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Original research article

Improving Storage Stability and Nutritional Quality of Smoked *Chrysichthys nigrodigitatus* Using Local Spices (Ginger and Black Pepper) in Cameroon

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ABSTRACT

In this study, we investigate the potential of local spices: ginger (*Zingiber officinale*), black pepper (*Piper nigrum*), and their mixture to improve the storage stability, nutritional composition, and sensory quality of smoked *Chrysichthys nigrodigitatus* from the Nkam Wouri River in Cameroon. These spices were chosen due to their local availability, traditional use in food preservation, and well-documented antimicrobial and antioxidant properties. Fresh fish samples were marinated with ginger, black pepper, a ginger–black pepper mixture, or salt (control), then smoked using the FAO Thiaroye technique. For storage, part of the smoked fish was packaged in carton paper and sealed in food-grade plastic, while another part was stored without packaging under controlled ambient or exposed conditions. Analyses were performed on dorsal and ventral muscle fillets to assess microbiological quality (Total Aerobic Mesophilic Flora, yeasts/molds, *Salmonella*), physicochemical parameters (pH, moisture, dry matter), nutritional composition (proteins, lipids, carbohydrates, ash, energy), and sensory attributes (9-point hedonic scale, 60 untrained panelists). Spice treatments, particularly the ginger–black pepper mixture, significantly ($p < 0.05$) reduced microbial loads by 35–40% compared to salt controls, stabilized pH and moisture, and improved dry matter (dm) retention. Ginger preserved protein integrity (up to 47.55% dm), while the mixture maximized lipid content (25.27% dm) and energy value (≈501 kcal/100 g dm). Sensory evaluation confirmed higher scores for odor, taste, texture, and overall acceptability in spiced samples, with packaged treatments maintaining desirable qualities for up to 28 days (mean scores 7.5–8.2 vs. 5.0–5.5 for controls). The combined use of ginger and black pepper, together with appropriate packaging, enhances the safety, nutritional quality, and consumer acceptability of smoked fish. Albeit promising, the study was limited to one species (*C. nigrodigitatus*) and did not include fatty acid profile analysis, highlighting the need for further research on other species and nutritional parameters. These findings indicate that local spices can serve as natural preservatives, offering a safe, sustainable, and culturally appropriate alternative to synthetic additives in artisanal fish processing in Cameroon.

Keywords: Smoked fish; *Chrysichthys nigrodigitatus*; Ginger; Black pepper; Food safety; Shelf life; Sensory quality; Natural preservatives; Cameroon.

RÉSUMÉ

Cette étude évalue le potentiel des épices locales, gingembre (*Zingiber officinale*), poivre noir (*Piper nigrum*) et leur mélange pour améliorer la stabilité de conservation, la composition nutritionnelle et la qualité sensorielle du *Chrysichthys nigrodigitatus* fumé issu du fleuve Nkam Wouri au Cameroun. Le choix de ces épices repose sur leur disponibilité locale, leur usage traditionnel en conservation alimentaire et leurs propriétés antimicrobiennes et

antioxydantes bien documentées. Les poissons frais ont été marinés avec du gingembre, du poivre noir, un mélange gingembre-poivre noir ou du sel (témoin), puis fumés selon la technique FAO Thiaroye. Une partie des échantillons fumés a été conditionnée dans du carton et scellée dans du plastique alimentaire, tandis qu'une autre partie a été stockée sans emballage, sous conditions ambiantes contrôlées ou exposées. Les analyses ont porté sur les filets dorsaux et ventraux pour évaluer la qualité microbiologique (flore mésophile totale, levures/moisissures, *Salmonella*), les paramètres physicochimiques (pH, humidité, matière sèche), la composition nutritionnelle (protéines, lipides, glucides, cendres, énergie) et les attributs sensoriels (échelle hédonique à 9 points, 60 panélistes non entraînés). Les traitements épicés, en particulier le mélange gingembre-poivre noir, ont réduit les charges microbiennes de 35–40 % par rapport aux témoins salés, stabilisé le pH et l'humidité, et amélioré la rétention de matière sèche. Le gingembre a favorisé la préservation des protéines (jusqu'à 47,55 % dm), tandis que le mélange a maximisé les lipides (25,27 % dm) et la valeur énergétique (≈501 kcal/100 g dm). L'évaluation sensorielle a confirmé des scores supérieurs pour l'odeur, le goût, la texture et l'acceptabilité globale dans les échantillons épicés, avec des qualités maintenues jusqu'à 28 jours (scores moyens de 7,5–8,2 contre 5,0–5,5 pour les témoins). L'utilisation combinée du gingembre et du poivre noir, associée au conditionnement, améliore la sécurité, la qualité nutritionnelle et l'acceptabilité des poissons fumés. Toutefois, l'étude présente des limites : elle est restreinte à une seule espèce (*C. nigrodigitatus*) et n'inclut pas l'analyse des profils en acides gras. Ces limites ouvrent la voie à des recherches futures sur d'autres espèces et paramètres nutritionnels. Les résultats confirment que les épices locales peuvent servir de conservateurs naturels, offrant une alternative sûre, durable et culturellement adaptée aux additifs synthétiques dans la transformation artisanale du poisson au Cameroun.

Mots-clés : Poisson fumé ; *Chrysichthys nigrodigitatus* ; Gingembre ; Poivre noir ; Sécurité alimentaire ; Durée de conservation ; Qualité sensorielle ; Conservateurs naturels ; Cameroun.

1. INTRODUCTION

Fish is a vital source of high-quality protein, essential fatty acids, vitamins, and minerals, and plays a critical role in global food and nutrition security. According to the Food and Agriculture Organization (FAO, 2020), fish contributes significantly to the dietary intake of omega-3 fatty acids (EPA, DHA), vitamin D, calcium, iodine, and iron, particularly in developing countries where it is often the primary source of animal protein. Several studies emphasize that fish consumption supports cardiovascular and cognitive health, underscoring its nutritional importance. Despite these benefits, fish and fish products are highly perishable and prone to rapid spoilage. Spoilage is driven by enzymatic degradation, lipid oxidation, and microbial contamination, leading to undesirable changes in odor, texture, and color. Tavares et al. (2021) reported that specific spoilage microorganisms such as Pseudomonas and Shewanella generate metabolites that accelerate deterioration, reducing safety and consumer acceptability.

Smoking is one of the oldest and most widespread preservation methods in Africa, providing both nutritional and economic value to local communities. Adeyeye &Oyewole (2016) highlighted that, although traditional smoking practices remain predominant, they are often associated with variability in product quality, microbial contamination, and limited shelf life. To address these challenges, the FAO developed the Thiaroye Processing Technique (FTT), which improves smoking efficiency, reduces losses, and enhances food safety (FAO 2021). Previous studies have shown that smoking strongly affects the protein and lipid quality of *Chrysichthys nigrodigitatus*, leading to significant lipid loss due to oxidation of unsaturated fatty acids and dripping of melted fats. These decrease lipid content and may alter the energy value of the product. Djopnang et al. (2018) confirmed that preserving *C. nigrodigitatus* from the Nkam River by traditional smoking significantly increased free fatty acids and hydroperoxides, while reducing the Polyunsaturated Fatty Acids (PUFA)/Saturated Fatty Acids (SFA) ratio, indicating deterioration of lipid quality. Tenyang et al. (2020) also reported increased lipid oxidation and reduced PUFA during artisanal smoking. Adeyeye (2019) demonstrated that adding natural spices such as ginger, garlic, and clove reduced rancidity indices and improved consumer acceptance of smoked fish. These findings highlight the need for improved preservation strategies that minimize nutrient degradation while ensuring microbial safety. We chose *Chrysichthys nigrodigitatus* as raw material because of its high nutritional value, local availability, and economic importance in Cameroon, where it represents a major source of animal protein but remains highly perishable and vulnerable to post-harvest losses (Djopnang et al. 2018; Tenyang et al. 2020). Its valorization through improved processing methods directly addresses food security and local market needs.

The use of natural preservatives such as spices and essential oils has gained attention as a sustainable alternative to synthetic additives. Ginger (*Zingiber officinale*) contains bioactive compounds (gingerols, shogaols) with

proven antimicrobial and antioxidant properties (Shahrajabian et al. 2019; Rodrigues dos Santos et al. 2023). Black pepper (*Piper nigrum*) is rich in piperine, an alkaloid shown to inhibit the growth of foodborne pathogens, including *Escherichia coli* and *Staphylococcus aureus* (Abd El Hack et al. 2022; Chen et al. 2024). Further, Ngo Mback et al. (2020) demonstrated that essential oils extracted from Cameroonian aromatic plants exhibit strong preservative potential, confirming the relevance of local bioresources in improving food safety and extending shelf life. Although essential oils are partly volatile at high temperatures, several studies (Sharma & Kaur 2024; Mao et al. 2019) have shown that bioactive compounds in ginger (gingerols, shogaols, paradols, zingerone) and black pepper (piperine) retain antimicrobial and antioxidant activity after thermal processing, thereby contributing to the microbiological and nutritional stability of smoked products.

Despite existing knowledge on the antimicrobial and antioxidant properties of ginger and black pepper, few studies have assessed their combined effect on the microbiological stability, nutritional composition, and sensory quality of smoked fish. Moreover, the use of synthetic antioxidants in food preservation raises concerns about potential toxicity and adverse health effects, further highlighting the need for safer natural alternatives. Therefore, we aimed to evaluate the effect of ginger (*Zingiber officinale*), black pepper (*Piper nigrum*), and their combination on the microbiological stability, nutritional composition, and sensory quality of smoked *Chrysichthys nigrodigitatus*, while considering the role of packaging in extending its shelf life.

2. MATERIALS AND METHODS

2.1. Fish samples and spices

Fresh *Chrysichthys nigrodigitatus* was collected from three landing sites along the Nkam Wouri River: Titina (4°45’ N; 9°97’ E), former River Port (4°27’ N; 9°57’ E), and Bodiman (4°24’ N; 9°53’ E) between February and July 2024. The fish were purchased from local fishermen, transferred into ice-containing boxes, and transported to the Food Processing and Quality Control Laboratory of the Institute of Fishery and Aquatic Sciences, University of Douala in Yabassi. The sample had a cumulative weight of 9,500 g, with an average individual weight of 1,900 ± 494.97 g and a mean total length of 63 ± 1.06 cm. The calculated condition factor was 0.63 ± 0.37, reflecting the general morphometric characteristics of the specimens. The pH of the fresh fish was 7.2, and the percentage moisture content was 74.68, confirming the freshness and high perishability of the raw material. Taxonomic identification was performed by ichthyologists at the Laboratory of Ecosystem and Fisheries Resources of the Institute of Fishery and Aquatic Sciences. These biometric, geographic, and taxonomic data ensured sample representativeness and allowed standardized processing. We selected *Chrysichthys nigrodigitatus* based on its economic and nutritional importance in Cameroon, where it is a major source of animal protein but remains highly perishable and prone to post-harvest losses (Djopnang *et al*. 2018; Tenyang *et al*. 2020). Two local spices were used for the spicing process: fresh ginger (*Zingiber officinale*) and dried black pepper seeds (*Piper nigrum*). Salt and spices were purchased from Buea, a town in the Southwest Region of Cameroon. Ginger and black pepper were selected based on their local availability, traditional use in food preservation in Cameroon, and well-documented antimicrobial and antioxidant properties (Mao et al., 2019; Sharma & Kaur, 2024).

2.2. Processing of formulations and the smoking process

2.2.1. Preparation of fish

Chrysichthys nigrodigitatus samples were washed with lime juice and salt to remove external dirt and mucus, then drained and weighed. The fish were subsequently eviscerated, thoroughly cleaned, and randomly divided into four groups to be treated in the formulated marination processes.

2.2.2. Preparation of spices and marinade formulations

Fresh ginger (*Zingiber officinale*) was washed, peeled, cut into small pieces, dried at 50 °C for 48 hours, and ground into fine powder. Dried black pepper (*Piper nigrum*) seeds were also reduced to fine powder. The prepared spices were packaged in food-grade plastic wrappers for use in the marinade formulations presented in Table 1. Four formulations were established (S = salt only, G = salt + ginger, BP = salt + black pepper, M = salt + ginger + black pepper mixture). This marination step directly preceded smoking and packaging, as illustrated in Figure 1.

Table 1. Composition of marinade formulations (ginger, black pepper, mixture, control) for 500 g of *Chrysichthys nigrodigitatus*.

Composition (/1000 g)	Ginger	Black Pepper	Mixture (ginger + black pepper)	Salt (control)
Fresh catfish	500	500	500	500
Ginger powder	20.00	0.00	10.00	0.00
Black pepper powder	0.00	20.00	10.00	0.00
Salt	12.50	12.50	12.50	12.50
Lemon juice	25.00	25.00	25.00	25.00
Water	442.50	442.50	442.50	462.50

2.2.3. Smoking

The smoking process was carried out in three successive phases to ensure reproducibility and product stability. The first pre-drying phase was conducted at 45–55 °C for 2 h to reduce surface moisture. The second cooking-smoking phase was performed at 75–85 °C for 4 h using local hardwood (*Irvingia gabonensis*), promoting protein denaturation and deposition of smoke compounds. Finally, the third drying phase was conducted at 55–65 °C for 3 h to stabilize the product and extend its shelf life. The distance between the heat source and the fish was maintained at approximately 40 cm, and the temperature was continuously monitored with a digital thermometer.

The marinated *Chrysichthys nigrodigitatus* samples were carefully arranged on smoking trays previously greased with a thin layer of vegetable oil, labeled, allowed to drain, and placed into the smoking kiln. The greasing was done uniformly to prevent the fish from adhering to the trays and to ensure the reproducibility of the smoking process. To minimize any influence on the lipid content, only a very small amount of oil was used, and proximate analyses were performed on smoked fillets to account for potential variations. This ensured that the measured lipid values reflected the fish's intrinsic composition rather than external oil residues. This improved kiln is equipped with a combustion chamber that uses stones and charcoal as fuel. The first tray is positioned approximately 50 cm above the heat source. The smoking chamber is fitted with a thermometer probe that records the chamber temperature and allows adjustment of the fuel to maintain the desired temperature range. Using an electronic probe thermometer, the internal temperature of the fish was monitored. The overall smoked fish production process is illustrated in Figure 1.

The smoking process was carried out in three successive phases to ensure reproducibility and product stability. The first, pre-drying, phase was conducted at 30–60 °C for 3 h to reduce surface moisture. The second, cooking-smoking, phase was performed at 60–100 °C for 4 h using local charcoal combined with plantain banana trunk, promoting protein denaturation and deposition of smoke compounds. Finally, a drying phase was conducted at 55–60 °C for 3 h to stabilize the product and extend its shelf life. The smoking process was considered complete when the following parameters were met: (i) stabilization of internal temperature of the fish muscle around 55–60 °C, (ii) reduction of surface and internal moisture to less than 10%, (iii) attainment of a firm texture with uniform coloration, and (iv) absence of visible condensation or dripping. These characteristics were evaluated by continuous monitoring with a digital thermometer, gravimetric measurement of moisture loss, and sensory inspection (color, odor, texture). Together, these ensured reproducibility and confirmed that the smoking process was over. The fish and trays were regularly turned during smoking to ensure uniform drying. A sensitive electronic balance (0.01 g) was used to weigh the products and calculate production yield.

2.2.4. Packaging of smoked fish

After smoking, the fish were cooled at ambient temperature and either wrapped in cardboard and sealed in food-grade plastic or left unpackaged, then stored at a controlled ambient temperature or exposed. The use of opaque packaging is necessary to prevent light penetration, which can cause lipid oxidation and alter the product's nutritional quality. These conditions enabled evaluation of the effect of packaging on the fish's microbiological stability, nutritional quality, and sensory attributes.

For clarity, the following abbreviations were used to designate the smoked fish formulations and storage conditions:

- SE: Fish smoked with salt, exposed condition
- SP: Fish smoked with salt, packaged condition
- GE: Fish smoked with ginger, exposed condition
- GP: Fish smoked with ginger, packaged condition
- BPE: Fish smoked with black pepper, exposed condition
- BPP: Fish smoked with black pepper, packaged condition
- ME: Fish smoked with both ginger and black pepper, exposed condition
- MP: Fish smoked with both ginger and black pepper, packaged condition

2.3. Microbiological analyses

Smoked fish samples were tested for bacteria and fungi at different stages: before storage (Day 1), after 7 days (D7), 14 days (D14), 21 days (D21), and 28 days (D28). Microbial load analyses were performed in triplicate on spiced fish and the control group (without spices).

2.3.1. Preparation of media and solutions

Culture media were prepared according to manufacturers' instructions and sterilized by autoclaving at 121 °C for 15 min. Dilutions followed the International Organization for Standardization (ISO) ISO 6887-2 (2017). Aseptically, 25 g of ground smoked fish fillet flesh was taken and diluted in a sterile Erlenmeyer flask containing 225 mL of sterile tryptone salt (LiofilChem, Italy). The mixture was homogenized and left at ambient temperature for 30 min to allow microbial resuscitation. The initial 10^{-1} dilution represented the stock solution. Serial decimal dilutions (10^{-1} to 10^{-6}) were then prepared.

2.3.2. Inoculation and culture conditions

Inoculation and culture were performed following standardized methods. The Total Aerobic Mesophilic Flora (TAMF) enumeration was performed using the pour plate method (ISO 4833:2013). Here,1 mL of each dilution was mixed with 15 mL of sterile PCA and incubated at 30 °C for 72 h, producing milky-white colonies. Yeasts and molds were enumerated according to ISO 21527:2008 on Sabouraud agar supplemented with chloramphenicol; plates were incubated at 25 °C for 2–5 days. Yeasts appeared beige-milky, and molds formed dark colonies. The detection of *Salmonella spp.* followed the three-step procedure described in ISO 6579-1:2017: pre-enrichment was performed by incubating 10 g of fish in 90 mL of buffered peptone water at 37 °C for 20 h, enrichment was achieved by transferring 0.1 mL of subculture into 10 mL of Rappaport-Vassiliadis broth incubated at 42 °C for 24 h, and isolation was conducted by streaking onto *Salmonella-Shigella* (SS) and Hektoen agars incubated at 37 °C for 24 h. Suspect colonies, characterized by colorless colonies with a black center on SS and greenish or bluish colonies with a black center on Hektoen, were subcultured for confirmation.

2.3.3. Colony counts

Only plates with 30–300 colonies were considered. Results were expressed as CFU/g using the ISO formula:

$N=\sum C/V(n_1+0.1n_2)d$

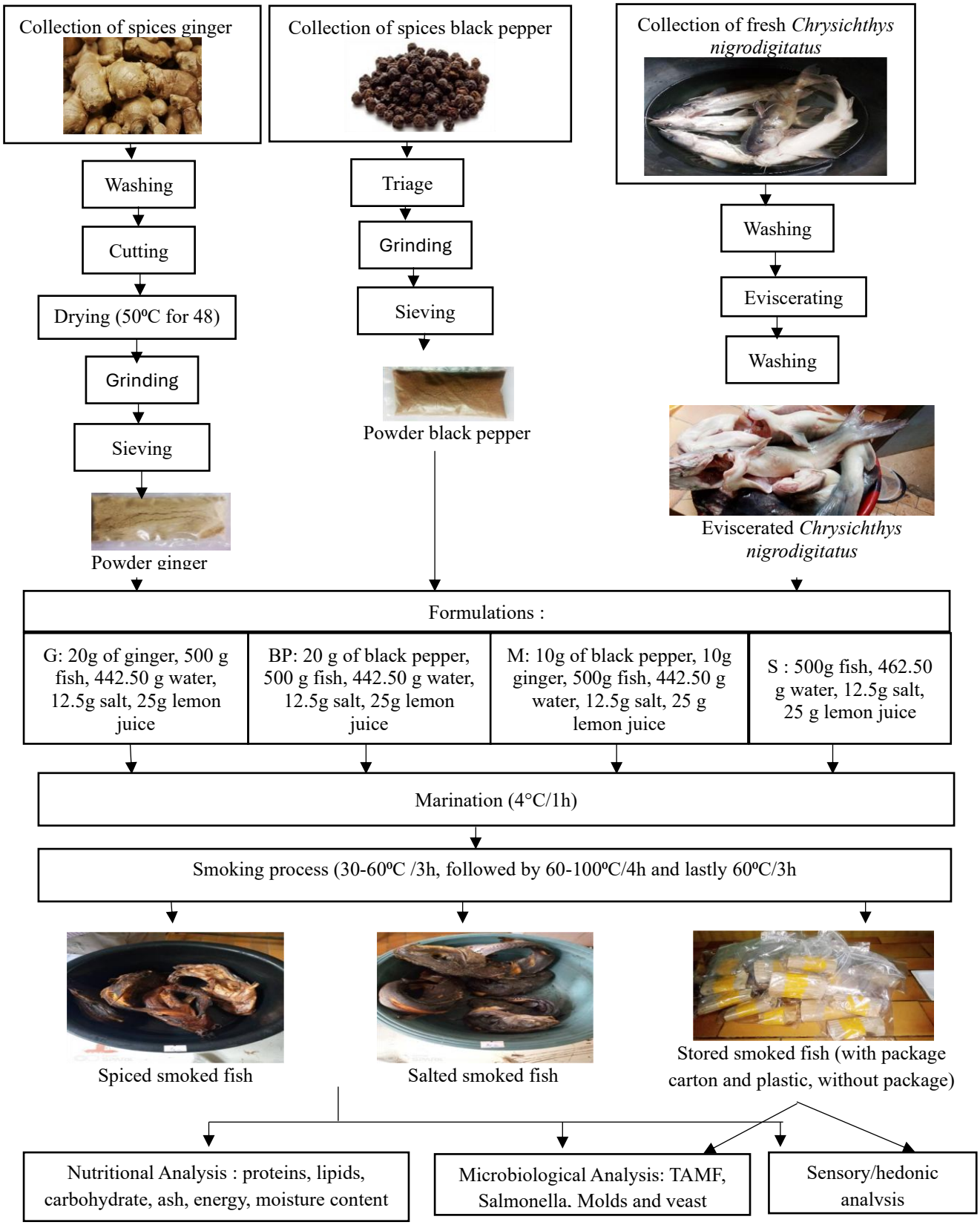
$\sum C$: Sum of the colonies counted on all the dishes of two successive dilutions;

V: volume of inoculum applied to each dish (mL)

n_1: number of dishes retained at the first dilution

n_2: number of dishes retained at the second dilution

d: dilution rate corresponding to the first dilution used



G, Ginger; BP, Black pepper; M, Mixture; S, Salt (control), TAMF; Total Aerobic Mesophilic Flora

Figure 1: Flowchart of the production process of smoked and spiced *Chrysichthys nigrodigitatus* (collection, marination, smoking, packaging, and analysis).

When the number of colonies was <15, the formula used to determine the number of colony-forming units was:

When colonies were fewer than 15, the simplified formula was applied:

Units were as follows: N= C/d

C = number of characteristic colonies on the dish

d = corresponding dilution rate

2.4. Physicochemical analyses

The determination of weight, smoking temperature, pH, and moisture content in foods was performed following well-established protocols. The weight of smoked fish samples (in grams) was measured using a Pioneer electronic balance, and yield was calculated as the ratio of smoked weight to eviscerated weight multiplied by 100. The smoking temperature was monitored by inserting a food thermometer into the center of the sample, avoiding contact with the bottom or sides of the container, and recording the stabilized reading. The pH of the products was measured using a calibrated pH meter with buffer solutions; the electrode was immersed in a suspension of the fish fillet flesh, and the stabilized value was noted (ISO 2917:1999). Moisture content was determined after dehydration at 105 °C in a ventilated oven, following the Association of Official Agricultural Chemists (AOAC) Official Method (1990).

2.5. Nutritional composition

Before storage, both spiced and unspiced smoked fish samples were analyzed to determine their protein, lipid, carbohydrate, ash, and energy content. Proximate analyses were conducted according to reference methods. Moisture content was measured by drying approximately 5 g of fish fillet flesh in an electric air oven at 105 °C until constant weight was obtained (16–24 h), following the AOAC Official Method (1990), and expressed as percentage weight loss. Ash content (A) was determined by incinerating approximately 5 g of the sample in a crucible at 550 °C until white or light gray ash was obtained (24 h), then calculating the percentage of ash relative to the initial sample weight (AOAC Official Method 1990). The lipid fraction (F) was extracted using a Soxhlet apparatus with hexane as a solvent. The crude protein (CP) content was calculated as (6.25 times N), where nitrogen content (N) was determined by the Kjeldahl method (AOAC Official Method 1990). Total carbohydrates (C) were estimated by difference, subtracting the sum of F, CP, and A contents from 100 g of fish dry matter (Onyeike *et al*. 2000). The gross energy value was calculated by multiplying the percentages of CP, F, and C with their respective energy conversion factors (4, 9, and 4 kcal per g of dry matter).

2.6. Sensory evaluation

Sensory evaluation of smoked *Chrysichthys nigrodigitatus* samples was conducted in accordance with ISO 8589:2009 (ANOR, 2009). Sixty panelists (male and female), recruited among regular consumers of smoked fish, participated in the study. Inclusion criteria were availability and absence of known allergies to fish or the spices used. All participants provided written informed consent prior to participation. Ethical clearance was not required for this study, as it involved only the sensory evaluation of a food product already validated for human consumption. The evaluation was carried out in a quiet, well-lit, ventilated sensory room conforming to ISO 8589 standards, with panelists seated in individual booths to minimize external influence. Sessions were conducted in the late morning to avoid sensory fatigue and bias related to mealtimes. Samples were presented blind, each treatment coded with a random three-digit number, and the serving order was randomized to avoid sequence bias. Each panelist received a standardized portion of 20–30 g, served at controlled ambient temperature (25–30 °C). Palate cleansers (water and plain crackers) were provided between tastings to minimize sensory carry-over. Attributes assessed included color, odor, taste, texture, and overall acceptability, using a 9-point hedonic scale (1 = dislike extremely; 9 = like extremely). Prior to the session, the scale was explained to all panelists to ensure uniform understanding. Responses were recorded on standardized paper forms. Participants were mostly naïve (untrained), reflecting consumer perception under real market conditions.

2.7. Statistical analysis

All data were subjected to statistical analysis at a 5% probability threshold, according to the nature of the variables. Nutritional and physicochemical parameters (proximate composition, dry matter, water content, pH) were analyzed in triplicate and subjected to one-way analysis of variance (ANOVA). When significant effects

were detected, Tukey's honest significant difference (HSD) post hoc test was applied to identify differences among means, with results expressed as mean ± standard deviation and significant differences indicated by superscript letters (a, b, c) in the tables. Sensory evaluation data, collected from 60 panelists and expressed as ordinal hedonic scores, were analyzed using non-parametric tests (Kruskal–Wallis followed by Dunn's post hoc test). Differences among treatments were considered significant at $p < 0.05$, and letters indicating significance were positioned in the sensory tables to highlight treatment effects. Microbiological data (TAMF, yeasts and molds, *Salmonella spp.*) were analyzed using two-way ANOVA to assess the effects of storage time, treatment, and their interaction. Tukey's HSD post hoc test was applied to separate means, with results expressed as mean ± SD (N = 3). Standards were translated into $\log_{10}$ CFU/g for consistency, and a three-class plan was adopted for TAMF (≤ 3.0 conform, 3.0–4.0 limit, ≥ 6.0 non-conform). All statistical analyses were performed using SPSS v.25, R 4.3.2, and GraphPad Prism, ensuring reproducibility and compliance with ISO/l'Association Française de Normalisation (AFNOR)/l'Agence des Normes et de la Qualité (ANOR) standards.

3. RESULTS

3.1. Processing Yield

The carcass yield of *Chrysichthys nigrodigitatus* was 84.2%. The smoking yield was 37.5%. The mean fish weight was 1900 ± 494.97 g, with a mean length of 63 ± 1.06 cm and a condition factor of 0.63 ± 0.37. The eviscerated weight was 8000 g, and the smoked weight was 3000 g.

3.2. Temperature profile of Smoking

Temperature monitoring showed a progressive increase during the pre-dehydration phase (30–60 °C), followed by a further rise during the cooking phase (60–100 °C). During the final drying stage (60 °C), the temperature stabilized (**Figure 2**).

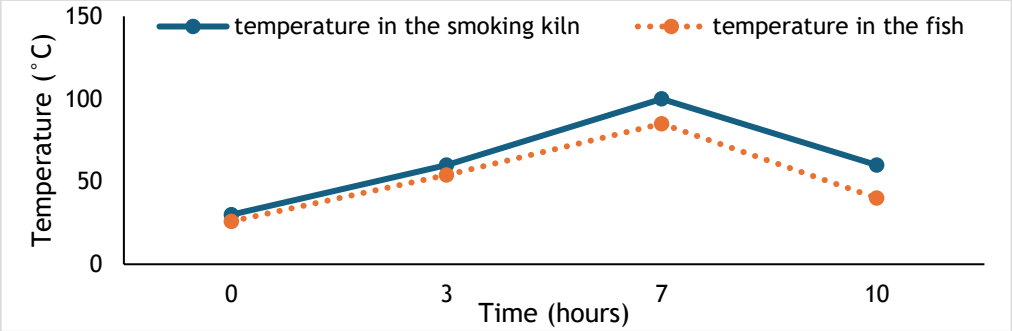


Figure 2: Temperature variation inside the smoking kiln and within fish muscle during the three phases of smoking (pre-dehydration, cooking, final drying).

3.3. Physicochemical parameters

3.3.1. pH

Two-way ANOVA revealed significant effects of storage time ($p < 0.001$), treatment ($p < 0.001$), and their interaction ($p < 0.05$) on pH. Salted (SE, SP) and ginger (GE) treatments showed a progressive increase from ~6.1 on day 0 to values above 7.4–8.1 on day 28 ($p < 0.001$). In contrast, packaged ginger (GP), packaged black pepper (BPP), and packaged mixture (MP) remained within the stability range of 5.8–6.5 throughout storage (ns, $p > 0.05$ vs. standard). The combination of packaging and spicing significantly ($p < 0.05$) maintained pH stability compared with exposed samples (**Table 2**).

3.3.2. Moisture and Dry Matter Content

Two-way ANOVA reveals significant effects of storage time ($p < 0.001$), treatment ($p < 0.001$), and their interaction ($p < 0.05$) on moisture content. SE and GE increased from ~3.7% at day 0 to values above 33–45% at day 28 ($p < 0.001$). In contrast, SP, GP, BPP, and MP maintained values between 4–6% at day 28 (ns, $p > 0.05$ vs. standard threshold of 10%; Table 3).

Table 2. Evolution of pH values of smoked *Chrysichthys nigrodigitatus* during storage

Storage time (days)	SE	SP	GE	GP	BPE	BPP	ME	MP	Standard range
T0	6.09 ± 0.36^{a}	6.15 ± 0.21^{a}	4.71 ± 0.28^{b}	4.59 ± 0.30^{b}	5.16 ± 0.46^{b}	5.08 ± 0.19^{b}	4.53 ± 0.32^{b}	4.53 ± 0.32^{b}	5.8–6.5
T7	7.50 ± 0.18^{c}	7.20 ± 0.30^{c}	5.55 ± 0.43^{b}	5.15 ± 0.14^{b}	6.92 ± 0.53^{c}	5.46 ± 0.14^{b}	5.41 ± 0.13^{b}	5.11 ± 0.13^{b}	
T14	7.80 ± 0.25^{c}	7.21 ± 0.30^{c}	6.15 ± 0.37^{a}	5.55 ± 0.10^{b}	6.71 ± 0.44^{c}	5.66 ± 0.38^{b}	6.30 ± 0.37^{a}	5.70 ± 0.37^{b}	
T21	7.90 ± 0.43^{c}	7.49 ± 0.18^{c}	7.00 ± 0.19^{c}	6.05 ± 0.42^{a}	6.91 ± 0.35^{c}	5.97 ± 0.29^{a}	6.72 ± 0.45^{a}	5.75 ± 0.45^{a}	
T28	8.11 ± 0.35^{c}	7.60 ± 0.14^{c}	7.41 ± 0.28^{c}	6.08 ± 0.44^{a}	7.10 ± 0.23^{c}	6.09 ± 0.49^{a}	7.65 ± 0.29^{c}	6.05 ± 0.29^{a}	

Values are Mean ± SD of 3 replicates. Different superscript letters (a, b, c) within the same row indicate significant differences between treatments at the same storage time (**$p < 0.05$**). Abbreviations: SE=Salted fish exposed; SP=Salted fish packaged; GE=Ginger exposed; GP=Ginger packaged; BPE=Black pepper exposed; BPP=Black pepper packaged; ME=Ginger + black pepper exposed; MP=Ginger + black pepper packaged.

Table 3. Variation in moisture content of smoked *Chrysichthys nigrodigitatus* during storage

Storage time (days)	SE	SP	GE	GP	BPE	BPP	ME	MP
T0	3.69 ± 0.36^{a}	3.79 ± 0.21^{a}	3.85 ± 0.28^{a}	3.46 ± 0.30^{a}	3.86 ± 0.46^{a}	3.07 ± 0.19^{a}	3.23 ± 0.32^{a}	3.23 ± 0.32^{a}
T7	35.16 ± 0.18^{c}	4.60 ± 0.30^{a}	30.33 ± 0.43^{c}	3.90 ± 0.14^{a}	16.92 ± 0.53^{b}	3.82 ± 0.14^{a}	22.21 ± 0.13^{b}	3.91 ± 0.13^{a}
T14	40.50 ± 0.25^{c}	5.09 ± 0.30^{a}	31.22 ± 0.37^{c}	4.39 ± 0.10^{a}	20.05 ± 0.44^{b}	4.55 ± 0.38^{a}	24.70 ± 0.37^{b}	4.70 ± 0.37^{a}
T21	42.50 ± 0.43^{c}	5.55 ± 0.18^{a}	31.65 ± 0.19^{c}	5.06 ± 0.42^{a}	23.59 ± 0.35^{b}	4.39 ± 0.29^{a}	26.90 ± 0.45^{b}	4.40 ± 0.45^{a}
T28	45.51 ± 0.35^{c}	6.20 ± 0.14^{a}	33.69 ± 0.28^{c}	6.38 ± 0.44^{a}	27.21 ± 0.23^{b}	4.71 ± 0.49^{a}	28.85 ± 0.29^{b}	4.75 ± 0.29^{a}

Values are Mean ± SD of 3 replicates. Different superscript letters (a, b, c) within the same row indicate significant differences between treatments at the same storage time ($p < 0.05$). Abbreviations: SE = Salted fish exposed; SP = Salted fish packaged; GE = Ginger exposed; GP = Ginger packaged; BPE = Black pepper exposed; BPP = Black pepper packaged; ME = Ginger + black pepper exposed; MP = Ginger + black pepper packaged.

Packaged samples (SP, GP, BPP, MP) showed minimal decrease (≈96.5% to 94%, ns, $p > 0.05$), while exposed samples decreased markedly (≈96.5% to ~55%, $p < 0.001$). Spice treatments mitigated the decline, with BPE and ME retaining ≥72–73% compared to SE and GE at 54–67% (Table 4).

Table 4. Variation of dry matter content of smoked *Chrysichthys nigrodigitatus* during storage

Storage time (days)	SE	SP	GE	GP	BPE	BPP	ME	MP
T0	96.8 ± 0.36^{a}	96.73 ± 0.21^{a}	96.99 ± 0.28^{a}	96.95 ± 0.30^{a}	97.33 ± 0.46^{a}	97.14 ± 0.19^{a}	97.00 ± 0.32^{a}	97.00 ± 0.32^{a}
T7	65.17 ± 0.18^{c}	96.28 ± 0.30^{a}	70.39 ± 0.43^{c}	96.33 ± 0.14^{a}	84.61 ± 0.53^{b}	96.56 ± 0.14^{a}	78.15 ± 0.13^{b}	96.45 ± 0.13^{a}
T14	60.23 ± 0.25^{c}	95.77 ± 0.30^{a}	69.31 ± 0.37^{c}	95.88 ± 0.10^{a}	80.84 ± 0.44^{b}	96.56 ± 0.38^{a}	76.27 ± 0.37^{b}	96.27 ± 0.37^{a}
T21	58.18 ± 0.43^{c}	94.77 ± 0.18^{a}	68.81 ± 0.19^{c}	96.08 ± 0.42^{a}	77.42 ± 0.35^{b}	96.32 ± 0.29^{a}	73.79 ± 0.45^{b}	96.29 ± 0.45^{a}
T28	54.86 ± 0.35^{c}	94.15 ± 0.14^{a}	66.88 ± 0.28^{c}	94.95 ± 0.44^{a}	73.22 ± 0.23^{b}	96.42 ± 0.49^{a}	71.93 ± 0.29^{b}	96.03 ± 0.29^{a}

Values are Mean ± SD of 3 replicates. Different superscript letters (a, b, c) within the same row indicate significant differences between treatments at the same storage time ($p < 0.05$). Abbreviations: SE = Salted fish exposed; SP = Salted fish packaged; GE = Ginger exposed; GP = Ginger packaged; BPE = Black pepper exposed; BPP = Black pepper packaged; ME = Ginger + black pepper exposed; MP = Ginger + black pepper packaged.

Exposed samples (SE, GE, BPE, ME) showed progressive and significant increases in weight during storage ($p < 0.001$), with the ME reaching +51.79 % at day 28. In contrast, packaged samples (SP, GP, BPP, MP) remained stable, recording non-significant changes. Packaging significantly prevented moisture absorption compared with exposed controls (Table 5).

Table 5. Weight variation of smoked *Chrysichthys nigrodigitatus* during storage

Storage time (days)	GE (g / %)	GP (g / %)	BPE (g / %)	BPP (g / %)	ME (g / %)	MP (g / %)	SE (g / %)	SP (g / %)
Day 1	100 / 0.00	100 / 0.00	100 / 0.00	100 / 0.00	100 / 0.00	100 / 0.00	100 / 0.00	100 / 0.00
Day 7	105.78 / +5.78	100.00 / 0.00	118.21 / +18.21	100.00 / 0.00	115.18 / +15.18	100.00 / 0.00	113.19 / +13.19	100.00 / 0.00
Day 14	107.41 / +7.41	100.00 / 0.00	125.94 / +25.94	100.00 / 0.00	121.61 / +21.61	100.00 / 0.00	117.94 / +17.94	99.10 / -0.90
Day 21	114.22 / +14.22	99.95 / -0.05	140.09 / +40.09	99.93 / -0.07	133.93 / +33.93	99.86 / -0.14	119.74 / +19.74	107.21 / +7.21
Day 28	121.55 / +21.55	99.95 / -0.05	143.87 / +43.87	99.93 / -0.07	151.79 / +51.79	99.86 / -0.14	122.02 / +22.02	106.31 / +6.31

- Values are mean of 3 replicates, expressed as absolute weight (g) and relative gain/loss (%) calculated against the initial weight (100 g). Abbreviations: GE = Ginger exposed; GP = Ginger packaged; BPE = Black pepper exposed; BPP = Black pepper packaged; ME = Ginger + black pepper exposed; MP = Ginger + black pepper packaged; SE = Salt exposed; SP = Salt packaged.

3.4. Microbiological quality

Two-way ANOVA revealed significant effects of storage time ($p < 0.001$), treatment ($p < 0.001$), and their interaction ($p < 0.05$) on microbial counts. For TAMF, exposed salt samples (SE) reached 6.40 $\log_{10}$ CFU/g at day 28, corresponding to the non-conform class (letter a), whereas packaged spice treatments (GP, BPP, MP) remained ≤ 2.3 $\log_{10}$ CFU/g, corresponding to the conform class (letter c). This reduction represented approximately 65–70 % compared to exposed controls, with the ginger–black pepper mixture packaged (MP) being the most effective (~2.10 $\log_{10}$ CFU/g at day 28). For yeasts and molds, exposed salt samples reached ~2.98 $\log_{10}$ CFU/g at day 28, placing them in the limit class (letter a), while packaged spice treatments remained

≤ 1.8 $\log_{10}$ CFU/g, corresponding to the conform class (letters b/c). This reduction represented approximately 40–50 % compared to exposed controls, with the mixture packaged (MP) maintaining the lowest counts (1.40 $\log_{10}$ CFU/g). *Salmonella spp.* were absent in all treatments throughout storage, confirming full compliance with ISO 6579-1:2017. The integration of letters of significance and percentage reductions highlights the protective effect of packaging and spices, as packaged spice treatments consistently belonged to the conform class (b/c), while exposed salt controls shifted to the non-conform class (a) after 14–21 days. The ginger–black pepper mixture packaged (MP) provided the strongest inhibitory effect, ensuring microbiological stability with ≥ 65–70 % reduction in TAMF and ≥ 40–50 % reduction in yeasts and molds compared to exposed controls, and full compliance with ISO/AFNOR/ANOR standards (Table 6).

Table 6. Microbiological quality of smoked *Chrysichthys nigrodigitatus* during storage

Microbial group	Day	SE	SP	GE	GP	BPE	BPP	ME	MP	Standard (ISO / AFNOR / ANOR, $\log_{10}$ CFU/g)
TAMF	1	1.90 ± 0.02^{a}	1.90 ± 0.02^{a}	1.62 ± 0.01^{b}	1.62 ± 0.01^{b}	1.46 ± 0.01^{b}	1.46 ± 0.01^{b}	1.30 ± 0.01^{c}	1.30 ± 0.01^{c}	≤ 3.0 (conform) / 4.0 (limit) / 6.0 (non-conform)
	7	3.87 ± 0.01^{a}	2.08 ± 0.01^{b}	3.79 ± 0.01^{a}	1.72 ± 0.01^{b}	3.66 ± 0.01^{a}	1.60 ± 0.01^{b}	3.58 ± 0.01^{a}	1.46 ± 0.01^{b}	
	14	6.01 ± 0.02^{a}	2.10 ± 0.01^{c}	5.98 ± 0.01^{a}	1.81 ± 0.01^{c}	5.75 ± 0.02^{a}	1.72 ± 0.01^{c}	5.67 ± 0.01^{a}	1.60 ± 0.01^{c}	
	21	6.06 ± 0.01^{a}	2.21 ± 0.01^{c}	6.19 ± 0.02^{a}	2.13 ± 0.01^{c}	6.07 ± 0.01^{a}	2.08 ± 0.01^{c}	6.03 ± 0.01^{a}	2.01 ± 0.01^{c}	
	28	6.40 ± 0.01^{a}	2.34 ± 0.01^{c}	6.42 ± 0.01^{a}	2.24 ± 0.01^{c}	6.14 ± 0.01^{a}	2.08 ± 0.01^{c}	6.24 ± 0.01^{a}	2.10 ± 0.01^{c}	
Yeasts & molds	1	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	≤ 2.0 (conform) / 3.0 (limit)
	7	2.51 ± 0.02^{a}	0.00 ± 0.00^{c}	1.85 ± 0.01^{b}	0.00 ± 0.00^{c}	1.70 ± 0.01^{b}	0.00 ± 0.00^{c}	1.60 ± 0.01^{b}	0.00 ± 0.00^{c}	
	14	2.76 ± 0.02^{a}	1.30 ± 0.01^{b}	2.08 ± 0.01^{a}	1.18 ± 0.01^{b}	1.81 ± 0.01^{b}	1.11 ± 0.01^{b}	1.71 ± 0.01^{b}	0.00 ± 0.00^{c}	
	21	2.93 ± 0.02^{a}	1.60 ± 0.01^{b}	2.37 ± 0.02^{a}	1.48 ± 0.01^{b}	2.21 ± 0.01^{a}	1.30 ± 0.01^{b}	2.06 ± 0.01^{a}	1.18 ± 0.01^{b}	
	28	2.98 ± 0.02^{a}	1.78 ± 0.01^{b}	2.58 ± 0.02^{a}	1.60 ± 0.01^{b}	2.49 ± 0.02^{a}	1.48 ± 0.01^{b}	2.32 ± 0.02^{a}	1.40 ± 0.01^{b}	
Salmonella spp.	1–28	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent in 25 g

Values are expressed as $\log_{10}$ CFU/g (Mean ± SD, N = 3). Different superscript letters (a, b, c) within a row indicate significant differences between treatments at the same storage time ($p < 0.05$). Standards were translated into $\log_{10}$ CFU/g for consistency: TAMF ≤ 3.0 (conform), 3.0–4.0 (limit), ≥ 6.0 (non-conform); yeasts and molds ≤ 2.0 (conform), 2.0–3. Abbreviations: SE = Salt exposed; SP = Salt packaged; GE = Ginger exposed; GP = Ginger packaged; BPE = Black pepper exposed; BPP = Black pepper packaged; ME = Mixture exposed; MP = Mixture packaged.

3.5. Nutritional composition

One-way ANOVA revealed significant differences among treatments for all nutritional parameters ($p < 0.05$). Dry matter ranged from 78.70 % in black pepper (BP) to 87.95 % in the mixture (M), with values in M and salt (S) significantly higher than those in BP ($p < 0.001$). Moisture content varied inversely, from 12.05 % in M to 21.30 % in BP, with ginger (G) and M showing significantly lower values ($p < 0.001$). Protein content was highest in G (47.55 % dm) and M (47.47 % dm), compared to lower values in S (44.07 % dm) and BP (41.46 % dm) ($p < 0.05$). Lipid levels peaked in M (25.27 % dm), significantly higher than BP (20.74 % dm) ($p < 0.05$). Ash content was

lowest in M (9.50 % dm), significantly different from BP (12.50 % dm) ($p < 0.05$). Carbohydrates were most abundant in BP (25.29 % dm) and lowest in G (17.78 % dm) and M (17.76 % dm) ($p < 0.05$). Energy values ranged from 453.70 kcal/100 g dm in BP to 500.97 kcal/100 g dm in M, with significant differences among treatments ($p < 0.001$) **(Table 7)**.

Table 7. Nutritional composition of smoked *Chrysichthys nigrodigitatus* under different treatments

Parameter	Unit	BP	G	M	S
Dry matter	%	78.70 ± 0.14^{b}	82.75 ± 0.07^{b}	87.95 ± 0.07^{a}	86.50 ± 0.14^{a}
Moisture	%	21.30 ± 0.14^{a}	17.25 ± 0.70^{b}	12.05 ± 0.07^{c}	13.05 ± 0.14^{c}
Proteins	% dm	41.46 ± 1.15^{b}	47.55 ± 4.64^{a}	47.47 ± 4.13^{a}	44.07 ± 0.06^{b}
Lipids	% dm	20.74 ± 0.22^{b}	23.17 ± 3.63^{ab}	25.27 ± 0.38^{a}	23.27 ± 3.49^{ab}
Ash	% dm	12.50 ± 0.71^{a}	11.51 ± 0.71^{a}	9.50 ± 0.24^{b}	10.50 ± 0.70^{ab}
Carbohydrates	% dm	25.29 ± 2.08^{a}	17.78 ± 1.29^{b}	17.76 ± 1.04^{b}	22.16 ± 2.72^{ab}
Energy	kcal/100 g dm	453.70 ± 1.69^{c}	491.25 ± 8.13^{b}	500.97 ± 3.11^{a}	474.35 ± 1.71^{b}

Values are Mean ± SD of 3 replicates. Different superscript letters (a, b, c) within a row indicate significant differences between treatments ($p < 0.05$). Abbreviations: BP = Black pepper; G = Ginger; M = Mixture (ginger + black pepper); S = Salt (control).

3.6. Sensory evaluation

Kruskal–Wallis analysis revealed significant differences ($p < 0.05$) across sensory attributes, particularly for color, texture, and overall acceptability. The mixture (M) was the most appreciated sample, with significantly higher scores in color, texture, and overall acceptability compared to the salt control (S) and ginger (G). The salt control (S) was the least preferred, consistently scoring lower than M and showing significant differences in color, texture, and overall acceptability ($p < 0.05$). Odor, taste, and fatty aftertaste did not differ significantly among treatments (ns, $p > 0.05$). Mean hedonic scores ranged between 7.5–8.2 for M, 6.5–7.0 for G and BP, and 5.0–5.5 for S, confirming consumer preference for spiced formulations, especially the ginger–black pepper mixture (Table 8).

Table 8. Sensory evaluation scores of smoked *Chrysichthys nigrodigitatus*

Attribute	M	G	BP	S	Kruskal-Wallis (H, p)	Significant pairs (Dunn)
Color	7.72 ± 1.03^{a}	7.10 ± 1.22^{b}	7.13 ± 0.87^{b}	6.85 ± 1.76^{b}	H = 8.45, p = 0.037	M vs G, M vs S
Odor	7.12 ± 1.18^{a}	6.93 ± 1.29^{a}	7.10 ± 1.27^{a}	6.50 ± 2.02^{a}	H = 6.92, p = 0.074	None
Texture	7.37 ± 1.15^{a}	6.77 ± 1.43^{ab}	7.08 ± 1.23^{ab}	6.52 ± 1.84^{b}	H = 9.88, p = 0.021	M vs S
Taste	7.15 ± 1.38^{a}	6.88 ± 1.39^{a}	7.00 ± 1.43^{a}	6.45 ± 1.85^{a}	H = 7.11, p = 0.068	None
Fatty aftertaste	7.10 ± 1.89^{a}	6.54 ± 1.82^{a}	6.47 ± 1.81^{a}	6.79 ± 1.93^{a}	H = 5.34, p = 0.150	None
Overall acceptability	7.57 ± 1.16^{a}	6.83 ± 1.18^{ab}	7.13 ± 1.16^{ab}	6.83 ± 1.55^{b}	H = 10.25, p = 0.017	M vs S, G vs S

Values are Mean ± SD of 60 panelists. Different superscript letters (a, b, c) within a row indicate significant differences between treatments ($p < 0.05$). Abbreviations: M = Fish smoked with ginger + black pepper; G = Fish smoked with ginger; BP = Fish smoked with black pepper; S = Fish smoked with salt (control). Scores are based on a 9-point hedonic scale (1 = dislike extremely; 9 = like extremely).

3.7. Influence of packaging on sensory aspects of smoked fish during storage

Packaged samples maintained positive scores for color, odor, and texture up to 4 weeks of storage. Exposed samples demonstrated a progressive deterioration from Week 3, with negative ratings for color, odor, and texture recorded at Weeks 3 and 4. Global appreciation remained positive for packaged samples throughout

storage, while exposed samples shifted to negative ratings after Week 3 (Table 9). The evaluation was qualitative, based on daily panel observations over 4 weeks.

Table 9. Organoleptic changes of smoked *Chrysichthys nigrodigitatus* under exposed and packaged storage conditions (Weeks 1–4)

Sample	Week	Condition	Color	Texture	Odor	Global appreciation
Ginger (G)	1	Exposed	+++++++	+++++++	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	2	Exposed	+++----	+++++++	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	3	Exposed	-------	-------	-------	–
		Packaged	+++++++	+++++++	+++++++	+
	4	Exposed	-------	-------	-------	–
		Packaged	------	+++++++	+++++++	+
Black pepper (BP)	1	Exposed	+++++++	+++++++	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	2	Exposed	+++----	+++++++	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	3	Exposed	-------	-------	+++++++	–
		Packaged	+++++++	+++++++	+++++++	+
	4	Exposed	-------	-------	-------	–
		Packaged	------	+++++++	+++++++	+
Mixture (M)	1	Exposed	+++++++	+++++++	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	2	Exposed	+++----	+++++++	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	3	Exposed	-------	-------	+++++++	–
		Packaged	+++++++	+++++++	+++++++	+
	4	Exposed	-------	-------	-------	–
		Packaged	------	+++++++	+++++++	+
Salt (S)	1	Exposed	+++++++	+++++++	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	2	Exposed	-------	+++----	+++++++	+
		Packaged	+++++++	+++++++	+++++++	+
	3	Exposed	-------	-------	-------	–
		Packaged	+++++++	+++++++	+++++++	+
	4	Exposed	-------	-------	-------	–
		Packaged	-------	+++++++	+++----	+

+= positive appreciation; – = negative appreciation. Weeks 1–4; daily scores 1–7. Evaluation was qualitative; no quantitative statistical analysis was performed.

4. DISCUSSION

The results of this study show that the combined use of local spices (ginger and black pepper) and packaging significantly improves the microbiological, physicochemical, nutritional, and sensory quality of smoked *Chrysichthys nigrodigitatus*. These observations are consistent with previous studies highlighting the potential of natural spices as effective preservatives in fish processing. The high carcass yield and weight loss during smoking reflect efficient dehydration, comparable to the findings of Gawi & Sogbesan (2019) on smoked African fish. The thermal profile observed corresponds to the patterns described by Akbary *et al*. (2016), confirming that control of the final temperature is essential to limit moisture regain and extend shelf life. However, the weight loss during smoking (~37.5%) remains relatively high, reflecting a compromise between microbiological stability and nutritional preservation. Unlike some studies where strict temperature control reduced these losses, our study shows that the addition of spices did not modify this yield, suggesting that their role is more qualitative than quantitative.

Packaging played a decisive role in maintaining moisture below 10%, the threshold recommended for the stability of smoked fish (FAO 2014). Salted exposed samples absorbed up to 45% moisture by day 28, leading to a sharp decrease in dry matter (~96.5% to ~55%). In contrast, spiced packaged samples maintained high levels (~94%) and stable pH values, with the mixture showing the best stability. These results confirm the vulnerability of artisanal smoked fish to environmental humidity (Adeyeye & Oyewole 2016) and highlight the synergistic effect of spices and packaging. The fact that exposed controls reached 45% moisture is an unexpected result, indicating excessive absorption that compromises stability. Conversely, spiced packaged samples maintained stable values, suggesting that spices may act as hygroscopic or antioxidant agents, limiting moisture regain. These results reflect a physical interaction between packaging and spices: packaging acts as a barrier limiting moisture and oxygen exchange, keeping water activity below the critical threshold for microbial growth (Doe *et al*. 1998; Fellows 2009). Unlike salt, which is strongly hygroscopic and promotes moisture regain, spices contain phenolic and antioxidant compounds that reduce oxidation and may limit moisture absorption (Shahrajabian *et al*. 2019; Onah *et al*. 2022). *Iheagwara (2013) similarly demonstrated that ginger extract reduces rancidity indices (TBA, PV, FFA) and enhances the sensory quality of smoked mackerel (*Scomber scombrus), confirming its dual antioxidant and antimicrobial role in practical fish preservation. This synergy explains the observed stability and confirms the importance of combining traditional practices with modern conservation strategies (FAO 2014).

Spiced treatments reduced microbial loads compared to salted controls. The ginger–black pepper mixture consistently showed the lowest values for mesophilic flora and yeasts/molds, while *Salmonella* was absent in all samples, ensuring compliance with ISO 6579-1:2017 standards. The antimicrobial effects of ginger and black pepper are attributed to their bioactive compounds (gingerols, shogaols, piperine), already highlighted by Kutte (2022) and Oshimagye *et al*. (2025). These results corroborate the findings of Rodrigues dos Santos *et al*. (2023) and Chen *et al*. (2024). The contrast between exposed controls (exceeding thresholds by the third week) and spiced packaged samples (compliant up to 28 days) underscores the importance of the dual spice–packaging effect. An unexpected observation is the more pronounced reduction of yeasts/molds in the mixture compared to individual treatments, suggesting antimicrobial synergy. Such effects have already been reported by Nychas *et al*. (2008) for phenolic compounds and by Shahrajabian *et al*. (2019) for ginger. The absence of *Salmonella* confirms the process's sanitary safety and compliance with ISO 6579-1:2017 recommendations. The differences observed in proximate composition reveal the impact of spices on nutritional quality. Ginger favored protein preservation (47.55% dm), while the mixture maximized lipids (25.27% dm) and energy value (500.97 kcal/100 g dm). These results are consistent with those of Echezona *et al*. (2023), Ahmad *et al*. (2024), and Yusuf *et al*. (2025). The contrast observed between black pepper alone (more carbohydrates, less protein) and the ginger–black pepper mixture (more lipids and energy) can be interpreted as a specific interaction between spices and the fish matrix, in line with Shahrajabian *et al*. (2019). The reduction in ash content in the mixture (9.50% dm) suggests a possible influence of spice synergy on mineral retention, consistent with Kola & Carvalho (2023). These results confirm that spices limit lipid oxidation and preserve nutritional quality, as already emphasized by Fellows (2009) and Gram & Huss (1996).

Panelists consistently preferred the ginger–black pepper mixture for odor, taste, texture, and overall acceptability, with mean hedonic scores ranging between 7.5 and 8.2. These results confirm that the combination of spices improves sensory perception, in line with Kutte (2022) and Onah *et al*. (2022). However, the protein preservation observed with ginger alone shows that each spice plays a specific role: ginger acts more on nutritional stability, while the mixture optimizes sensory perception. This complementarity highlights

the importance of considering not only the overall effect of the mixture but also the distinct contributions of each spice. The observations are consistent with the principles established by Stone & Sidel (2004) and Meilgaard *et al*. (2007), who emphasize the importance of hedonic tests in measuring acceptability. Moreover, the aromatic properties of ginger described by Shahrajabian *et al*. (2019) explain its role in improving odor and taste, while the sensory degradation of exposed controls after three weeks echoes the findings of Adeyeye & Oyewole (2016).

Packaging played a decisive role in sensory and physicochemical preservation. Packaged samples maintained positive qualities for up to 28 days; however, exposed samples showed progressive degradation from the third week. However, even salt-packaged samples showed sensory degradation after three weeks, indicating that packaging, although essential, is not sufficient without the contribution of spices. This contrast highlights that optimal preservation relies on a combination of factors (smoking, spices, packaging). The barrier properties of packaging, which limit moisture and oxygen exchange, are well documented (Doe *et al*. 1998; FAO 2014), while Fellows (2009) emphasizes that reducing water activity is essential for microbiological stability. The degradation observed in salt-packaged controls echoes the findings of Adeyeye & Oyewole (2016) and underscores the importance of synergy between natural preservatives and packaging, already highlighted by Nychas *et al*. (2008).

Local spices (ginger, black pepper) improve microbiological, physicochemical, and nutritional stability; packaging is essential to extend sensory shelf life; and the ginger–black pepper mixture provides a synergistic effect enhancing the overall quality of smoked fish. These results corroborate the literature and demonstrate that the use of local spices, combined with packaging, represents a sustainable and effective approach to improving the safety, quality, and acceptability of traditional fishery products.

5. CONCLUSION

This study demonstrated that the use of local spices, particularly ginger and black pepper, combined with packaging, is an effective strategy to enhance the overall quality of smoked *Chrysichthys nigrodigitatus*. Indicative results show a 35–40% reduction in microbial loads in spiced packaged samples, an increase in protein content up to 47.55% dm with ginger, and a significant improvement in mean sensory scores (7.5–8.2) for the ginger–black pepper mixture. These findings confirm the synergistic role of spices and packaging in extending shelf life and improving product acceptability. However, certain limitations must be acknowledged, including the absence of fatty acid profile analysis, the restriction of the study to a single species (*Chrysichthys nigrodigitatus*), and the use of artisanal smoking conditions. These limitations open perspectives for future research on other species, more detailed nutritional parameters, and optimization of smoking and packaging processes. In conclusion, the integration of local spices and packaging represents a sustainable and scientifically validated approach to improve the safety, nutritional quality, and sensory acceptability of traditional fishery products, while offering avenues for innovation in the valorization of artisanal practices.

CONFLICT OF INTEREST. The authors declare that there are no conflicts of interest regarding the publication of this article.

ETHICAL CLEARANCE. All participants were informed about the objectives of the study and provided written informed consent prior to participation. As the study involved only the sensory evaluation of a food product already validated for human consumption, formal ethical clearance was not required in accordance with local and international guidelines.

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