

## Comparative Efficacy of Garlic Powder, Oil, and Paste as Natural Antioxidants for Improving Oxidative Stability and Sensory Quality of Hot-Smoked Fish

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**Abstract:** Hot-smoked fish products remain highly susceptible to lipid oxidation during storage, resulting in quality deterioration, off-flavour development, and reduced consumer acceptability. This study evaluated the comparative efficacy of garlic powder, garlic oil, and garlic paste as natural antioxidants for improving oxidative stability and sensory quality of hot-smoked fish. Fresh long croaker (*Pseudotolithus typus*) portions were hot-smoked and treated with garlic powder (2% w/w), garlic oil (1 mL/100 g), or garlic paste (5% w/w), while untreated samples served as the control. Samples were stored at ambient temperature ( $28 \pm 2^\circ\text{C}$ ) for 30 days and analyzed for pH, water-holding capacity (WHC), lipid oxidation using thiobarbituric acid reactive substances (TBARS), and sensory attributes. Garlic treatments significantly affected lipid oxidation ( $p = 0.001$ ). Garlic oil and garlic paste markedly reduced TBARS values to 3.43 and 3.22 mg MDA/kg, respectively, compared with the control (4.68 mg MDA/kg), whereas garlic powder recorded the highest TBARS value (7.81 mg MDA/kg). Garlic oil and paste also resulted in slightly lower pH values (6.43) compared with the control (6.57), while WHC was not significantly affected (62.22–66.67%,  $p = 0.339$ ). Sensory evaluation revealed significant differences among treatments ( $p < 0.001$ ), with garlic paste achieving the highest scores for flavour, texture, aroma, and overall acceptability (8.50), followed by garlic oil (7.00–8.00), garlic powder (6.50), and the control (5.00). The results demonstrate that garlic paste and garlic oil are effective natural antioxidants for controlling lipid oxidation and enhancing the

sensory quality of hot-smoked fish, with garlic paste showing the greatest overall efficacy. These findings support the use of garlic-based treatments as practical clean-label strategies for improving the shelf life and consumer acceptance of smoked fish products.

**Keywords :** Garlic preparations; lipid oxidation; TBARS; sensory quality; hot-smoked fish

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## 1.0 Introduction

Hot-smoked fish is widely consumed because smoking enhances flavour, reduces moisture content, and improves marketability. In Nigeria and other coastal countries, smoked

fish contributes significantly to daily protein intake, but up to 30–40% of smoked fish products may experience quality deterioration due to lipid oxidation during storage (Baten *et al.*, 2020). However, smoked fish products remain highly susceptible to lipid oxidation during storage, particularly because fish lipids contain large proportions of polyunsaturated fatty acids that are vulnerable to oxidative degradation. Lipid oxidation results in the formation of hydroperoxides and secondary oxidation products that generate rancid odours, off-flavours, nutrient losses, and progressive decline in consumer acceptability (Baten *et al.*, 2020; Mozzon, 2024). Although smoking contributes some antioxidative phenolic compounds, it does not provide sufficient protection against oxidative rancidity, especially during extended storage under ambient conditions.

Lipid oxidation is therefore recognized as one of the principal mechanisms of quality deterioration in smoked and stored fish products. Among available analytical tools, thiobarbituric acid reactive substances (TBARS) remain widely used for estimating secondary lipid oxidation products, particularly malondialdehyde, due to their practicality and sensitivity (Abeyrathne *et al.*, 2021). Nevertheless, recent studies emphasize that TBARS values should be interpreted alongside sensory evaluation, since chemical oxidation indices ultimately translate into sensory rejection and reduced consumer acceptance (Hao *et al.*, 2021; Pierozan *et al.*, 2024).

Growing concerns about the safety and long-term health implications of synthetic food preservatives have accelerated the search for natural, clean-label alternatives. Plant-derived antioxidants and essential oils have attracted considerable attention as natural preservation agents capable of slowing lipid oxidation and microbial spoilage in seafood products (Presenza *et al.*, 2023; Pierozan *et al.*, 2024). Evidence from experimental studies and reviews demonstrates that natural antioxidants can significantly delay oxidative

deterioration in fish and fish products when appropriately selected and applied (Hao *et al.*, 2021; Gökoglu, 2019).

In parallel, modern preservation strategies increasingly emphasize combining natural antioxidants with supportive technologies such as edible coatings, active packaging, and hurdle-based systems to enhance bioactive stability and effectiveness. Edible coatings and films help reduce oxygen transfer, retain antioxidant compounds, and maintain sensory quality during storage (Kurek *et al.*, 2024; Gürdal and Çetinkaya, 2024). Furthermore, active coating systems incorporating plant extracts or essential oils have been shown to reduce TBARS values and maintain sensory acceptability in fish fillets and other aquatic products (Albendea *et al.*, 2023; Pierozan *et al.*, 2024). Within this context, garlic (*Allium sativum*) represents a promising natural antioxidant because it contains organosulfur compounds such as allicin, diallyl sulfides, and ajoene, which exhibit both antioxidant and antimicrobial activities (Verma *et al.*, 2023; El-Saadony *et al.*, 2024). Garlic-based treatments have shown potential in reducing lipid oxidation and suppressing spoilage microorganisms in various food matrices, including muscle foods and seafood products (Sallam *et al.*, 2004; Kumolu-Johnson *et al.*, 2010; Ibrahim *et al.*, 2024). Recent reviews confirm garlic's suitability as a natural preservative due to its dual functionality (Noshirvani *et al.*, 2024; Sulieman *et al.*, 2023).

Importantly, garlic is commonly applied in different technological forms, including powder, oil, and paste. Garlic preparations—powder, oil, and paste—differ in moisture content, solubility, volatility, and bioactive compound stability, factors that influence their effectiveness in lipid-rich foods. Processing and formulation have been shown to strongly affect the availability and activity of plant-derived antioxidants, leading to variable preservation outcomes even when the same plant source is used (Ma *et al.*, 2023; Presenza *et al.*, 2023). Lipid-soluble antioxidants, such as essential oils, often



exhibit improved interaction with fish lipids and consequently stronger oxidative protection compared with dry powdered forms (Pierozan *et al.*, 2024).

For smoked fish products, natural antioxidant applications have demonstrated promising results. Propolis extracts, basil essential oil, rosemary oil, and clove oil have been reported to reduce TBARS values and improve sensory quality in smoked or processed fish products (Çoban and Patir, 2013; Gökoglu, 2019; Harmankaya *et al.*, 2024; Güngören *et al.*, 2023). Despite growing research on garlic as a natural preservative, comparative studies evaluating powder, oil, and paste in the same hot-smoked fish system are scarce, especially those linking chemical measures of oxidation with sensory quality. Therefore, this study aimed to evaluate the comparative efficacy of garlic powder, garlic oil, and garlic paste as natural antioxidants for improving oxidative stability and sensory quality of hot-smoked fish by assessing physicochemical properties, lipid oxidation (TBARS), and sensory attributes during storage. This approach provides practical evidence to guide processors in selecting the most effective garlic preparation for clean-label preservation of smoked fish products. The findings of this study will provide practical guidance for fish processors, enabling selection of the most effective garlic preparation to extend shelf life, preserve sensory quality, and meet consumer demand for clean-label products

## 2.0 Materials and Methods

### 2.1 Experimental Design

The experiment was conducted using a completely randomized design (CRD) with four treatments: control (no garlic), garlic powder, garlic oil, and garlic paste. Each treatment was prepared in triplicate, resulting in twelve experimental units. Each replicate consisted of one smoked fish portion and served as the experimental unit for physicochemical, oxidative, and sensory analyses.

### 2.2 Study Area

The study was carried out at the Fish Farm Estate, Odogunyan, Ikorodu, Lagos State, Nigeria. Laboratory analyses were conducted under standard food science laboratory conditions.

### 2.3 Sample Collection and Preparation

Fresh long croaker (*Pseudotolithus typus*) were obtained from artisanal fishermen at the Ikorodu fish landing site, Lagos State, Nigeria. Twelve (12) fish with an average weight of  $250 \pm 15$  g were used. Fish were washed with potable water, eviscerated, rinsed thoroughly, and cut into uniform portions of approximately 200 g.

#### 2.3.1 Smoking Procedure

Fish portions were hot-smoked using a traditional smoking kiln at  $70\text{--}80^\circ\text{C}$  for approximately 8 h until a uniform brown colour and desirable moisture reduction were achieved. Smoked samples were allowed to cool to ambient temperature before treatment application.

#### 2.3.2 Preparation and Application of Garlic Treatments

Garlic treatments were applied immediately after smoking, and dosages were standardized relative to fish weight. Control samples received no garlic treatment. For the garlic powder treatment, food-grade garlic powder was mixed with distilled water to form a slurry, which was evenly rubbed onto the fish surface at a rate of 2 g per 100 g smoked fish (2% w/w). In the garlic oil treatment, food-grade garlic oil was evenly brushed onto the surface at 1 mL per 100 g smoked fish. For the garlic paste treatment, fresh garlic cloves were peeled, washed, and blended into a smooth paste, which was then evenly spread over the fish at a rate of 5 g per 100 g smoked fish (5% w/w). The selected dosage levels were based on preliminary trials and previously reported effective ranges for garlic application in muscle foods.

#### Storage Conditions

All treated and control samples were stored at ambient temperature ( $28 \pm 2^\circ\text{C}$ ) for 30 days.

### 2.4 Physicochemical Analyses

#### 2.4.1 pH Measurement



The pH of each sample was measured using a calibrated digital pH meter. Measurements were taken at three different points on each sample, and the mean value was recorded.

#### 2.4.2 Water-Holding Capacity (WHC)

Water-holding capacity was determined using a gravimetric method. Approximately 5 g of each sample was weighed ( $W_1$ ), wrapped in filter paper, and centrifuged at 4000 rpm for 10 min. The sample was reweighed ( $W_2$ ) after centrifugation and the WHC was calculated using equation 1

$$\text{WHC (\%)} = \frac{W_2}{W_1} \times 100 \quad (1)$$

#### 2.4.3 Determination of Lipid Oxidation (TBARS)

Lipid oxidation was determined as thiobarbituric acid reactive substances (TBARS) following standard procedures. Approximately 5 g of homogenized sample was mixed with trichloroacetic acid solution and filtered. The filtrate was reacted with thiobarbituric acid reagent and heated in a water bath at 95°C for 30 min. After cooling, absorbance was measured at 532 nm using a spectrophotometer.

TBARS values were calculated as:

$$\text{TBARS (mg MDA/kg)} = \frac{A_{532} \times K}{W} \quad (2)$$

where  $A_{532}$  is absorbance at 532 nm,  $K$  is the conversion factor derived from the molar extinction coefficient of the malondialdehyde-TBA complex, and  $W$  is sample weight (kg).

#### 2.5 Sensory Evaluation

Sensory evaluation was conducted by a trained panel of ten (10) members familiar with smoked fish products. Samples were coded and presented in random order.

A nine-point hedonic scale was used:

- 1 = Dislike extremely,
- 2 = Dislike very much,
- 3 = Dislike moderately
- 4 = Dislike slightly
- 5 = Neither like nor dislike
- 6 = Like slightly
- 7 = Like moderately
- 8 = Like very much
- 9 = Like extremely

Panelists evaluated colour, flavour, texture, aroma, and overall acceptability. Drinking water was provided for palate cleansing between samples.

#### 2.6 Statistical Analysis

All data were expressed as mean  $\pm$  standard error of mean (SEM). Data were subjected to one-way analysis of variance (ANOVA). Differences among treatment means were separated using Tukey's post-hoc test. Statistical significance was established at  $p < 0.05$ .

### 3.0 Results and Discussion

#### 3.1 Results

##### 3.1.1 Physicochemical Properties and Lipid Oxidation

The effects of garlic powder, garlic oil, and garlic paste on pH, water-holding capacity (WHC), and lipid oxidation (TBARS) of hot-smoked fish are presented in Table 1.

Garlic treatments significantly affected the pH of smoked fish samples ( $p < 0.001$ ), with variations among treatments reflecting differences in garlic form and chemical composition. Garlic powder produced an intermediate pH value (6.50), which differed significantly from both the control and the oil/paste treatments. Garlic powder resulted in a moderate pH value (6.50), significantly different from both the control and the garlic oil/paste treatments. The control sample exhibited the highest pH value (6.57), while garlic oil and garlic paste treatments resulted in significantly lower pH values (6.43). Garlic powder produced an intermediate pH value (6.50), which differed significantly from both the control and the oil/paste treatments.

Water-holding capacity ranged from 62.22% to 66.67%. Although garlic-treated samples showed higher WHC values than the control, the differences among treatments were not statistically significant ( $p = 0.339$ ). This indicates that surface application of garlic preparations did not substantially alter water-binding properties of the muscle proteins. Lipid oxidation, expressed as TBARS (mg MDA/kg), differed significantly among



treatments ( $p = 0.001$ ). Garlic powder-treated samples recorded the highest TBARS value (7.81 mg MDA/kg), indicating greater oxidative deterioration. In contrast, garlic oil (3.43 mg MDA/kg) and garlic paste (3.22 mg MDA/kg) treatments significantly reduced TBARS values compared with the control (4.68 mg MDA/kg). This suggests that dehydration and processing of garlic powder may reduce its antioxidant effectiveness compared with oil and paste forms

### 3.1.2 Sensory Evaluation

Mean sensory scores for colour, flavour, texture, aroma, and overall acceptability of hot-smoked fish treated with different garlic preparations are shown in Table 2.

Significant differences were observed among treatments for all sensory attributes evaluated ( $p < 0.001$ ). Colour scores ranged from 4.00 to 7.00. Garlic powder-treated samples

received the lowest colour score (4.00), while the control and garlic oil treatments recorded the highest scores (7.00). Garlic paste produced an intermediate colour score (5.00). Similar trends were observed for flavour, texture, aroma, and overall acceptability. Garlic paste achieved the highest scores for flavour (8.50), texture (8.50), aroma (8.50), and overall acceptability (8.50). This may be attributed to the higher content of reactive sulfur compounds in fresh garlic paste, which enhance both flavour and aroma while reducing oxidative off-notes. Garlic oil ranked second with scores of 7.00 for flavour, texture, and overall acceptability, and 8.00 for aroma. Garlic powder exhibited moderate scores (6.50), while the control sample consistently recorded the lowest scores (5.00).

**Table 1 : Physicochemical Properties and Lipid Oxidation of Hot-Smoked Fish Treated with Different Garlic Preparations**

Parameter	Control	Garlic Powder	Garlic Oil	Garlic Paste	SEM	p-value
pH	6.57 <sup>a</sup>	6.50 <sup>b</sup>	6.43 <sup>c</sup>	6.43 <sup>c</sup>	0.02	<0.001
WHC (%)	62.22	66.67	65.56	66.67	0.96	0.339
TBARS (mg MDA/kg)	4.68 <sup>b</sup>	7.81 <sup>a</sup>	3.43 <sup>c</sup>	3.22 <sup>c</sup>	0.60	0.001

Values are means of three replicates (n = 3). Means within a row with different superscripts differ significantly ( $p < 0.05$ ).

**Table 2: Sensory Scores of Hot-Smoked Fish Treated with Different Garlic Preparations**

Attribute (9-point scale)	Control	Garlic Powder	Garlic Oil	Garlic Paste	SEM	p-value
Colour	7.00 <sup>a</sup>	4.00 <sup>c</sup>	7.00 <sup>a</sup>	5.00 <sup>b</sup>	0.41	<0.001
Flavour	5.00 <sup>c</sup>	6.50 <sup>b</sup>	7.00 <sup>b</sup>	8.50 <sup>a</sup>	0.36	<0.001
Texture	5.00 <sup>c</sup>	6.50 <sup>b</sup>	7.00 <sup>b</sup>	8.50 <sup>a</sup>	0.35	<0.001
Aroma	5.00 <sup>c</sup>	6.50 <sup>b</sup>	8.00 <sup>a</sup>	8.50 <sup>a</sup>	0.34	<0.001
Overall acceptability	5.00 <sup>c</sup>	6.50 <sup>b</sup>	7.00 <sup>b</sup>	8.50 <sup>a</sup>	0.33	<0.001

Values are means of ten panelists (n = 10). Means within a row with different superscripts differ significantly ( $p < 0.05$ )

The present study demonstrates that the effectiveness of garlic as a natural antioxidant in hot-smoked fish is strongly dependent on its form of application. Garlic paste and garlic oil significantly reduced lipid oxidation and

improved sensory quality compared with garlic powder and the untreated control, indicating that formulation plays a critical role in determining preservative efficacy. These findings support growing evidence that



plant-derived antioxidants can meaningfully retard oxidative deterioration in fish products when their physicochemical compatibility with the food matrix is optimized (Hao *et al.*, 2021; Presenza *et al.*, 2023; Pierozan *et al.*, 2024).

### 3.1.3 Effect of Garlic Treatments on pH and Water-Holding Capacity

The modest yet statistically significant reduction in pH observed for garlic oil and paste treatments suggests that these formulations influenced the chemical environment of the smoked fish. Lower pH values in processed fish products are frequently associated with improved shelf stability, as acidic conditions can suppress spoilage reactions and slow microbial and enzymatic activity (Mozzon, 2024). Similar modest pH reductions have been reported in fish treated with plant extracts and essential oils, without compromising sensory acceptability (Harmankaya *et al.*, 2024; Ibrahim *et al.*, 2024). The present results therefore indicate that garlic oil and garlic paste may contribute to preservation partly through pH-mediated effects.

Water-holding capacity was not significantly affected by garlic treatments, although slightly higher values were observed in garlic-treated samples. This indicates that the antioxidant treatments preserve muscle water retention while not negatively affecting texture or yield. This outcome is consistent with reports that surface-applied natural antioxidants and essential oils typically exert limited influence on protein–water interactions in muscle foods (Kurek *et al.*, 2024). From a processing perspective, this is advantageous because it indicates that garlic-based treatments can be applied without negatively affecting product yield or texture.

### 3.1.4 Garlic Form and Control of Lipid Oxidation

Lipid oxidation, as measured by TBARS, differed markedly among garlic forms. Garlic oil and garlic paste significantly reduced TBARS values compared with the control, whereas garlic powder produced the highest

TBARS level. These results highlight the importance of garlic formulation, as lipophilic and fresh preparations interact more effectively with fish lipids to prevent oxidation. These findings are consistent with extensive evidence that lipid-soluble antioxidants and essential oils provide superior oxidative protection in fatty food systems due to improved dispersion and interaction within lipid phases (Hao *et al.*, 2021; Pierozan *et al.*, 2024). Garlic oil likely exhibited enhanced antioxidant activity because its lipophilic organosulfur compounds readily partition into fish lipids, where oxidative reactions primarily occur.

Garlic paste demonstrated strong antioxidant performance, likely due to the higher content of reactive organosulfur compounds, including allicin and its derivatives. Fresh garlic preparations have been reported to contain higher levels of reactive sulfur compounds than dehydrated powders, resulting in stronger radical-scavenging activity (Verma *et al.*, 2023; El-Saadony *et al.*, 2024). The superior performance of garlic paste in the present study therefore aligns with current understanding of garlic chemistry and bioactivity.

In contrast, the poor oxidative performance of garlic powder suggests that dehydration and processing may reduce the stability or availability of key antioxidant compounds. This aligns with reports that processing-induced degradation and reduced solubility of bioactive compounds in powdered plant materials often limit antioxidant efficacy. Processing-induced degradation and reduced solubility of bioactive components in powdered plant materials have been widely reported, often leading to diminished antioxidant effectiveness compared with fresh or oil-based forms (Ma *et al.*, 2023; Presenza *et al.*, 2023). Similar observations have been made in fish products treated with powdered herbs, where inconsistent or weak reductions in TBARS were reported relative to essential oil treatments (Harmankaya *et al.*, 2024; Pierozan *et al.*, 2024).



The strong agreement between lower TBARS values in garlic oil- and garlic paste-treated samples and their improved sensory scores supports recommendations that oxidative indices should be interpreted alongside sensory evaluation, as chemical oxidation ultimately drives sensory rejection (Abeyrathne *et al.*, 2021; Mozzon, 2024).

### **Sensory Quality and Consumer Acceptability**

Sensory evaluation showed that garlic paste achieved the highest scores for flavour, texture, aroma, and overall acceptability, followed by garlic oil, garlic powder, and the control. These findings demonstrate that garlic paste effectively mitigates lipid oxidation while simultaneously enhancing sensory attributes, making it the most preferred formulation among the treatments tested. Similar sensory improvements have been reported for fish products treated with plant extracts and essential oils, where reduced lipid oxidation corresponded with improved flavour and aroma (Gökoglu, 2019; Güngören *et al.*, 2023; Harmankaya *et al.*, 2024).

Garlic oil produced particularly favourable aroma scores, which may reflect the presence of volatile sulfur compounds that contribute pleasant garlic notes at appropriate concentrations. Essential oils are widely reported to enhance aroma and mask oxidative off-flavours in fish products when applied at optimized levels (Hao *et al.*, 2021; Pierozan *et al.*, 2024). Conversely, garlic powder-treated samples received lower colour and overall acceptability scores, possibly due to uneven surface distribution, colour darkening, and the development of oxidative off-notes associated with higher TBARS values. The lower sensory scores for garlic powder are consistent with its higher TBARS values, reinforcing the connection between chemical oxidation and consumer perception.

### **3.1.5 Implications for Smoked Fish Preservation**

The present findings have important practical implications for clean-label preservation of smoked fish. Garlic paste and garlic oil were significantly more effective than garlic powder in controlling lipid oxidation and improving sensory quality. These results reinforce broader conclusions in seafood preservation research that the physical and chemical form of plant-derived antioxidants is often more critical than the botanical source itself (Prezenza *et al.*, 2023; Kurek *et al.*, 2024; Pierozan *et al.*, 2024). These findings provide practical guidance for artisanal and small-scale smoked fish processors seeking clean-label preservation strategies.

The strong performance of garlic paste suggests that minimally processed garlic formulations may offer the most effective balance between antioxidant efficacy and sensory acceptability for artisanal and small-scale processors. Garlic oil represents a viable alternative where paste application is impractical, particularly when aroma enhancement is desirable.

### **3.1.6 Future Perspectives**

Although this study focused on direct surface application of garlic preparations, recent research demonstrates that incorporation of plant bioactives into edible coatings and active packaging systems can further enhance oxidative stability and control release of active compounds (Kurek *et al.*, 2024; Albendea *et al.*, 2023). Future work could therefore evaluate garlic paste or garlic oil within coating or packaging matrices, as well as assess synergistic effects with other natural antioxidants. Additionally, extended storage trials and evaluation under refrigerated or vacuum-packaged conditions would provide further insight into the shelf-life potential of garlic-treated smoked fish. Additionally, evaluating the stability of garlic bioactives over longer storage periods and under varying temperature and packaging conditions could address current knowledge gaps.

## **4.0 Conclusion**

This study demonstrated that the preservative efficacy of garlic in hot-smoked fish is



strongly dependent on its form of application. Garlic paste and garlic oil significantly reduced lipid oxidation, as reflected by lower TBARS values, compared with garlic powder and untreated samples. Among the garlic preparations evaluated, garlic paste provided the greatest improvement in oxidative stability and achieved the highest sensory scores for flavour, texture, aroma, and overall acceptability. Garlic oil also exhibited substantial antioxidant effectiveness and favourable sensory performance, whereas garlic powder was comparatively less effective in controlling oxidative rancidity and enhancing product quality.

These findings confirm that garlic paste and garlic oil function as effective natural antioxidants in hot-smoked fish and represent practical clean-label alternatives to synthetic preservatives. Garlic paste, in particular, offers the most favourable balance between oxidative protection and sensory enhancement and is therefore recommended as the preferred natural antioxidant for improving the shelf life and consumer acceptability of smoked fish products. Garlic oil may serve as a suitable alternative in situations where paste application is impractical or where aroma enhancement is desirable, while the use of garlic powder should be approached with caution due to its limited antioxidant efficacy under the conditions of this study.

Further research is warranted to evaluate the performance of garlic paste and garlic oil in combination with complementary preservation strategies such as vacuum packaging, edible coatings, and refrigerated storage, as well as to assess their effectiveness during extended storage periods. Such studies would provide additional insight into optimizing garlic-based preservation systems for smoked fish products.

Further studies on dose optimization, longer storage periods, and different fish species are recommended to better define the industrial applicability of garlic-based natural preservatives.

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#### Declaration

#### Ethics Approval and Consent to Participate

This study involved the processing and sensory evaluation of commercially obtained fish samples and did not involve human clinical trials, animal experimentation, or collection of personal or sensitive data.



Sensory evaluation was conducted using informed volunteer panelists who participated willingly under standard food evaluation conditions. Ethical approval was therefore not required under institutional guidelines.

#### **Consent for Publication**

All authors have read and approved the final manuscript and consented to its publication.

#### **Availability of Data and Materials**

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

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#### **Competing Interests**

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

#### **Authors' Contributions**

SA conceptualized and designed the study, conducted the experiment, analyzed the data, and prepared the manuscript draft. ANA contributed to methodology development, data interpretation, and manuscript revision. ODO assisted with laboratory analyses, statistical evaluation, and interpretation of results. ASM contributed to sensory evaluation coordination, literature review, and manuscript editing. All authors read and approved the final manuscript.

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