moreover, the flour demonstrates potential utility in the production of bakery items, such as bread (1.02) and biscuits (1.62) [46]. Nonetheless, determining the most suitable flour formulation demands a nuanced understanding of each food application's unique requirements, emphasizing the importance of a tailored approach to fully leverage the innovative qualities of MaCB25 flour. The study also includes an in-depth analysis of the normalized scores for the functional properties of MaCB25 flour, specifically dedicated to different types of food ***(Figure 3)***. This analysis reveals a diversity of potential applications for MaCB25, thus offering food industry professionals a multifunctional option to enhance the functional quality of their products. Furthermore, the "Beverages" category stands out with a higher score (1.93), suggesting that MaCB25 could be particularly suitable for beverage formulation. This suitability is attributable to properties such as dispersibility (96.88 ± 0.38), the hydrophilic-lipophilic balance (HLB : 0.87±0.05), and water absorption capacity (WAC: 105.20 ± 5.68 %) [43 - 46]. Also, this flour can be used in the formulation of bakery products such as bread (1.02), biscuits (1.62) [46]. However, the selection of the optimal formulation will depend on the specific requirements of each intended food application, thus marking the necessity of a targeted approach to maximize the benefits of this innovative flour.

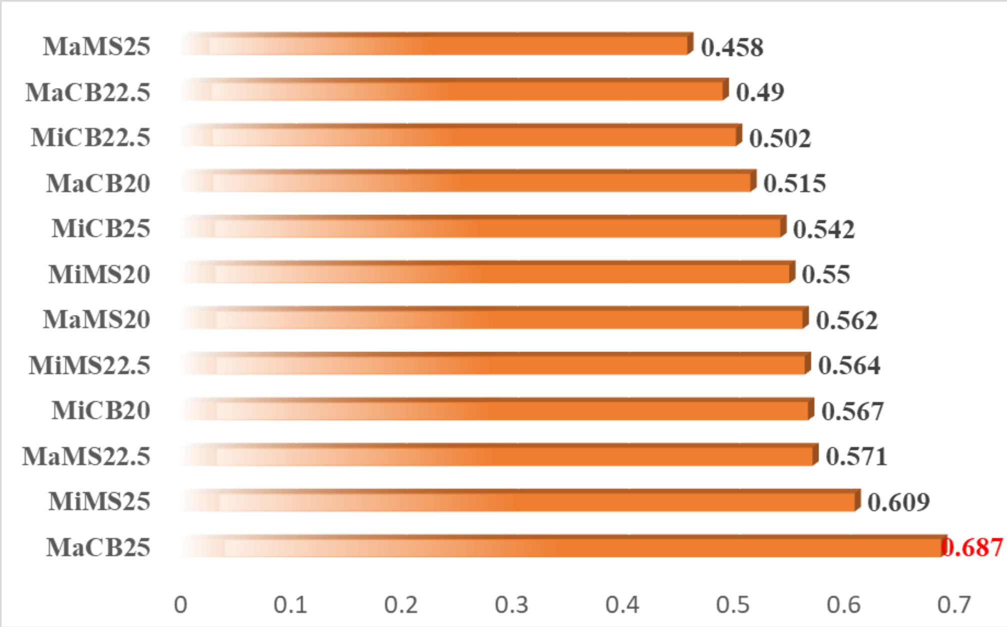

Figure 2 : *Classification of Flours According to TOPSIS (MCDM) Score*

MaMS20: corn flour (80 %) and Macrotermes subhyalinus (20 %); MaMS22.5: corn flour (77.5 %) and Macrotermes subhyalinus (22.5 %); MaMS25: corn flour (75 %) and Macrotermes subhyalinus (25 %); MiMS20 : millet flour (80 %) and Macrotermes subhyalinus (20 %); MiMS22.5: millet flour (77.5 %) and Macrotermes subhyalinus (22.5 %); MiMS25: millet flour (75 %) and Macrotermes subhyalinus (25 %); MaCB20 : corn flour (80 %) and Cirina butyrospermi (20 %); MaCB22.5: corn flour (77.5 %) and Cirina butyrospermi (22.5 %); MaCB25 : corn flour (75%) and Cirina butyrospermi (25 %); MiCB20: millet flour (80 %) and Cirina butyrospermi (20 %); MiCB22.5: millet flour (77.5 %) and Cirina butyrospermi (22.5 %); MiCB25 : millet flour (75 %) and Cirina butyrospermi (25 %).

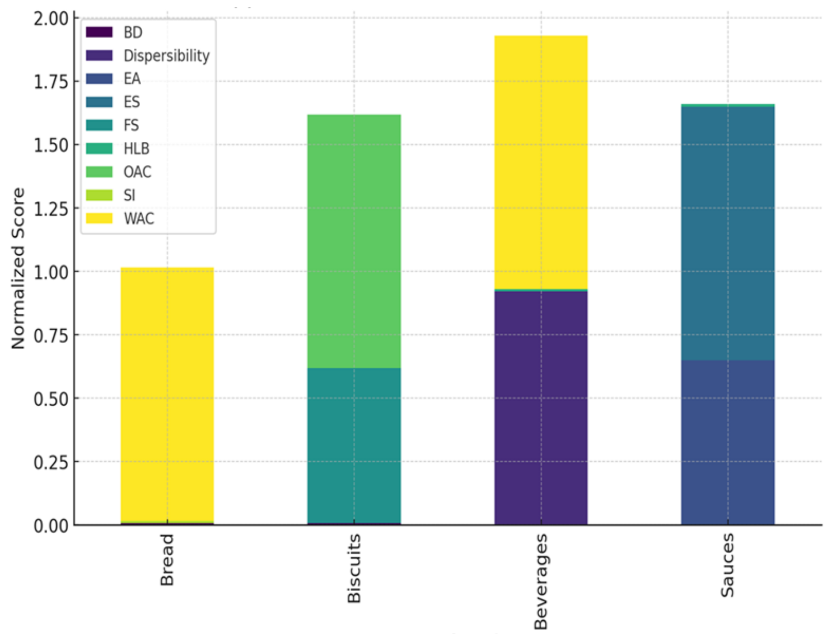

Figure 3 : *Classification of MaCB25 flour properties according potential food applications*

WAC : Water Absorption Capacity, OAC : Oil Absorption Capacity, EA : Emulsifying Activity, ES : Emulsion Stability, FC : Foaming Capacity, FS : Foam Stability, and BD : Bulk Density, SI : Swelling index, HLB : Hydrophilic/lipophilic balance.

III-5. Sensory Quality of Biscuits Formulated from the Best Composite Flours

The sensory quality assessment of biscuits crafted from local cereals augmented with edible insects (MaCB25 and MiMS25) was meticulously performed ***(Figure 4)***. The panelists universally recognized the acceptability of all biscuit variants, with scores uniformly surpassing the benchmark of 5. Within this assortment, the MaCB25 variant emerged as the clear favorite, registering a commendable score of 5.18, and was distinguished by its exceptional sensory qualities, including texture (5.42), crunchiness (5.87), and visual appeal (7.55). These appealing sensory traits are largely ascribed to its notable oil absorption capacity [46, 47]. The fats absorbed by the flour contribute significantly to a distinctive softness and creaminess in the biscuit's texture, a phenomenon corroborated by analogous studies focusing on cream and butter biscuits [48]. The observed disfavor regarding the aftertaste of MiMS25 (4.45) and MaCB25 (4.38) biscuits can be rationalized by the proportion of insect incorporation. A parallel investigation by [49] indicated that the integration of termites into biscuit formulations is optimally capped at a 25 % substitution rate for wheat flour to maintain acceptability. Furthermore, [50] established that wheat buns incorporating a modest 5 % termite content achieved optimal acceptance, a stark contrast to buns with a higher termite inclusion rate of 20 %.

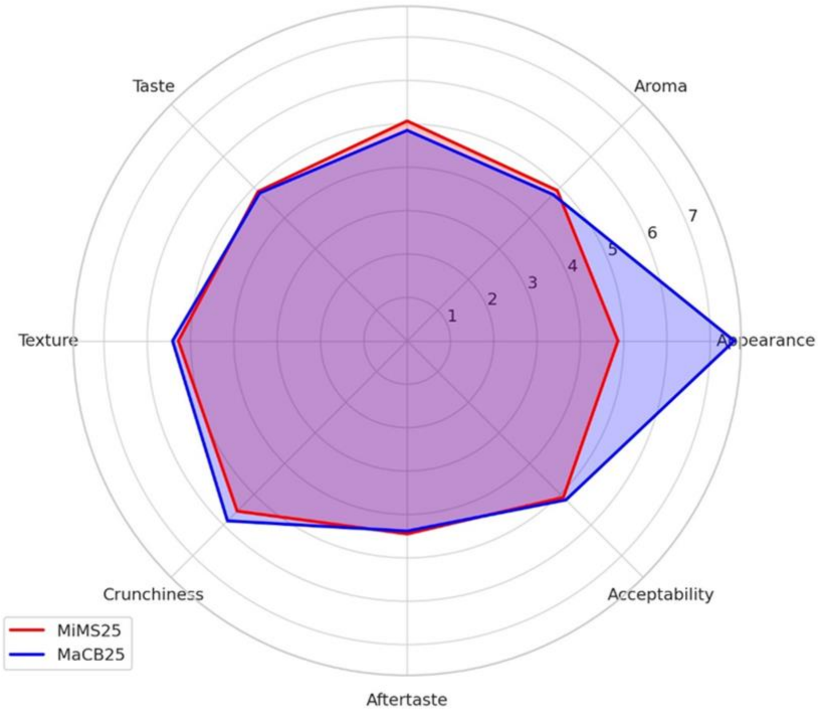

Figure 4 : *Sensory attributes comparison of biscuits made from MiMS25 and MaCB25 flours*

IV - CONCLUSION

This investigation was centered on developing composite flours by enriching local cereals with insects, specifically *Macrotermes subhyalinus* and *Cirina butyrospermi*, with the aim of enhancing their functional and rheological properties for potential food industry applications. The incorporation of insects significantly influenced these properties, exhibiting variability based on the type of insect, incorporation rate, and cereal matrix used. The study found that adding *Macrotermes subhyalinus* led to a reduction in water absorption capacity (WAC), while the integration of *Cirina butyrospermi* yielded varied effects. Notably, an increase in oil absorption capacity (OAC) was observed in flours MaCB20 (121.23 ± 12.38) and MaCB25 (120.36 ± 5.46), contrasting with a decrease in millet-based formulations, especially MiMS22.5.

Furthermore, all enriched flour samples demonstrated a high dispersibility in water, with the exception of MaMS25 (87.22 ± 0.96 %). The study identified MaCB25 flour, scoring 0.687, as possessing the most favorable functional and rheological profile, making it particularly suitable for the formulation of beverages and bakery products (bread and biscuits) with acceptable sensory qualities. However, the selection of the optimal flour formulation is contingent upon the specific requirements of the intended application due to the observed variability in functional and rheological properties. In conclusion, this array of insect-enriched flours presents a promising avenue for diverse applications within food technology, offering a potential contribution to food security enhancement.

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