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# Sensory profiling of traditional Sorghum porridge (*Aceda*): advancing nutritious and culturally accepted biofortified products

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**Introduction:** Micronutrient deficiencies remain a significant public health concern in Sudan and are exacerbated by conflict and displacement.

**Methods:** This study assessed the sensory attributes and acceptability (hedonic scale) of *Aceda*, a traditional Sudanese fermented sorghum-based porridge prepared using biofortified (Dahab) and non-biofortified (Wad Ahmed and Dabar) sorghum cultivars and their blends. Sensory evaluation by 28 semi-trained assessors identified color, firmness, and mouthfeel as the key preference drivers.

**Results and discussion:** *Aceda* made from the Dahab and Dahab + Wad Ahmed blends had the highest overall liking scores. Cluster analysis revealed two preference groups: 11 assessors favored Dahab, and 17 preferred the Dahab + Wad Ahmed blend, with age being the most influential demographic factor. Product characterization analysis showed that texture and firmness were critical for overall liking, whereas aroma and taste had a minimal impact. The sensory profiles of the *Aceda* products were mainly influenced by F1 (76.20%) and F2 (16.25%), accounting for 92.45% of the variance. PLS analysis identified the Dahab + Wad Ahmed blend as the most promising porridge for addressing malnutrition. STATIS analysis showed weights between 0.142 and 0.213 (mean, 0.188) and a consensus configuration range of 0.572–0.857 (mean, 0.755). These findings underscore the acceptability of biofortified sorghum porridge among consumers and highlight the role of targeted blending strategies in optimizing sensory attributes, which may support its future potential as part of broader nutritional interventions.

KEYWORDS

**biofortified sorghum, hidden hunger, indigenous food processing, sensory profile, Sustainable food systems**

# 1 Introduction

Micronutrient deficiencies, particularly those of iron, zinc, and vitamin A, remain critical public health concerns in Sudan, intensified by ongoing conflicts, economic instability, and widespread population displacement (Homeida, 2023). According to the Integrated Food Security Phase Classification (IPC) report (October 2024), 24.6 million people in Sudan are projected to face acute food insecurity (IPC Phase 3 or above) between December 2024 and May 2025, with 8.1 million in IPC Phase 4 (Emergency) and 638,000 in IPC Phase 5 (Catastrophe), as a result of the ongoing war. This escalating food and nutrition crisis has severely affected vulnerable populations, particularly children under five and pregnant or breastfeeding women, with disrupted health services further compounding the problem (Integrated Food Security Phase Classification, 2024).

Sorghum is a major food source in Sudan and other African countries and is known for its high carbohydrate content and as a valuable protein source. It is also packed with dietary phenolics and a range of phytochemicals (Ahmad et al., 2021; Punia et al., 2021), which may have significant health benefits owing to their potent antioxidant properties, with potential benefits comparable to those offered by fruits and vegetables (Awika and Rooney, 2004). With the growing impact of climate change on crop yields, especially in sub-Saharan Africa, it is important to promote the inclusion of sorghum in staple foods, such as porridge, to contribute to food security and enhance human health (Apea-Bah et al., 2014). However, local sorghum varieties consumed as staple foods in Sudan lack certain micronutrients, which should be addressed to prevent potential negative health effects and enhance the overall nutritional benefits for consumers. The biofortification of staple crops, such as sorghum and pearl millet, to enhance their micronutrient content by modern breeding is considered a sustainable approach to addressing micronutrient deficiencies (Rehman et al., 2021). This strategy is a sustainable long-term solution and holds promise for addressing these issues in conflict-affected regions such as Sudan, where access to diverse foods is limited. However, logistical barriers and the cultural acceptance of biofortified foods remain significant challenges for their adoption in local food systems (Bechoff et al., 2018; Onyango et al., 2020; Talsma et al., 2017). Integrating biofortified crops into traditional food systems can promote cultural connectedness and empower vulnerable rural communities to reclaim food sovereignty while improving nutritional outcomes (Trott and Mulrennan, 2024).

According to Birol et al. (2015), consumer acceptance, influenced by sensory attributes such as taste, texture, color, and aroma, is critical for the success of such interventions. Previous studies have indicated that unfamiliar sensory properties often lead consumers to prefer conventional varieties to biofortified ones (Beswa et al., 2020; Govender et al., 2019; Talsma et al., 2017). Strategies, such as blending biofortified crops with traditional varieties, can enhance both sensory appeal and nutritional value (Delimont et al., 2017). Additionally, participatory, community-based sensory evaluations are essential for tailoring biofortified foods to local tastes and preferences (Birol et al., 2015). Awareness campaigns and targeted nutritional education play a crucial role in increasing acceptance by highlighting the health benefits of biofortified foods and addressing resistance to changes in traditional diets (Govender et al., 2019). However, according to Huey et al. (2024), few studies have explored the acceptance of biofortified products. However, interest in this topic has grown recently, with several investigations focusing on crops such as sweet potatoes, maize, and sorghum (Buzigi et al., 2025; Dlamini et al., 2025; Hamid et al., 2025; Sayed Abdelhalim et al., 2025).

In Sudan, Aceda, a stiff porridge made from sorghum, is a dietary staple traditionally prepared from Feterita-type sorghum (Mohamed et al., 2022). According to (Boutros, 1986; Sukkar et al., 1975), Aceda consists of 78.6% water, 17.1% carbohydrates, 2.4% crude protein, 0.2% fat, 0.8% crude fiber, and 0.5% ash and it also provides 21 mg of calcium and 0.2 mg of iron per 100 g. However, its low micronutrient content contributes to widespread anemia and stunted growth, particularly among lactating women and children under 5 years of age, for whom Aceda constitutes a significant portion of their diet. Enhancing the nutritional profile of Aceda through biofortification is essential; however, ensuring consumer acceptance of the biofortified versions presents a challenge.

The hedonic scale is an essential method for measuring consumer preferences based on sensory attributes to facilitate nuanced product acceptance. Fiorentini et al. (2020) noted that consumer acceptability tests often use hedonic scales to evaluate enjoyment based on flavor and texture, and such an approach remains crucial for understanding overall product likability. This study evaluated the sensory and hedonic acceptance of Aceda prepared using biofortified and non-biofortified sorghum cultivars and identified the most suitable products for development and commercialization. This study aimed to link key sensory descriptors with consumer preferences using advanced sensory evaluation methods, thereby supporting the development of nutritionally enhanced Aceda products that align with culturally accepted preparation and consumption practices.

# 2 Materials and methods

## 2.1 Plant materials

Three sorghum cultivars, namely Wad Ahmed, Dabar, and Dahab, were used in this study. Wad Ahmed is a Feterita type II tannin sorghum cultivar classified as caudatum. It is widely used in Sudan to prepare Aceda (a thick, stiff porridge), and is known for its highly condensed tannin testa layer, which is rich in polyphenols. Dabar, an ancient cultivar of the tan plant, Type I (non-tannin) sorghum, is traditionally cultivated in the Gadareif region of Sudan and is commonly used to produce Kisra (flatbread) (AwadElkareem and Taylor, 2011). Dahab is a biofortified, high-yielding, creamy-seeded sorghum cultivar that contains 45 ppm Fe and 32 ppm Zn. Initially released in India in 2018 as Parbhani Shakti, developed through a collaboration between the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Vasantrao Naik Marathwada Krishi Vidyapeeth (VNMKV) in Maharashtra, India. It was officially released in Sudan in 2022 and provides an improved nutritional profile for combating micronutrient deficiencies.

According to El Hag et al. (2015), Wad Ahmed exhibited the highest levels of protein (14.40 ± 0.17%) and fat (4.07 ± 0.04%), along with fiber (3.39 ± 0.11%) and ash (1.71 ± 0.22%). Carbohydrate and starch contents were 76.19 ± 0.36% and 68.61 ± 0.44%, respectively. As reported by AwadElkareem and Taylor (2011), Dabar had a comparable protein content (10.50 ± 0.91%) but slightly higher carbohydrate content (74.43 ± 0.06%). Dabar also contained 3.09 ± 0.16% fat, 1.81 ± 0.14% fiber, 1.60 ± 0.50% ash, and 7.50 ± 0.98% moisture. The biofortified cultivar Dahab contained 10.38% protein, 71.02% carbohydrates, 1.8% fat, 1.2% crude fiber, 1.46% ash, and 8.2% moisture (Sawant, 2020). All grain samples were obtained from the Al-Gadarif Research Station of the Agricultural Research Corporation (ARC), Sudan. The selected cultivars represent a diverse range of genetic, sensory, and nutritional characteristics.

## 2.2 Porridge preparation

To prepare the porridge, sorghum grains were first thoroughly cleaned to remove any broken seeds or impurities, ensuring a consistent and high-quality flour. The cleaned grains were then milled using a commercial stone grinder to produce whole-grain flour. This flour was stored in plastic bags, kept in a cool, dry place, and used within one week of milling to preserve freshness and quality. Five Aceda samples were prepared for the study. Three were made from single-cultivar flours, Dabar, Dahab, and Wad Ahmed, while two additional samples were formulated using equal-weight blends of Dahab with Wad Ahmed, and Dahab with Dabar, respectively, each at a 1:1 ratio.

Fermented dough (Ajin) was prepared following the method described by Abdelrahim et al. (2016), where a portion of previously fermented dough was mixed with fresh flour and water. This Ajin was then added to boiling water at a 1:10 (v/v) ratio to act as a starter. Subsequently, flour was gradually incorporated at a 1:2 (w/v) flour-to-water ratio, while stirring continuously with a wooden spatula until a smooth, homogenous texture was achieved.

The porridge mixture was then boiled for five minutes, with continuous stirring, until it thickened and reached the traditional stiff consistency typical of Sudanese Aceda. After cooking, the porridge was portioned into approximately 50-gram servings using plastic containers, allowed to cool for 10 min, sealed, and maintained at a temperature of 35–40°C in preparation for sensory evaluation.

## 2.3 Panelist training

A four-hour training session was conducted at the conference hall of the Al-Gadareif Research Station, Agricultural Research Corporation (ARC), Al-Gadareif State, Sudan. The session aimed to equip semi-trained panelists with the skills necessary to conduct practical sensory evaluations. The panelists confirmed that they were well-aligned with the study's target population. The selection process also ensured diversity in gender, age, and educational background. A total of 28 panelists aged 25–65 years were recruited, with a balanced distribution of male and female participants. Educational levels varied from secondary school to postgraduate qualifications (see Table 1 for details).

The interactive session started with a theoretical overview of sensory assessment principles and objectives, emphasizing their crucial role in evaluating the quality of indigenous sorghum-based stiff porridge and informing product development. This foundational knowledge was reinforced through practical exercises designed to enhance sensory evaluation skills (Kemp et al., 2011).

Sensory awareness has been developed through attribute identification exercises, such as distinguishing between varying levels of sweetness or saltiness in food samples (Schamarek et al., 2024).

TABLE 1 Demographic profile of the assessors ($N$ = 28).

| Variables | Categories | Frequency | % |
|---|---|---|---|
| Gender | Female | 15 | 53.6 |
| | Male | 13 | 46.4 |
| Education levels | Secondary | 15 | 53.6 |
| | Bachelor | 10 | 35.7 |
| | Master | 3 | 10.7 |
| Age | 25–35 | 7 | 25.0 |
| | 36–45 | 6 | 21.4 |
| | 46–55 | 9 | 32.1 |
| | 56–65 | 6 | 21.4 |

Triangle tests have also been used to train panelists to detect subtle differences between similar samples, thereby sharpening their ability to discriminate (Sinkinson, 2017). Additional exercises focused on flavor recognition, requiring participants to identify specific species or herbs (Palmay-Paredes et al., 2023), as well as texture assessments, such as comparing the crispness of apples or the softness of bread (Chen and Opara, 2013).

## 2.4 Sensory evaluation method

The sensory evaluations were conducted in a controlled environment to ensure consistency and reliability. Approximately 50 g of the porridge samples were served in plastic containers covered with aluminum foil and labeled with randomized three-digit codes to maintain anonymity and prevent bias. The samples were kept at a constant temperature, and panelists were provided with water to rinse their mouths between samples, minimizing sensory carry-over effects as per (Ríos, 2024). Uniform service conditions, including standardized sample sizes and environmental controls, were maintained throughout the evaluation.

## 2.5 Descriptive sensory evaluation

Descriptive sensory profiling was conducted at the Al-Gadarif Research Station by 28 assessors who regularly consumed sorghum and/or millet porridge. The panelists evaluated sensory attributes, including appearance, color, aroma, cohesiveness, firmness, taste, mouthfeel, and texture, using descriptive analysis based on a 9-point quantitative line scale. The scores ranged from 1 (lowest intensity) to 9 (highest intensity) for each attribute.

## 2.6 Statistical analysis

All statistical analyses were performed using XLSTAT (Addinsoft 2024, https://www.xlstat.com/en/) and its sensory analysis packages to evaluate the five sorghum porridge products comprehensively. Hedonic scores were analyzed using the "Like Analysis" feature (Fliedel et al., 2022) and internal preference mapping was applied to validate the clustering results and visualize panelist preferences (Fernández-Vázquez et al., 2018). Demographic factors were linked to hedonic scores using an intelligence pivot table, which provided insight into how demographic factors influenced preferences.

Agglomerative hierarchical clustering grouped panelists based on preference patterns, whereas descriptive analysis identified sensory descriptors that distinguished the products (Bugaud et al., 2022). Product characterization was conducted according to the method of Dijksterhuis (1995). To evaluate the panelist consensus, individual deviations, and contributions to the overall evaluation, the STATIS method (*Structuration des Tableaux à Trois Indices de la Statistique*) was employed to identify shared patterns and deviations across the assessor responses (Tenenhaus et al., 2005). To further explore and visualize the relationships between sensory descriptors and product characterization, Principal Component Analysis (PCA) was used to reduce data dimensionality and uncover key sensory dimensions (Vidal et al., 2020). Additionally, Partial Least Squares Regression (PLSR) was applied to explore the relationships between sensory descriptors and product characteristics. PLSR is particularly effective in identifying the sensory characteristics that are most predictive of consumer acceptance (Tenenhaus et al., 2005), thus informing product optimization and commercialization strategies.

# 3 Results

## 3.1 Assessor's demographic profile

A total of 28 assessors participated in the sensory evaluation of the Aceda samples. Among them, 15 were women (53.6%) and 13 were men (46.4%). Regarding education level, 15 assessors (53.6%) had completed secondary school, 10 assessors (35.7%) held bachelor's degrees, and three assessors (10.7%) held master's degrees (Table 1). The age distribution ranged from 25 to 65 years, with the largest group being those aged 46 to 55 (9 assessors, 32.1%), followed by the 25 to 35 years category (7 assessors, 25%). The 36–45 and 56–65 years age groups had equal numbers of assessors (6 assessors, 21.4%) (Table 1).

## 3.2 Overall hedonic-liking

Among all assessors, Aceda prepared from the biofortified sorghum cultivar Dahab and Dahab + Wad Ahmed blend received the highest overall liking scores (7.18), significantly surpassing those of Aceda made from Dabar and Dahab + Dabar blend. Aceda, prepared by Wad Ahmed alone, received a moderate score (6.71).

Based on agglomerative hierarchical clustering of individual preference data, the 28 assessors were classified into two distinct segments: Group 1 (11 assessors) and Group 2 (17 assessors), as illustrated in Figure 1. For Group 1 assessors, Aceda prepared from Dahab received the highest preference score (7.64), which was significantly higher ($p < 0.001$) than that of all the other Aceda samples. The lowest preference score was recorded for Aceda, prepared by Wad Ahmed. Aceda prepared using Dabar and the Dahab + Dabar blend had similar liking scores (approximately 6.3).

In Group 2, the highest preference score was observed for Aceda made from the Dahab + Wad Ahmed blend, whereas the lowest score was observed for the Dahab + Dabar blend. Aceda made from the sorghum and/or Dahab + Wad Ahmed blend was significantly ($p < 0.001$) preferred over Aceda made from the Dabar, Dahab, and Dahab + Dabar blends (Table 2). This high preference score for the Dahab + Wad Ahmed blend, and to a lesser extent for Dahab alone, may be attributed to the successful masking of any unfamiliar sensory attributes of the biofortified cultivar through blending with a familiar local variety. This strategy likely enhanced cultural acceptability, overcoming initial resistance by aligning the product more closely with traditional flavor expectations.

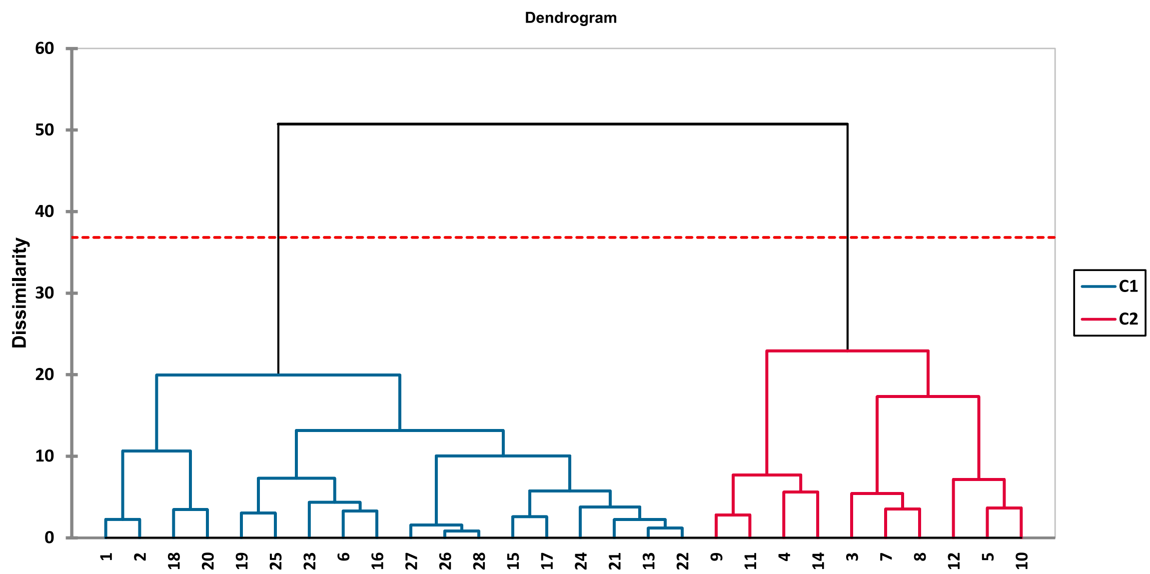


FIGURE 1
Cluster analysis of assessors using agglomerative hierarchical clustering (AHC) based on euclidean distance, grouping panelists into two distinct clusters according to their overall liking scores.

TABLE 2 One-way ANOVA of overall liking scores for five porridge products from sorghum cultivars and blends by assessors and cluster groups.

| Product | All assessors | Group 1 | Group 2 |
|---|---|---|---|
| Dabar | 6.11B | 6.27B | 6.00C |
| Wad Ahmed | 6.71AB | 5.73B | 7.35AB |
| Dahab | 7.14A | 7.64A | 6.82 BC |
| Dahab+Dabar | 6.04B | 6.36AB | 5.82CD |
| Dahab+Wad Ahmed | 7.18A | 6.00B | 7.94A |
| F | 6.46 | 7.34 | 14.69 |
| Pr > F | <0.0001 | <0.0001 | <0.0001 |
| *p*-values signification | *** | *** | *** |

Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 <. < 0.1 < ° < 1.

## 3.3 Assessor segmentation and internal preference mapping

The agglomerative hierarchical clustering analysis identified two main clusters: C1 (blue), 11 assessors; and C2 (red), 17 assessors. The assessors in Cluster 1 displayed greater homogeneity, as indicated by the more compact and flatter cluster structure compared to those in Cluster 2 (Figure 1).

Across all assessors, the biplot of internal preference mapping, based on the principal component analysis (PCA) for the sensory evaluation of five sorghum porridge products, showed that the first two principal components (F1 and F2) accounted for 67.43% of the total variation, with F1 explaining 42.78% and F2 explaining 24.65% of the variance (Figure 2A). The Aceda prepared from Dahab was positioned in the upper-right quadrant, indicating the strongest positive association with F2 (4.77) and favorable loading on F1 (1.18), indicating strong overall liking from assessors aligned with these factors. Aceda, made from the Dahab + Wad Ahmed blend, was situated near the center right, demonstrating a strong positive association with F1 (3.96) and a slight negative loading on F2, reflecting a balance preference. Aceda made by Wad Ahmed appeared in the lower-right quadrant, showing a strong positive alignment with F1 (3.01) but a negative association with F2 (−3.31). In contrast, Acedas prepared from the Dabar and Dahab + Dabar blends were negatively correlated with both F1 and F2, indicating the least preference among all assessors (Figure 2A). These results indicated that Cluster 2 (C2), representing a larger and more diverse group of assessors, showed stronger preferences for Dahab and its blend with Wad Ahmed, while Cluster 1 (C1) showed more specific and conservative preferences, favoring individual cultivars such as Dahab. For Group 1, the biplot illustrated that the first two principal components, F1 and F2, contributed 70.81% of the total variation, with F1 explaining 45.49% and F2 accounting for 25.32% (Figure 2B). Aceda, made from Dahab, located in the far upper-right quadrant, demonstrates a stronger positive association with F1 than F2 (2.14), indicating the highest preference among assessors. However, Aceda, made by Wad Ahmed, which was located in the far upper left quadrant, demonstrated a positive association with F2 (1.82) and a strong negative association with F1 (−3.6), indicating mixed perception. Aceda made from Dabar displayed slight negative loadings on F1 (−0.61) and F2 (−1.45), revealing a lower preference than that of Dahab. Aceda, made from the Dahab + Dabar blend, placed in the lower-left quadrant, exhibited negative associations with F2 (−1.90) and a slightly favorable loading on F1 (0.70), demonstrating low overall acceptance. Similarly, the Dahab + Wad Ahmed blend, which appeared near the center, showed a slight positive association with F1 (0.16) and a negative correlation with F2 (−0.61), indicating a moderate but balanced preference (Figure 2B). This indicated that Group 1 strongly favored the biofortified cultivar Dahab on its own, while other samples received mixed or lower levels of acceptance.

For Group 2, Figure 2C shows that the first two principal components, F1 and F2, accounted for 81.20% of the total variation, with F1 explaining 55.72%, and F2 accounting for 25.48%. Aceda prepared from the Dahab + Wad Ahmed blend showed a strong positive association with F1 (3.80) and a favorable loading on F2 (0.91), demonstrating the highest preference among all samples. Similarly, Aceda prepared by Dahab, located in the upper-right quadrant, displayed slightly positive loadings on F1 (1.20) and F2 (0.40), indicating a moderate preference among assessors aligned to these components. However, Aceda, made by Wad Ahmed, appeared in the lower-right quadrant with a strong positive association with F1 (2.26), demonstrating a higher preference among assessors aligned with F1. In contrast, Aceda prepared using Dabar and the Dahab + Dabar blend showed negative associations with F1 and F2, lower preference scores, and a limited appeal (Figure 2C). These findings reveal that Group 2 had a clear preference for the blended formulation of Dahab + Wad Ahmed. The contribution and percentage of demographic factors to overall liking scores.

The results from the intelligence pivot table indicated that age was the most significant factor, with a contribution value of 100, accounting for 61.56% of the total variation in sensory preferences among assessors. Gender was the second most influential factor, with a contribution value of 36.0 and a percentage of 22.16%. Education was the least influential factor with a contribution value of 26.46%, accounting for 16% of the total variation among assessors (Figure 3A).

## 3.4 Product characterization analysis

Product characterization analysis indicated that six out of the eight tested descriptors significantly influenced the sensory preferences of the assessors when discriminating against the Aceda product samples (Figure 3B). Among these, color displayed the highest discriminating power (4.91) with a $p$-value of 0.001, followed by firmness with a test value of 3.96, and mouthfeel (3.38, p-value 0.000). In addition, cohesiveness (test value: 3.01, $p = 0.001$) and appearance (test value: 2.89, $p = 0.002$) displayed significantly moderate positive discriminating power. Texture showed the least significant positive discriminating power for sensory preference, with a test value of 2.61 and a p-value of 0.005. Conversely, neither aroma nor taste had discriminating power over the sensory preferences of the five Aceda products (Figure 3B).

Table 3 presents the adjusted means for each combination of product and sensory descriptors, with blue indicating that the means had positive discrimination ability and red indicating a negative discriminability for the Aceda product samples. Among the five Aceda products, Dabar displayed mixed performance, with favorable scores for appearance (8.0), aroma (7.1), color (7.9), and mouthfeel, indicating excellent appeal. However, it showed negative

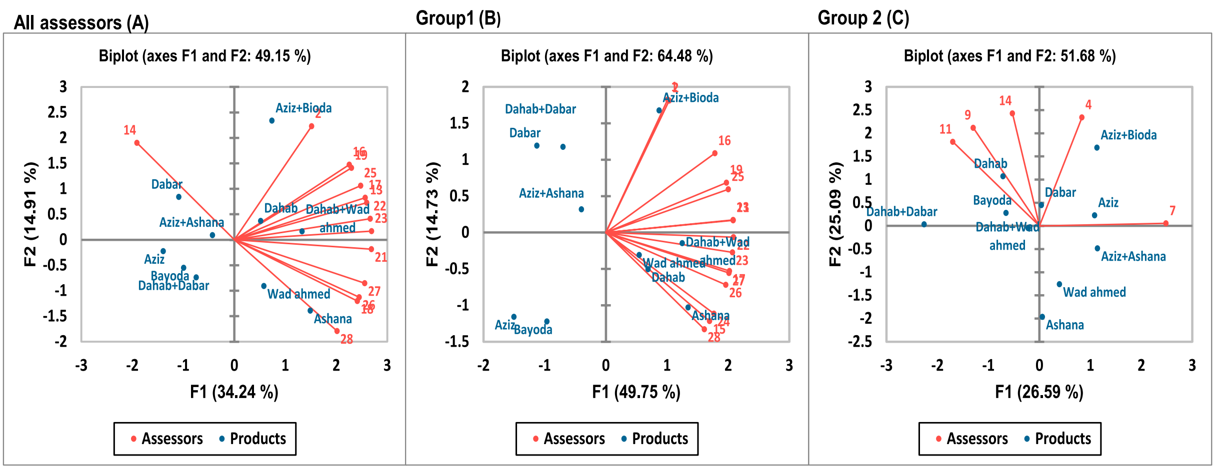


FIGURE 2
Internal preference mapping (IPM) of porridge products and assessor preferences: **(A)** All assessors combined, **(B)** Group 1, and **(C)** Group 2.

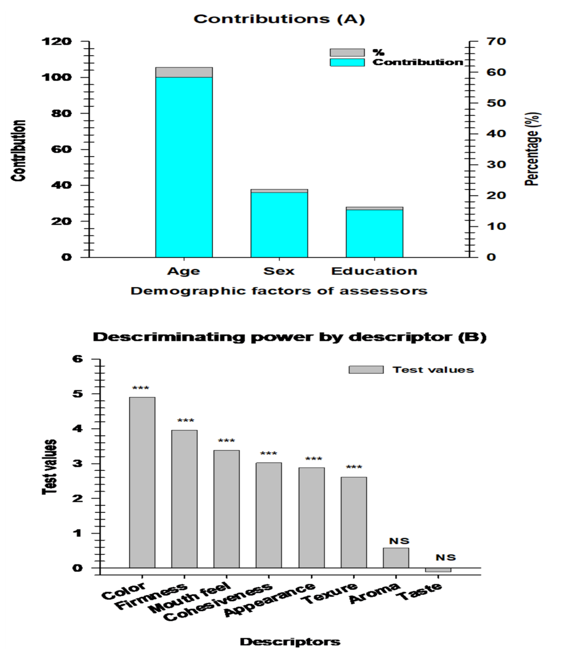


FIGURE 3
Contribution and percentage of demographic factors to overall liking scores **(A)** and discriminating power by descriptor **(B)**.

discriminability for firmness, texture, cohesiveness, and taste, indicating poor textural and firmness attributes (Table 3).

Aceda, made from Dahab, received positive preferences for nearly all descriptors. It received the highest preference scores for color (8.32) and appearance (8.18), indicating a better visual appeal and overall performance across all descriptors. In contrast, Aceda, made from the Dahab + Dabar blend, received negative scores for most descriptors, including firmness, texture, cohesiveness, taste, mouthfeel, and aroma. However, it recorded positive scores for color and appearance, revealing its strengths in terms of visual appeal despite its poor performance in other sensory descriptors (Table 3).

Porridges made from Wad Ahmed and Dahab + Wad Ahmed blends displayed positive preference scores across all descriptors. Nevertheless, they had negative aroma, color, and appearance scores; thus, these visual and aromatic attributes did not enhance their sensory preferences. Interestingly, the Dahab + Wad Ahmed blend received strong positive scores for mouthfeel (7.5) and firmness (7.29), emphasizing the potential merits of these attributes. Similarly, Aceda prepared exclusively, Wad Ahmed showed strong sensory performance in terms of cohesiveness (7.43) and firmness (7.36), highlighting its merits in these areas (Table 3).

Figure 4 shows the sensory profiles of the Aceda products, with the first two principal components, F1 and F2, accounting for 92.45% of the total variance, with F1 having an eigenvalue of 4.57, explaining 76.20%, and F2 with an eigenvalue of 0.98, contributing 16.25%. All the tested Aceda products, except for Dahab, were positively correlated with F1. Dahab + Dabar exhibited the highest squared cosine (0.94) for F1. Wad Ahmed and its blend with Dahab had a similar square cosine (0.87). Dabar recorded the lowest square-cosine value (0.53) for F1. Conversely, Aceda prepared solely from Dahab displayed a dominant square cosine value for F2 (0.97), implying that F2 primarily accounted for its sensory profile (Figure 4).

Table 4 shows the squared cosines ($Cos^2$) of five porridge products related to the first four principal components (F1–F4), which were obtained from the PCA of the sensory data. The Dabar distribution was mostly represented by F1 (0.533) and somewhat represented by F3 (0.453). The Dabar distribution is primarily represented by F1 (0.533) and moderately represented by F3 (0.453). Dahab strongly aligns with F2 (0.967). Dahab+Dabar, Dahab+Wad Ahmed, and Wad Ahmed are predominantly associated with F1, with $Cos^2$ values of 0.940, 0.872, and 0.878, respectively. The first two components capture most variance across products.

## 3.5 Partial least squares regression analysis

Partial least squares (PLS) regression analysis was performed to evaluate the impact of the sensory descriptors (y variables) on the overall liking scores and acceptability of Aceda products derived from

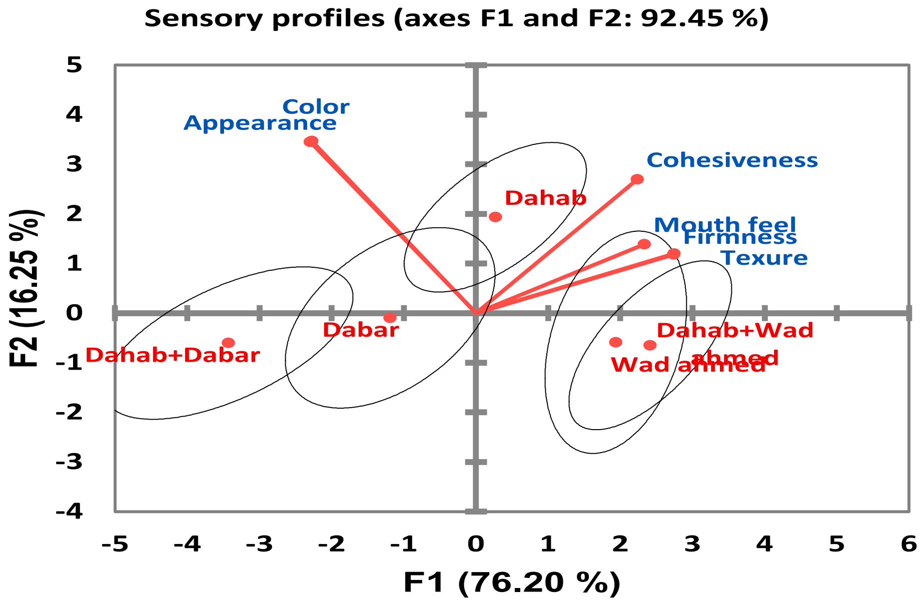


FIGURE 4
Biplot of sensory profiles of porridge products based on Principal Component Analysis (PCA) of the product-descriptor contingency table.

TABLE 3 Adjusted means for each combination of porridge product characteristics.

| Products | Firmness | Texture | Cohesiveness | Taste | Mouth feel | Aroma | Color | Appearance |
|---|---|---|---|---|---|---|---|---|
| Dabar | 6.14 | 6.46 | 5.75 | 6.82 | 7.29 | 7.14 | 7.86 | 7.96 |
| Dahab | 7.04 | 7.07 | 7.46 | 7.39 | 7.25 | 7.64 | 8.32 | 8.18 |
| Dahab+Dabar | 5.32 | 5.93 | 5.68 | 6.82 | 5.82 | 6.89 | 8.25 | 8.14 |
| Dahab+Wad Ahmed | 7.29 | 7.29 | 6.71 | 7.14 | 7.50 | 7.00 | 6.79 | 7.18 |
| Wad Ahmed | 7.36 | 7.25 | 7.43 | 7.32 | 7.29 | 6.89 | 6.29 | 7.14 |

Blue corresponds to coefficients with significantly positive values, and red corresponds to coefficients with significantly negative values.

TABLE 4 Squared cosines ($Cos^2$) of porridge products concerning principal components from PCA.

| Products | F1 | F2 | F3 | F4 |
|---|---|---|---|---|
| Dabar | **0.533** | 0.003 | 0.453 | 0.011 |
| Dahab | 0.019 | 0.967 | 0.014 | 0.000 |
| Dahab+Dabar | **0.940** | 0.029 | 0.030 | 0.000 |
| Dahab+Wad Ahmed | **0.872** | 0.080 | 0.027 | 0.021 |
| Wad Ahmed | **0.878** | 0.063 | 0.051 | 0.008 |

Values in bold correspond for each observation to the factor for which the squared cosine is the largest.

the three sorghum cultivars and their blends. Based on their sensory attributes, the PLS model identified three distinct clusters of the Aceda samples. Dahab is located in the upper-right quadrant. Wad Ahmed and its blend with Dahab are located in the lower-right quadrant. Dabar and its blend with Dahab are depicted in the lower-left quadrant. However, Aceda prepared using the Dahab + Wad Ahmed blend was the most favorable, highlighting its potential as an indigenous fortified meal to overcome micronutrient deficiencies. Moreover, the model proposed that texture and firmness were critical attributes influencing Component 1, whereas appearance and color were more influential in Component 2 (Figure 5).

## 3.6 STATIS analysis

Figure 6 presents a two-dimensional map derived from STATIS analysis of the five Aceda product samples, illustrating their sensory proximity. The Dahab and Dahab + Dabar blends were placed close together. However, the Dabar sample was placed on the opposite side of the map, indicating a sensory profile distinct from that of Dahab-based blends. Wad Ahmed is located separately from Dahab + Wad Ahmmed blend, and the Wad Ahmed sample was located far from the Dabar sample (Figure 4).

The weights assigned to the 28 assessors ranged from 0.142 (24 assessors) to 0.213 (16 assessors), with an average of 0.188. Assessors 24, 4, and 9 displayed weights below 0.160, indicating less alignment with the consensus and categorizing them as atypical. In contrast, nine assessors (11, 1, 17, 26, 15, 6, 23, 27, and 16) demonstrated high alignment, with weights exceeding 0.200. The remaining 16 assessors were classified into the moderate alignment category weighted from 0.160–0.200 (Figure 7A).

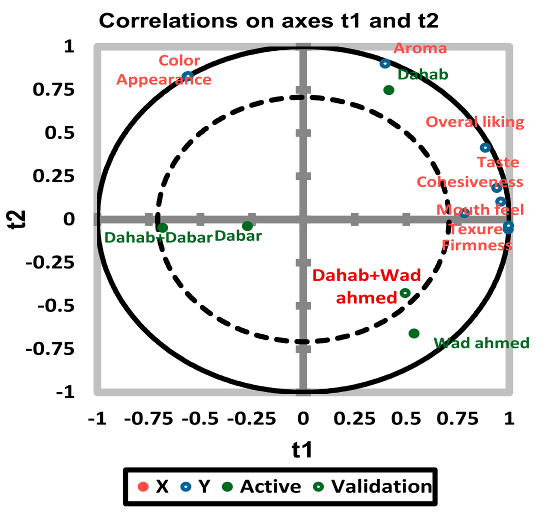


FIGURE 5
Biplot representing Partial Least Squares Regression (PLSR) derived from the contingency table of porridge products and sensory descriptors.

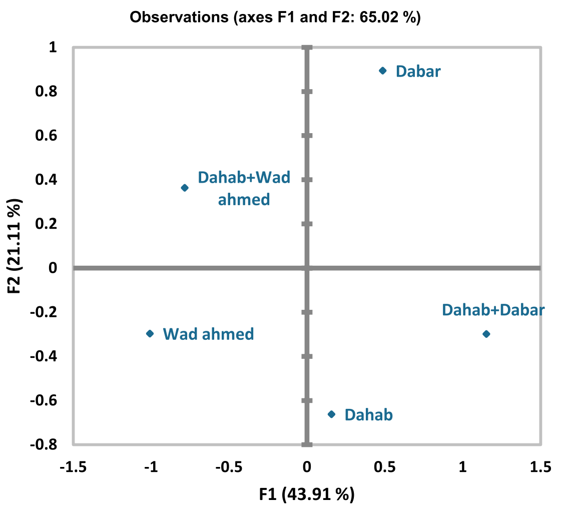


FIGURE 6
Proximity of Aceda product samples on a 2-dimensional map derived from the STATIS analysis.

The results from the STATIS analysis involving 28 semi-trained assessors showed that the RV coefficients measured the similarity between each assessor's configuration, and the consensus configuration ranged between 0.572 (assessor 24) and 0.857 (assessor 16), with an average of 0.755 (Figure 7B). Assessors 4, 8, and 9, with RV coefficients less than or equal to 65, exhibited low similarity to the consensus, revealing clear deviations. By contrast, assessors 6, 11, 14, 15, 16, 17, 23, 26, and 28 showed high similarity (RV $\geq$ 0.80), indicating substantial agreement with the overall consensus. The remaining 16 assessors showed moderate similarity, with RV coefficients between 0.65 and 0.80 (Figure 7B).

In the context of the STATIS analysis, the residuals for the 28 assessors ranged from 0.265 (assessor 16) to 0.672 (assessor 24), with an overall mean of 0.423. The residuals were inversely related to both the weight and RV coefficients. This indicated that assessors with low residuals were similar to the consensus configuration, indicating substantial agreement with the group's overall perception (Figure 7C). The residuals of the Aceda products varied from 2.232 for Dabar to 2.603 for Wad Ahmed, with a mean of 2.370. The remaining three Aceda products showed similar residuals, indicating that the assessors similarly placed these products (Figure 7D).

# 4 Discussion

Sorghum stiff porridge (Aceda), a traditional staple food widely consumed across many regions in Sudan, holds great potential for delivering micronutrient-fortified foods. Beswa et al. (2020) emphasized that biofortified stiff porridge made from yellow maize endosperm can provide significant micronutrients and provitamin A to targeted consumers, although its sensory acceptance remains unexplored. Therefore, evaluating the sensory acceptance of biofortified and non-biofortified sorghum Aceda is crucial for its adoption, as consumer preferences play a pivotal role in governing dietary choices and nutritional outcomes.

In this study, five Aceda products, including those made from the biofortified sorghum and/or cultivar Dahab, were evaluated by 28 semi-trained assessors using descriptive sensory analysis. Eight sensory attributes were identified during the focus group discussion and were subsequently assessed. The overall liking scores were captured using a widely adopted 9-point hedonic scale for food acceptability. This study compared biofortified sorghum porridge (high Fe and Zn) with non-biofortified local sorghum cultivars.

Our original statement acknowledged the general challenge of achieving consumer acceptance for biofortified versions of culturally traditional foods like Aceda. However, the observed high liking scores for Aceda made from the biofortified cultivar Dahab and its blend with Wad Ahmed demonstrate that this challenge can be overcome when the sensory profile of the biofortified product aligns well with consumer expectations. In this case, the blending strategy likely helped to retain familiar organoleptic qualities while enhancing the nutritional value, thereby facilitating acceptance. This finding does not negate the initial hypothesis but rather highlights a successful outcome within its framework, showing that acceptance is possible through thoughtful cultivar selection and blending. The result aligns with the findings of Awobusuyi et al. (2016), who reported that a high level of consumer preference for provitamin-A biofortified Amahewu, attributing most of the variation to the maize cultivar rather than the fermented method. Similarly, our study underscores the importance of sensory-oriented breeding and formulation strategies as key enablers of consumer acceptance in biofortification programs. These insights support the development of culturally acceptable, nutritionally enhanced food products and offer a pathway to address hidden hunger without compromising traditional preferences.

In contrast, Beswa et al. (2020) noted that biofortified maize porridge exhibited undesirable sensory attributes, such as bitterness, stickiness, smoothness, and high-intensity residual grains, negatively impacting its acceptability compared to white maize porridge. This study highlights the urgent need to improve the acceptance of provitamin A-biofortified maize through recipe refinement and nutritional education. Govender et al. (2019) further demonstrated

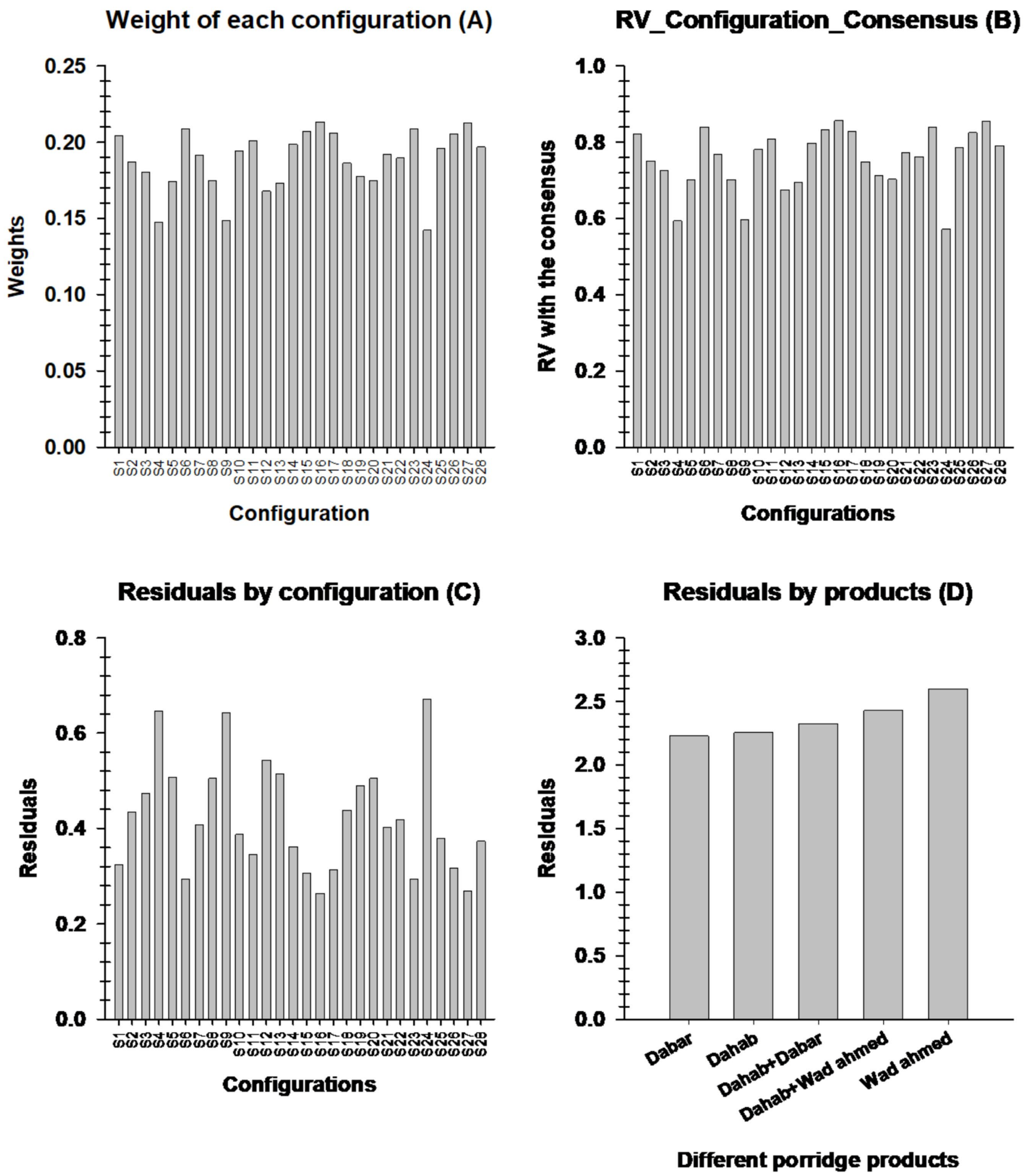


FIGURE 7
Weight of each assessor **(A)**, RV between each assessor (configuration) and the consensus **(B)**, residuals by the assessor **(C)**, and residuals of porridge products **(D)** derived from the STATIS analysis package in XLSTAT statistical software.

that pairing provitamin A-biofortified maize porridge with chicken stew significantly enhances its acceptability. Therefore, future studies should explore strategies to increase acceptance of biofortified sorghum cultivars before large-scale dissemination.

Cluster analysis identified two distinct groups with specific preferences: Group 1 favored the Aceda made from Dahab, whereas Group 2 preferred the Dahab + Wad Ahmed blend. This variation in sensory perception provides valuable insights for targeted product development, validated through internal preference mapping using principal component analysis. Using agglomerative hierarchical clustering (AHC) to segment assessors by overall liking scores is crucial for identifying market segments and tailoring products to diverse Aceda consumer needs.

These results agree with those reported by Swegarden et al. (2019), who employed cluster analysis to link consumer hedonic scores with a descriptive lexicon of 44 sensory attributes in the Kale germplasm. They identified four consumer clusters that bridge sensory evaluations with the breeding and selection of new Kale varieties. Understanding the importance of sensory attributes and consumer perceptions enables plant breeders to prioritize these traits and guide future breeding efforts. This provides a framework for targeted product formulation for specific market segments.

Our results indicate the potential integration of internal preference mapping (PCA-based) AHC to visualize the relationships between consumer preferences and Aceda product samples. This approach enhances the design of biofortified Aceda products by aligning the offerings with consumer expectations, thereby boosting satisfaction and market success. Anuar and Othman (2020) emphasized that involving end users early in product design can significantly improve product quality, relevance, and loyalty.

Among the demographic factors influencing sensory preferences for Aceda samples, age accounted for 62% of the variation, highlighting its critical role in consumer acceptance and market appeal. This aligns with the findings of Mahboob et al. (2020) and Razzaq et al. (2021), who identified age as a key factor in the sensory preferences for biofortified crops. Younger consumers are more open to new foods than older generations tend to favor traditional meals. Similarly, Bechoff et al. (2018) found that younger consumers in South Africa were more likely to accept biofortified cassava-based products, such as Eba and Fufu, owing to their dietary benefits. Kwak et al. (2017) also observed age-specific sensory differences in preferences for traditional Korean fermented soybean paste, emphasizing the importance of age-targeted consumer acceptance tests.

Product characterization analysis indicated that color, firmness, and mouthfeel significantly influenced preferences, highlighting the strong discrimination potential of Aceda. Porridge formulations with appealing colors are preferred because visual appeal often signifies quality and safety, especially in traditional contexts (Kayitesi et al., 2010; Moussa et al., 2011). West African consumers prefer white or light-colored sorghum and millet porridge because they are associated with freshness and quality. However, owing to perceived health benefits, Sudanese rural consumers often favor red sorghum porridges, Koja, and Benicarboo, which are made from tannin-rich Feterita sorghum. In contrast, urban consumers tend to prefer white porridges. These findings highlight the importance of evaluating the interaction between sorghum genotypes (including biofortified Dahab) and regional consumer preferences, with attention to gender and locality.

Partial least squares regression analysis revealed that texture and firmness were the key factors influencing overall liking. These differences were primarily attributed to the sorghum cultivars used, as all samples were processed using the same standardized method. This aligns with Kayitesi et al. (2010), who reported that the firmness and texture of Marama/sorghum composite porridge are influenced by sorghum cultivar., processing methods, and added ingredients. Similarly, Mukisa et al. (2012) showed that fermentation with specific Lactobacillus strains significantly improves the rheological and sensory properties of sorghum porridge. Fermentation enhances these attribute sets by promoting hydrolysis and pre-gelatinization, which breaks down complex biopolymers into shorter chains, reducing their thickness and stickiness (Makame et al., 2019).

Our findings showed that Aceda made from the Feterita sorghum cultivar Wad Ahmed exhibited greater firmness and texture than those made from Dahab and Dabar. The superior textural and mouthfeel attributes of Wad Ahmed can be attributed to its high carbohydrate content, which serves as an excellent substrate for lactic acid fermentation, resulting in an enhanced texture and firmness. The favorable sensory performance of the Wad Ahmed cultivar may be linked to its compatibility with indigenous microflora commonly involved in Sudanese fermentation. Previous studies have shown that certain sorghum genotypes interact effectively with lactic acid bacteria and yeasts, enhancing flavor and texture (Pranoto et al., 2013; Zaroug et al., 2014). Although this interaction was not directly assessed, the high acceptability scores and traditional use of Wad Ahmed support its suitability for both traditional and modern food applications, warranting further research on genotype–microflora interactions.

Our findings indicate that aroma and taste had a minimal influence on the overall liking scores and preference for Aceda samples. This observation is consistent with the findings of Onyango et al. (2020), who noted that hydrothermal treatment significantly masks the aroma of finger millet porridge. Similarly, Makame et al. (2019) reported that hydrothermal cooking of rice increases the abundance of furans, aldehydes, alcohols, and esters, while hydrocarbons and aromatics decrease. These results highlight the need to investigate aromatic compounds at different stages of Aceda production in various sorghum cultivars. Advanced omics techniques, particularly metabolomic profiling, offer promising approaches to unravel these complexities. In addition, applying analytical methods, such as Fourier Transform Mid-Infrared Transform Spectroscopy (FTIR), can deepen our understanding of aromatic and nutritional attributes, paving the way for the development of more appealing and nutrient-rich biofortified sorghum-based porridges.

Blending biofortified Dahab with non-biofortified Sudanese sorghum cultivars is a promising strategy for improving the nutritional profile of local Aceda while addressing sensory challenges. Product characterization revealed that Wad Ahmed had a poor appearance and color, whereas Dabar exhibited inferior sensory attributes despite its excellent visual appeal, particularly in terms of color and appearance. These limitations can be efficiently addressed through a three-part blend (Dahab: Wad Ahmed: Dabar), which combines the nutritional benefits of Dahab, the texture and firmness of Wad Ahmed, and the superior color of Dabar This approach aligns with findings by Hamid et al. (2025), where Kisra prepared from the biofortified Dahab and Daber cultivar achieved high consumer acceptability due to its sweetness, smoothness, and appealing porous texture, supporting its potential for enhancing traditional sorghum-based foods both nutritionally and sensorially.

The results of the PLS model demonstrated that the Dahab + Wad Ahmed blend was the most preferred, highlighting the feasibility of developing biofortified sorghum-based local foods to combat micronutrient deficiencies without compromising consumer preferences. In addition, incorporating other ingredients, such as legumes (Bambara groundnut, pigeon pea, and cowpea for protein enrichment) or cereals (biofortified pearl millet and yellow endosperm maize) could further enhance the sensory and nutritional properties.

## 5 Conclusion

Blending biofortified Dahab with non-biofortified Wad Ahmed and Dabar offers a promising approach for developing nutrient-rich Aceda with a broad consumer appeal. The Dahab + Wad Ahmed blend was preferred, highlighting its potential as a fortified local food to address micronutrient deficiency. Key sensory attributes, such as texture, firmness, and color, significantly influenced overall liking, whereas aroma and taste had a minimal impact. Further sensory and nutritional properties can be improved by incorporating complementary ingredients such as legumes and other cereals. This study provides a framework for designing biofortified sorghum products that align with consumer preferences while addressing critical nutritional challenges. Although Dahab performed well in this study, the challenge lies in achieving consistent consumer acceptance across diverse cultural contexts and sensory expectations, especially for biofortified crops that may differ in appearance or flavor from traditional varieties. Our findings show that strategic blending with familiar cultivars like Wad Ahmed can effectively mitigate this challenge, supporting nutritional goals and market adoption.

Considering these findings, future efforts should also focus on industrial-scale production and dissemination strategies for biofortified Aceda products. Public awareness campaigns and targeted consumer education programs are essential to promote the acceptance and adoption of these nutritionally enhanced foods, especially in rural and nutritionally vulnerable communities. Although the number of panelists ($N = 28$) was sufficient for semi-trained sensory evaluations and aligned with previous studies of a similar scale, it is important to acknowledge this as a limitation. Future studies could benefit from larger and more diverse consumer panels to enhance generalizability and explore regional or cultural variability in preferences.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by the National Health Research Ethics Committee at the Federal Ministry of Health, Sudan. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

MG: Data curation, Methodology, Writing – original draft. CB: Funding acquisition, Writing – review & editing. KM: Data curation, Methodology, Writing – review & editing. YI: Writing – review & editing. MH: Data curation, Methodology, Writing – review & editing. FM: Writing – review & editing. MR: Writing – review & editing. ME: Validation, Visualization, Writing – review & editing. TA: Visualization, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Supervision, Writing – original draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

## Publisher's note



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