Vol. 15, No. 1 (2026): 63 - 78
https://dx.doi.org/10.23960/jtepl.v15i1.63-78

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

# The Use of Botanical Preservatives to Maintain the Quality of Smoked Catfish

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**Article History:**

Received : 3 October 2025
Revised : 8 January 2026
Accepted : 22 January 2026

**Keywords:**

*Botanical preservatives,*
*Microbiological contamination,*
*Quality,*
*Sensory evaluation,*
*Smoked catfish.*

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**ABSTRACT**

*The use of botanical preservatives in smoked catfish is a natural approach to maintaining quality during initial storage through the antioxidant and antimicrobial activities of its bioactive compounds. This study aims to examine the effect of garlic, red ginger, and red galangal extracts in maintaining the sensory quality, color stability, and microbiological contamination of smoked catfish. Smoked catfish were coated with botanical extracts according to the formulation, then stored at room temperature and evaluated after five days of storage. The parameters observed included color changes, sensory evaluation, and microbial contamination. The data were analyzed using ANOVA, Pearson's correlation, and quadratic regression models to identify the relationship between treatment and quality response. The results showed that botanical preservatives were significantly ($p < 0.05$) effective in slowing the deterioration of smoked catfish quality. The preservative formulation of 25% garlic, 50% red ginger, and 25% red galangal was the best treatment, with better color stability, improved sensory acceptance, and a more effective mechanism of inhibiting microbial growth. These findings confirm the potential of botanical preservatives as a natural preservative alternative for smoked catfish products.*

## 1. INTRODUCTION

Smoked catfish (*Pangasius hypothalamus*) is a widely consumed freshwater processed product due to its distinctive taste, appealing texture, and added value compared to fresh products. The smoking process not only serves as a traditional processing method but also produces a distinctive aroma and color, thereby increasing consumer appeal and product value (Bilgin & Değirmenci, 2019). This product has the potential to become a leading commodity because it is relatively easy to produce, is popular with the public, and has a longer shelf life than fresh pangasius fish (Ayeloja *et al.*, 2020). However, storage at room temperature still faces significant problems and challenges related to product quality and safety. During storage, smoked catfish is prone to deterioration in organoleptic quality, color changes, and an increased risk of microbiological contamination, which can negatively impact consumer acceptance. Factors that accelerate this deterioration include the chemical composition of smoked catfish, such as its high water content, fat (10–25%), and protein, which make it prone to oxidation and an ideal medium for the growth of spoilage bacteria (Hafsat *et al.*, 2024; Vijayan *et al.*, 2021).

The issue of quality and safety deterioration is a significant challenge in storage, requiring innovation to maintain the quality of smoked catfish during storage. One promising innovation is the use of natural preservatives derived from spice extracts, which can slow down the oxidation process and inhibit the growth of microorganisms. The innovative use of tropical spices, such as red ginger (*Zingiber officinale* var. *rubrum*), red galangal (*Alpinia galanga* var.

*rubra*), and garlic (*Allium sativum*), has great potential because they contain key bioactive compounds, including *allicin*, *gingerol*, and *galangin*, which act as natural antioxidants and antimicrobials. These compounds serve to extend shelf life and maintain the sensory quality of the product without reducing the distinctive characteristics of smoked catfish.

Garlic extract is known to have a high *allicin* content and sulfur compounds as potent antimicrobial agents in inhibiting bacteria such as *E. coli*, *Salmonella*, and *S. aureus* (Xainhiaxang *et al.*, 2018), and high antioxidant activity due to its flavonoid and phenolic compound content (Cocom *et al.*, 2025; Jang *et al.*, 2017). Red ginger has high antioxidant activity in the form of polyphenolic compounds (gingerol) and is capable of inhibiting *E. coli* and *S. aureus* (Budiari *et al.*, 2022; Mesomo *et al.*, 2013; Sholikhati *et al.*, 2021). Meanwhile, red galangal is rich in flavonoids that function as antioxidants and antimicrobials, effective in suppressing the growth *E. coli*, *S. aureus*, and *Salmonella* (Hidayati *et al.*, 2023; Xainhiaxang *et al.*, 2018).

Several previous studies have proven that the use of these spice extracts can improve the quality of products such as smoked mackerel (Iheagwara, 2013), *Clarias Gariepinus* fish (Utah *et al.*, 2021), presto milkfish (Iriani *et al.*, 2022), smoked catfish (Ubadire-Agua *et al.*, 2023), and catfish balls (Aisyah *et al*., 2025). However, most of these studies only examined individual extracts, while studies on the combination of garlic, red ginger, and red galangal extracts in smoked catfish are still minimal. *Allicin*, *gingerol*, and *galangin* have the potential to interact and enhance their antioxidant and antimicrobial activities. However, this study was not designed to test the factorial synergy between individual extracts or two- or three-way combinations. The findings obtained can be more accurately understood as the composite contribution of each compound, which, as a whole, shows a tendency to maintain color stability, sensory quality, and suppress microbiological contamination in smoked catfish. The synergy claim remains hypothetical and requires verification through a specific experimental design.

This study aimed to investigate the impact of garlic, red ginger, and red galangal extracts on the quality and microbiological contamination of smoked catfish, focusing on color changes, sensory evaluation, and microbial contamination after five days of storage. Smoked catfish is a semi-perishable product with a high water content, so quality deterioration occurs more rapidly in the early stages of storage at room temperature. The first few days after processing are a critical period, marked by accelerated lipid oxidation, the formation of volatile compounds, and a decline in sensory characteristics. On that basis, quality evaluation focused on a five-day storage period to capture the most intense changes in quality while sensitively assessing the role of botanical preservatives in slowing the rate of deterioration. This approach is also relevant because it reflects the actual consumption patterns of smoked fish in a distribution system without refrigeration. This study employs a formulation engineering approach to develop optimal natural preservatives that produce significant effects in maintaining warmth, enhancing sensory evaluation, inhibiting microbial growth, and increasing the added value of smoked catfish.

## 2. MATERIALS AND METHODS

### 2.1. Materials and Sample Preparation

Fresh garlic (*Allium sativum*), red ginger (*Zingiber officinale* var. *rubrum*), and red galangal (*Alpinia galanga* var. *rubra*) were obtained from local markets in Pekanbaru, Riau. Thirty smoked catfish were obtained from UMKM Putra Niaga, Desa Koto Mesjid, Kecamatan XIII Koto Kampar, Kabupaten Kampar, Riau, at a harvest age of 3.5 months with a length of 25±0.6 cm and a width of 7±1.2 cm. Before use, fresh catfish were processed into smoked catfish through the stages of sorting, gutting, separating the entrails, washing, draining, and smoking. Smoking was conducted for eight hours, with smoke sourced from burning ubau and rambutan wood, following standard operating practices consistently applied by UMKM at the research location. The smoking duration was kept constant to represent the actual processing conditions at the producer level and was not used as a variable in the research. Ubau wood and rambutan were chosen based on their local availability and everyday use by UMKM thus reflecting the actual processing conditions in the field. After smoking, the catfish had a final length of 22±0.6 cm and a width of 7±1.2 cm. The materials used for microbiological contamination analysis were Buffered Peptone Water (BPW), Peptone Dilution Fluid (PDF), MacConkey Broth (MCB), Baird-Parker Agar (BPA), and Rappaport-Vassiliadis Broth (RVB). Other supporting materials used included filter paper, distilled water, and pH 4 and 7 buffer solutions.

Figure 1. (a) Garlic extract, (b) red ginger extract, and (c) red galangal extract

## 2.2. Methods

### 2.2.1. Extraction of Garlic, Red Ginger, and Red Galangal

The extraction of garlic, red ginger, and red galangal was carried out using the method described by Iriani *et al.* (2022) with modifications. Fresh materials were washed with running water, then the garlic was peeled, while the red ginger and red galangal were thinly peeled. All materials were cut into small pieces (1–2 cm) to facilitate the extraction process. The pieces were extracted using a slow juicer (e-Home, WJE-F1B) without the addition of distilled water to obtain a pure extract. The filtrate was collected in a sterile container, while the residue was separated. The yield of garlic and red ginger extract was 50% (±50 mL per 100 g of ingredients), while the yield of red galangal extract was 25.13% (±25.13 mL per 100 g of ingredients). The filtrate was then filtered using filter paper to remove any remaining solid particles. All pure extracts were placed in sterile plastic containers and immediately applied in their fresh condition, without storage, to maintain stability against degradation of bioactive compounds due to light exposure.

### 2.2.2. Formulation of Garlic, Red Ginger, and Red Galangal Extracts

Pure extracts of garlic, red ginger, and red galangal were formulated in various combinations, with ratios determined based on previous studies and modifications (Nendissa & Nendissa, 2021; Thaker *et al.*, 2015). The mixing process was carried out in a sterile plastic container and homogenized using a stirring rod for 10 minutes to maintain the solution's stability. The four formulations were coded, as shown in Table 1.

### 2.2.3. Application of Extract Formulation on Smoked Catfish

Smoked catfish of uniform size (length 22±0.6 cm, width 7±1.2 cm) were divided into five treatment groups, namely four extract treatments (Table 1) and one control without extract. The application was carried out using the immersion method for five minutes based on previous studies with modifications (Azzahra *et al.*, 2013; Jiménez-Ruíz *et al.*, 2023). Immersion was carried out by soaking the entire surface of the fish in the extract solution. The first immersion lasted three minutes, followed by a brief draining period, and then a second immersion for two minutes to obtain a more uniform extract layer while minimizing the loss of coating material during removal. The percentage of extract adhering to the surface of smoked catfish after dipping was not quantitatively determined; however, the duration and conditions of application were kept constant throughout the treatment to ensure uniform coating. The immersion procedure was controlled and applied uniformly to all samples, ensuring a relatively consistent surface coating that allowed for the evaluation of the extract's effect without bias due to differences in application techniques. The control treatment on smoked catfish did not involve immersion in the extract. After soaking, the smoked catfish was drained

Table 1. Formulation of garlic, red ginger, and red galangal extracts

| Treatment | Description |
|---|---|
| 25B25J50L | Preservative 25% garlic, 25% red ginger, 50% red galangal |
| 33B33J33L | Preservative 33.3% garlic, 33.3% red ginger, 33.3% red galangal |
| 25B50J25L | Preservative 25% garlic, 50% red ginger, 25% red galangal |
| 50B25J25L | Preservative 50% garlic, 25% red ginger, 25% red galangal |

for two minutes, placed in a styrofoam container, and stored at room temperature (±27 °C) with an average relative humidity (RH) of (63±1.03)% for five days. The evaluation was conducted on the fifth day, with the parameters analyzed including color measurement, sensory evaluation (descriptive and hedonic) covering color, aroma, texture, and overall evaluation, as well as microbiological contamination analysis for *E. coli*, *S. aureus*, and *Salmonella*. Analysis on day 0 was not performed because the smoked catfish used was freshly smoked; therefore, the samples were still in optimal condition, with minimal microbial contamination and no changes in sensory quality. The interpretation of the research results was limited to comparisons between treatments after five days of storage at room temperature, without considering changes in quality relative to the initial condition (day 0). This study was designed as an endpoint storage evaluation, so all quality parameters were analyzed on day 5 to describe the product condition and differences between treatments at that time.

### 2.3. Test Parameters

The testing focused on the effectiveness of botanical extract formulations as natural preservatives in maintaining the quality of smoked catfish. The characterization of the extract was limited to measuring pH as a fundamental parameter that reflects the acidity of the solution and its relevance to microbial stability and compatibility with the structure of smoked catfish meat. At the same time, phytochemical analysis and antioxidant activity were not included in the scope of this study. The pH of the extract solution was measured using a pH meter (pH 5 plus, LaMotte) that had been calibrated with pH 4 and 7 buffer solutions (Rusita *et al.*, 2024). A total of 50 mL of each treatment was placed in a beaker, and the electrode was immersed until the value stabilized. The measurement was performed three times, and the results were expressed as the mean ± standard deviation.

The color of smoked catfish was measured using a colorimeter (3nh, NH300) that had been calibrated according to the procedure prior to sample analysis based on the CIE-Lab color system (Biassi *et al.*, 2018; Jiménez-Ruíz *et al.*, 2023; Kefale *et al.*, 2023). The parameters measured included lightness ($L^*$), red-green color intensity coordinates ($a^*$), yellow-blue color intensity coordinates ($b^*$), chroma value ($C^*$), and color change ($\Delta E^*$). Each measurement was performed three times, and the results were expressed as the mean ± standard deviation. The chroma value ($C^*$) and total color change ($\Delta E^*$) were obtained from the colorimeter measurement system after the calibration process, which automatically calculated the chroma value and color difference based on the instrument's internal reference values. Conceptually, $C^*$ and $\Delta E^*$ were calculated using Equation 1 and Equation 2.

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{1}$$

$$\Delta E^* = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{1}$$

where $L^*$, $a^*$, $b^*$ are brightness value, red-green color coordinate, yellow-blue color coordinate; $L_0^*$, $a_0^*$, $b_0^*$ are standard color value (reference).

Sensory evaluation was conducted to assess the quality of smoked catfish treated with the extract formulation after five days of storage (Sanjaya *et al.*, 2018; Yusuf *et al.*, 2025). Sensory evaluation was performed through descriptive and hedonic tests of color, aroma, texture, and overall assessment attributes. The assessment involved 80 semi-trained panelists who had a basic understanding of sensory attributes and the use of scales, enabling them to assess attribute intensity and preferences. The same panelists conducted both types of tests to maintain consistency of perception between attributes. All parameters were assessed using a 1−9 point scale. Testing was carried out in a well-lit and ventilated room to minimize assessment bias.

Microbiological contamination analysis aimed to detect the presence of *E. coli*, *S. aureus*, and *Salmonella* in smoked catfish treated with extract formulations after five days of storage (Kefas *et al.*, 2022; Nurmila & Kusdiyantini, 2018). A 25 g sample was mixed with 225 mL of diluting medium according to the standard for each microbe (PDF for *E. coli*, BPW for *S. aureus* and *Salmonella*), incubated, and observed for growth. Microbial detection was observed based on colony growth, characterized by reddish-pink growth on MCB for *E. coli*, typical colonies on BPA for *S. aureus*, and pinkish-white growth with a reddish zone on RVB for *Salmonella*. Microbiological analysis was performed in triplicate, and the results are expressed as the mean ± standard deviation. Interpretation focused on comparisons between treatments.

### 2.4. Experimental Design and Data Analysis

This study employed a completely randomized design (CRD) with one factor: the treatment of smoked catfish immersion in each extract formulation. Five treatments were applied, namely four test groups according to the extract combination formulation (Table 1) and one control group without extract, each with three replicates. Data were analyzed using IBM SPSS Statistics 25 and Microsoft Excel software, with statistical analyses including one-way analysis of variance (ANOVA), Pearson's correlation test, and polynomial regression models. Analysis of variance (one-way ANOVA) was used to compare the means between treatments at a significance level of $\alpha = 0.05$, followed by the Tukey post hoc test to determine which treatment groups were significantly different. The results were interpreted descriptively to identify differences between treatments, without attempting to make statistical generalizations. Pearson's correlation analysis was used to evaluate the relationship between the measured parameters and understand the correlation between variables. A polynomial regression model was developed using MS Excel to evaluate the direction of the relationship and the relative influence of the treatment variables on the response. This model was not intended as a predictive tool, but rather to understand the relationship between variables within the limits of the observed experimental data. The results of the analysis are presented in tables and graphs to facilitate data interpretation and to compare the effectiveness of the extract formulation as a natural preservative in smoked catfish.

## 3. RESULTS AND DISCUSSION

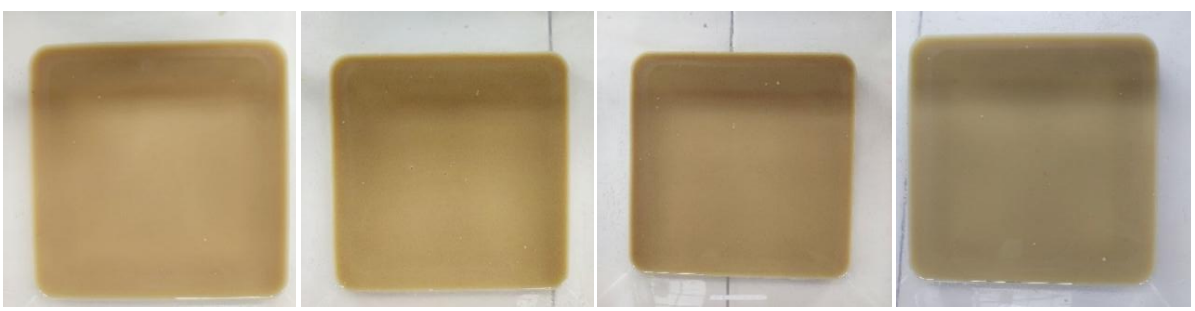
### 3.1. pH of Extract

The pH value is an initial parameter for characterizing the extract solution, as it reflects the chemical composition and potential interactions between bioactive compounds that affect its effectiveness as a natural preservative. pH variation indicates the acidity level of each extract. pH measurements were performed on garlic, red ginger, red galangal, and mixed formulations, and the results are presented in Table 2 and visualized in Figures 2.

Table 2. pH values of extracts

| Garlic | Red ginger | Red galangal | 25B25J50L | 33B33J33L | 25B50J25L | 50B25J25L |
|---|---|---|---|---|---|---|
| $6.60 \pm 0.03^{g}$ | $5.49 \pm 0.02^{b}$ | $4.65 \pm 0.02^{a}$ | $5.96 \pm 0.03^{d}$ | $6.12 \pm 0.04^{e}$ | $5.88 \pm 0.02^{c}$ | $6.38 \pm 0.03^{f}$ |

Mean ± SD, n = 3. Different letters in each column indicate significant differences ($p < 0.05$) based on Tukey's post-hoc test.



(a) (b) (c) (d)

Figure 2. Treatments 25B25J50L (a), 33B33J33L (b), 25B50J25L (c), and 50B25J25L (d)

Table 2 shows a significant difference in pH values ($p < 0.05$between single extracts and mixed extract formulations. The difference in pH between extracts and mixed formulations reflects the chemical properties of the dominant bioactive compounds inherent in each ingredient. The pH value represents the balance of phenolics, organosulfur, organic acids, and volatile components that affect the stability of the system. Red ginger and red galangal extracts are rich in phenolics and organic acids, which lower the pH and possess the most acidic properties. In contrast, garlic extract tends to be more alkaline (neutral) due to the dominance of organosulfur compounds such as allicin, which are reactive but not strongly acidic. In mixed extract formulations, the pH effect is both additive and interactive, reflecting the modulation between bioactive components that produces a characteristic pH identity at each extract ratio. The pH values obtained are in line with previous reports, namely garlic 6.03–6.06 (Kefale *et al.*, 2023; Setiyoningrum *et al.*, 2020), red ginger extract 5.76–6.9 (Kefale *et al.*, 2023; Tetelepta, 2024), and red galangal 3.7–4.31 (Rialita *et al.*, 2019; Winarti *et al.*, 2007).

The mixed extract formulation produced varying pH values depending on the ratio of each treatment. The extract mixture formulation exhibited changes in pH due to chemical interactions between its components. In general, the proportion of red ginger and red galangal lowered the pH, while the proportion of garlic increased the pH of the formulation. These differences in pH values were related to the concentration of each extract in the formulation; the higher the concentration of acidic extract, the lower the pH value produced. Low pH enhances antimicrobial activity by increasing the positive charge of the active compound. However, excessively low pH reduces stability, so moderate pH serves as a balance point between the effectiveness and consistency of the system. A mixture formulation of 25% garlic extract, 50% red ginger extract, and 25% red galangal extract is a mixture formulation with low pH (acidic), so it has the potential to be effective in inhibiting microbial growth, because the more acidic a solution is, the more potential it has to reduce the growth of spoilage microbes (Rusita *et al.*, 2024). Therefore, the extract composition can be considered the primary variable that determines the pH response, rather than just an additional factor.

### 3.2. Color of Smoked Catfish

Color is one of the important quality attributes of smoked catfish that affects consumer perception of quality and attractiveness. Color changes during storage indicate quality degradation due to pigment oxidation, protein degradation, and enzyme activity. The brightness ($L^*$), redness ($a^*$), yellowness ($b^*$), chroma ($C^*$), and total color difference ($\Delta E^*$) values of smoked catfish after five days of storage are presented in Table 3 and Figure 3.

Table 3. Color values of smoked catfish after five days of storage

| Color attribute | Control | 25B25J50L | 33B33J33L | 25B50J25L | 50B25J25L |
|---|---|---|---|---|---|
| $L^*$ | 39.85±5.99$^{ab}$ | 38.12±3.17$^{a}$ | 40.04±4.27$^{ab}$ | 40.36±2.93$^{ab}$ | 41.27±2.07$^{b}$ |
| $a^*$ | 13.82±1.83$^{b}$ | 12.91±0.72$^{a}$ | 13.59±1.07$^{ab}$ | 13.14±1.12$^{ab}$ | 13.30±0.76$^{ab}$ |
| $b^*$ | 9.51±1.37$^{b}$ | 8.65±0.46$^{a}$ | 9.35±0.63$^{b}$ | 9.23±1.06$^{ab}$ | 9.42±0.63$^{b}$ |
| $C^*$ | 16.78±2.27$^{a}$ | 15.55±0.80$^{a}$ | 16.50±1.20$^{a}$ | 16.06±1.49$^{a}$ | 16.30±0.94$^{a}$ |
| $\Delta E^*$ | 24.72±29.16$^{b}$ | 3.16±2.11$^{a}$ | 3.51±1.65$^{a}$ | 4.27±1.97$^{a}$ | 4.47±1.91$^{a}$ |

Note: values are (mean ± SD), $n = 18$. Different letters in each row indicate significant differences ($p < 0.05$) based on Tukey's post-hoc test.

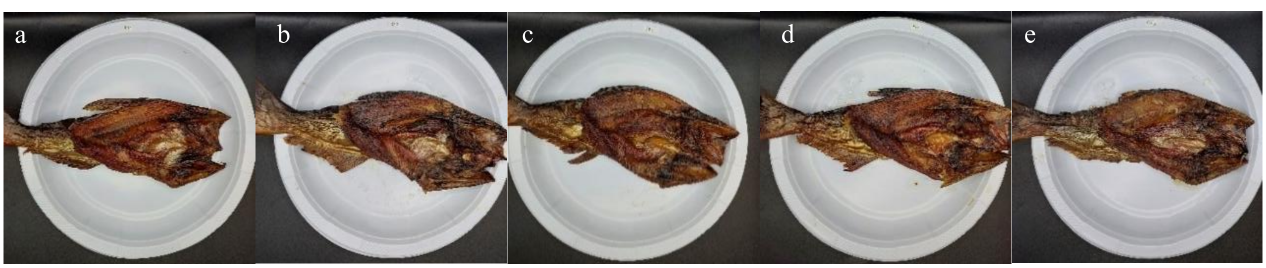



Figure 3. Control treatment (a), 25B25J50L (b), 33B33J33L (c), 25B50J25L (d), and 50B25J25L (e)

Table 3 shows that $L^*$, $a^*$, $b^*$, and $\Delta E^*$ differed significantly between treatments ($p < 0.05$), while $C^*$ values did not differ significantly ($p > 0.05$). The extract formulation affected brightness, red and yellow color intensity, and reduced color change without altering the chroma of smoked catfish. The highest $L^*$ value was found in the 50B25J25L treatment (41.27±2.07), the highest $a^*$ value was found in the 33B33J33L treatment (13.59±1.07), and the highest $b^*$ value was found in the 50B25J25L treatment (9.42±0.63), while the control treatment had a low $L^*$ value (39.85±5.99) and high $a^*$ (13.82±1.83) and $b^*$ (9.51±1.37) values compared to the extract treatments.

Significant differences in the $L^*$ parameter between treatments indicate the effect of the extract formulation on the surface reflectance of smoked catfish. This change is related to the formation of a thin layer that modifies the interaction of light with the smoked catfish tissue. Phenolic compounds and volatile components selectively absorb and reflect light, so that variations in the extract ratio produce noticeably different brightness. The difference in $a^*$ is relatively more limited than in brightness, indicating the role of the extract as a stabilizer of the red hue resulting from smoking. The extract layer prevents the degradation of Maillard pigments and carbonyl compounds, which contribute to the reddish-brown color. The $b^*$ parameter responds selectively to treatment, reflecting the sensitivity of yellow pigments to oxidative conditions. Phenolic compounds act as antioxidants that inhibit the formation of yellow to brown lipid oxidation products.

The increase in $L*$ is thought to be related to water loss from the surface of smoked catfish and the effect of the thin extract coating. $a^*$ is influenced by non-enzymatic browning reactions (Maillard reactions) during storage, and the carotenoid pigments influence the antioxidant interaction of the extract, and $b^*$ in red ginger and red galangal extracts. The color change of smoked catfish depends on the type of material and formulation of the extract coating used, which changes the overall appearance of the smoked catfish, according to de Lima *et al.* (2024). Additionally, the increase in $L^*$, $a^*$, $b^*$ values is attributed to the brighter color of the extract formulation and its faster drying time compared to other treatments. The increase in $L*$ value and decrease in $a^*$ and $b^*$ values are likely due to water loss from the surface and reduced myoglobin and hemoglobin levels in the meat during storage, resulting in a brighter surface effect (Jiménez-Ruíz *et al.*, 2023). Erkan (2012) noted that the application of garlic oil to rainbow trout fillets in vacuum packaging resulted in an increase in $L^*$ values and a decrease in $a^*$ and $b^*$ values, leading to a brighter color after seven weeks of storage.

The absence of significant differences in $C^*$ indicates that the color saturation of smoked catfish remains consistent across treatments. The extract formulation maintains the color intensity of the smoked product without causing it to fade. The chroma stability indicates that the extract layer does not interfere with the main pigment structure, but rather maintains the balance between the red and yellow components. The highest C value in the control treatment (16.78 ± 2.27) produced a more intense color compared to the other treatments. The combined intensity of red and yellow colors influences the $C^*$ value. Treatment 33B33J33L produced a more intense color than the other extract treatments, likely due to the balanced combination of pigments from garlic, red ginger, and red galangal extracts. The $\Delta E^*$ difference shows a clear separation between the extract-coated samples and the uncoated (control) samples. These results confirm that the extract coating suppresses cumulative visual changes over a five-day storage period. This effect is related to the coating's ability to limit the diffusion of oxygen and water vapor, thereby slowing the oxidation and degradation of the pigment. The $\Delta E^*$ value of the extract treatment is lower than that of the control, indicating that the extract formulation acts as a color-protecting agent. This mechanism is related to the antioxidant activity of the extract, which can inhibit the oxidation of myoglobin and hemoglobin pigments, thereby slowing down the browning reaction during the storage of smoked catfish. The control treatment without coating resulted in a high $\Delta E^*$ value because there was no protection to inhibit the oxidation reaction. Jeong *et al.* (2018) stated that color values were influenced by immersion treatment in the extract solution, which had a substantial effect on the resulting color attributes.

Analysis of the $a^*$ and $b^*$ colors using the CIE Lab system revealed significant variations between treatments ($p < 0.05$), indicating that the extract formulation had an impact on the visual appearance of smoked catfish. The color of smoked catfish is presented in the form of $a^*$ (red-green) and $b^*$ (yellow-blue) coordinate systems, which can be seen in Figure 4. It shows the $a^*$ and $b^*$ coordinates of different smoked catfish according to the extract composition and color dominance, with a red-yellow color coordinate tendency. These coordinates reflect the mixture of red and yellow intensities, resulting in the dark brown color characteristic of smoked catfish. The control treatment tended to be a reddish-brown color. 25B25J50L produced a faded brown color, transitioning away from yellow. 33B33J33L was balanced between red and yellow, with a reddish-brown hue. 25B50J25L and 50B25J25L approached yellow, resulting in colors ranging from yellowish-brown to dark brown.

The extract treatment can reduce the decrease in $a^*$ and $b^*$ values caused by the oxidation of myoglobin, thereby maintaining the red color of smoked catfish, as seen in the relatively stable values after five days of storage (Table 3), in accordance with the opinion of de Lima *et al.* (2024), who stated that a protective layer can slow down the oxidation process. The $a^*$ and $b^*$ values were more stable. They experienced a minimal decrease with the addition of 1% red galangal essential oil, as red galangal essential oil contains antioxidants that can inhibit pigment reduction in fish fillets during storage (Azzahra *et al.*, 2013).

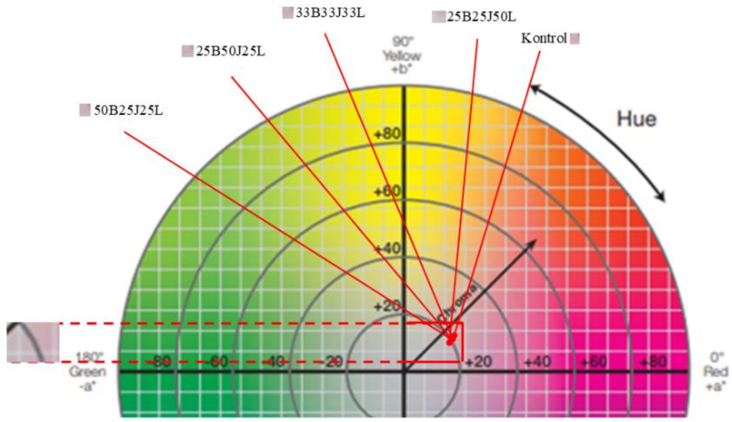



Figure 4. CIElab color chart of smoked catfish from different treatments. Sample name = *a** and *b** coordinates.

### 3.3. Sensory Evaluation of Smoked Catfish

Sensory evaluation of smoked catfish was conducted using two approaches: descriptive testing and hedonic testing. This test aimed to assess sensory attributes and the panelists' acceptance level of smoked catfish after being coated with various extract formulations. The results of the descriptive and hedonic sensory evaluations are presented in Table 4. The table shows that the descriptive sensory evaluation of color, aroma, and firmness showed significant differences between treatments ($p < 0.05$). The panelists assessed that the mixed extract formulation made a significant contribution to the descriptive sensory attributes. The panelists' assessment of the descriptive sensory attribute of color showed that they were able to distinguish the intensity and character of color between treatments. This variation is related to the interaction of phenolic compounds and browning pigments; however, the changes that occur are gradual, allowing them to remain within the typical color spectrum of smoked fish. The 25B50J25L and 25B25J50L treatments tended to produce a browner color compared to the other treatments, while the control treatment and 50B25J25L showed less attractive colors. This suggests that ginger and red galangal extracts contribute to the intensification of the brown color in smoked catfish.

Table 4. Descriptive and hedonic sensory evaluation of smoked catfish

| Quality Factor | Criteria | Control | 25B25J50L | 33B33J33L | 25B50J25L | 50B25J25L |
|---|---|---|---|---|---|---|
| Descriptive sensory | Color | $6.48 \pm 1.19^{a}$ | $7.43 \pm 1.11^{c}$ | $6.98 \pm 1.32^{b}$ | $7.30 \pm 1.19^{bc}$ | $6.31 \pm 1.36^{a}$ |
| | Aroma | $4.25 \pm 1.51^{a}$ | $6.64 \pm 0.85^{c}$ | $6.29 \pm 1.54^{bc}$ | $6.18 \pm 1.44^{b}$ | $7.13 \pm 0.97^{d}$ |
| | Texture | $7.33 \pm 0.97^{b}$ | $6.66 \pm 1.28^{a}$ | $6.53 \pm 1.74^{a}$ | $6.76 \pm 1.05^{a}$ | $6.81 \pm 0.94^{a}$ |
| Hedonic Sensory | Color | $6.20 \pm 1.13^{a}$ | $6.04 \pm 1.08^{a}$ | $6.11 \pm 1.04^{a}$ | $6.23 \pm 1.18^{a}$ | $6.34 \pm 0.98^{a}$ |
| | Aroma | $6.40 \pm 0.99^{a}$ | $6.74 \pm 1.11^{a}$ | $6.69 \pm 1.22^{a}$ | $6.53 \pm 0.97^{a}$ | $6.66 \pm 0.95^{a}$ |
| | Texture | $5.81 \pm 1.32^{a}$ | $6.10 \pm 1.21^{a}$ | $6.13 \pm 1.19^{a}$ | $6.00 \pm 1.44^{a}$ | $5.94 \pm 1.33^{a}$ |
| | Overall | $6.19 \pm 0.94^{a}$ | $6.54 \pm 0.73^{ab}$ | $6.63 \pm 0.85^{b}$ | $6.23 \pm 1.16^{ab}$ | $6.21 \pm 1.26^{ab}$ |

Note: values are (mean ± SD), $n = 80$. Different letters in each column indicate significant differences ($p < 0.05$) based on Tukey's post-hoc test. Description for **Color**: 6 (brown), 7 (dark brown), 8 (blackish brown), 9 (black). **Aroma**: 4 (slightly smoky fish aroma), 5 (neutral aroma), 6 (slightly spicy aroma), 7 (spicy aroma), 8 (very spicy aroma), 9 (extremely spicy aroma). **Hardness**: 6 (slightly hard), 7 (hard), 8 (very hard), 9 (extremely hard); **Hedonic** = 5 (neutral), 6 (slightly liked), 7 (liked), 8 (very liked), 9 (extremely liked).

Descriptive sensory attributes of aroma showed the most apparent differences among all parameters, indicating that the extract formulation enriched the aroma profile of smoked fish through the interaction of volatile compounds of garlic, red ginger, and red galangal, which the panelists easily recognized. Sulfur compounds from garlic and aromatic components of red ginger and red galangal contribute to the complexity of the spice aroma that interacts with the smoke aroma. Descriptive sensory analysis of hardness attributes reveals that, except for the control treatment, all other treatments are not significantly different from each other. These results confirm that the application of the extract mixture formulation does not affect the physical structure of the fish tissue and produces a relatively dense and compact texture. Descriptive hardness assessment revealed that the extract formulation still had a significant impact, characterized by a dense and compact texture, on smoked catfish. Texture was more influenced by the smoking process and protein coagulation, so that the extract formulation served only as a sensory enhancer without altering the structure.

Hedonic sensory evaluation of color, aroma, and hardness showed no significant differences between treatments ($p > 0.05$), while overall acceptance differed significantly ($p < 0.05$) (Table 4). These results confirm that the extract formulation does not significantly alter the sensory characteristics of color, aroma, and hardness; however, it still has a positive effect on the overall preference of the panelists. The hedonic sensory assessment pattern was consistent with the descriptive sensory assessment; the extract formulation can increase panelists' acceptance of smoked catfish. The hedonic color rating fell into the "somewhat like" category, the aroma was rated as "somewhat like" to "like", the texture was rated as "somewhat like", and the overall assessment was categorized as "somewhat like" to "like". Hedonic sensory color shows that the variations in perception that appeared in the descriptive test were not strong enough to influence panelist preferences. In terms of hedonic sensory, all treatments were accepted in the same preference category, indicating that consumers still accept color variations as long as they resemble the typical appearance of smoked fish. Hedonic sensory aroma indicates that panelists rated smoked catfish at the same level of liking, despite being able to distinguish aroma characteristics in detail. This finding confirms that a more complex aroma does not always make a product more likable. Hedonic sensory hardness shows that the extract formulation does not affect the texture of smoked catfish. All samples remained at a level of hardness that was acceptable to consumers. These findings are consistent with the descriptive test and confirm that texture is not a limiting factor for sensory acceptance in this study. Overall hedonic acceptance shows that overall acceptance is not determined by a single attribute, but rather by a combination of color, aroma, and texture. The highest overall hedonic acceptance was found in 33B33J33L (6.63±0.85) with the category "like", while the lowest value was in 50B25J25L (6.21±1.26) with the category "somewhat like". The balanced extract formulation in 33B33J33L produced a balanced and easily recognizable sharp aroma profile by the panelists, thereby increasing the overall hedonic score even though it was not followed by high antimicrobial efficacy. The effectiveness of microbial inhibition in treatment 33B33J33L is limited, presumably because the levels of allicin, gingerol, and shogaol are below the effective threshold for suppressing the growth of *S. aureus* (Table 5), resulting in lower antimicrobial activity, despite maintaining high sensory acceptance. This difference confirms that the quality of smoked catfish has two dimensions: sensory preference, as reflected in hedonic scores, and microbiological safety, as indicated by the effectiveness of the extract as a natural preservative.

The findings in this study align with previous studies, which have found that the addition of extracts can enhance the sensory attributes of smoked fish. Idris *et al.* (2010) reported that panelists preferred smoked catfish with 2.5% ginger extract over the control, particularly in terms of color, aroma, firmness, and overall acceptance. Iheagwara (2013) stated that the hedonic sensory properties of smoked mackerel with ginger extract (1–5%) had better sensory quality than the control, due to increased lipid oxidation, which affected appearance, tenderness, firmness, taste, aroma, and overall assessment. Raimi & Salami (2025) also reported that a combination of 2% moringa and ginger can improve the aroma, taste, texture, appearance, and overall acceptance of smoked catfish. Ahmed *et al.* (2019) stated that garlic and ginger extracts can improve the hedonic sensory quality of taste and overall acceptance of herring fillets.

### 3.4. Microbial Contamination of Smoked Catfish

Microbial contamination analysis of smoked catfish was conducted to assess the effectiveness of the extract formulation in suppressing the presence of pathogenic bacteria, including *E. coli*, *S. aureus*, and *Salmonella*. This microbial contamination analysis is important because the presence of pathogenic bacteria is a key indicator of food safety in smoked catfish products. The results of the microbial contamination analysis of smoked catfish are presented in Table 5, which shows that *E. coli* and *Salmonella* were not detected in all treatments, indicating that the bacterial population was below the method's detection threshold. The undetectable levels of *E. coli* and *Salmonella* in all treatments were attributed to exposure to high temperatures during the smoking process, as well as the presence of phenolic compounds and antimicrobial components that worked synergistically to suppress the growth of these two bacteria. This condition indicates that the method of processing smoked catfish through smoking and extract formulation treatment is effective in inhibiting these two types of pathogenic bacteria from the outset. Storage conditions also do not support the regrowth of these two microorganisms. These results confirm that the combination of smoking and extract treatment has the potential to protect against pathogenic bacterial contamination. Microbial variability primarily originates from *S. aureus*, which is more tolerant to environmental stress, making it a sensitive indicator in antimicrobial evaluations. Statistical analysis showed a significant difference ($p < 0.05$) in *S. aureus* microbes between treatments. These significant differences reflect the complex interaction between phenolic compounds, organosulfur, and volatile components with the cell walls of Gram-positive bacteria. Phenolic compounds cause protein denaturation and membrane disruption, while sulfur compounds interact with cellular enzymes. The 33B33J33L formulation exhibited higher levels of *S. aureus* contamination compared to the control, which can be attributed to a matrix effect rather than a failure of the extract formulation. This condition may occur because certain water-soluble compounds increase the availability of surface nutrients for bacteria, forming a hygroscopic layer that increases micro-moisture and supports the growth of *S. aureus*.

The absence of *E. coli* and *Salmonella* in all treatments indicates that smoked catfish products meet the basic safety requirements outlined in SNI 2725:2013 (BSN, 2013). The absence of *E. coli* and *Salmonella* indicates the successful implementation of hygiene, processing, and storage standards that meet global food safety principles (Codex Alimentarius Commission, 2019). In contrast, the presence of *S. aureus* in limited quantities is considered an indicator of process quality, reflecting microbial control by the extract formulation, and remains within acceptable regulatory limits. Based on SNI 2725:2013 and *Codex Alimentarius*, the application of extract formulations can be used as a risk management strategy, with its effectiveness evaluated to protect consumers without compromising the microbiological safety of smoked catfish. The 25B50J25L treatment proved to be the most effective in suppressing the growth of *S. aureus* compared to other treatments. This effectiveness is related to the proportion of red ginger (50%), which possesses potent antimicrobial activity due to it bioactive compounds, specifically gingerol and shogaol. These results align with the research by Utah *et al.* (2021), which reported that ginger and garlic extracts inhibited the growth of *Staphylococcus* spp. and *Micrococcus* spp. in smoked *Clarias gariepinus* fish. The combined effect of garlic and ginger is attributed to the presence of phenolic compounds that can kill microbes (Rajendrasozhan, 2024).

Table 5. Microbial contamination of smoked catfish

| Criteria | Control | 25B25J50L | 33B33J33L | 25B50J25L | 50B25J25L |
|---|---|---|---|---|---|
| *E. coli* (CFU/g) | Not detected | Not detected | Not detected | Not detected | Not detected |
| *S. aureus* (CFU/g)* | $2.32\times10^6\pm1\times10^{4c}$ | $1.56\times10^6\pm0.00^a$ | $7.4\times10^6\pm0.00^e$ | $6.0\times10^4 \pm 0.00^d$ | $2.0\times10^6 \pm 0.00^b$ |
| *Salmonella* (CFU/g) | Not detected | Not detected | Not detected | Not detected | Not detected |

*) Mean±SD, $n$ = 3. Different letters in each column indicate significant differences ($p < 0.05$) based on Tukey's post-hoc test.

Treatment 25B50J25L had lower microbial contamination values compared to those reported in the study by Ubadire-Agua *et al.* (2023). The use of 1.5% ginger extract and 1.5% garlic extract can inhibit the growth of *E. coli* ($4.2\times10^5$ CFU/g), *S. aureus* ($8.0\times10^5$ CFU/g), and *Salmonella* ($8.3\times10^5$ CFU/g) on the fourth day of storage at room temperature. These differences in results are likely influenced by several factors, including the type of spice, extract concentration, formulation combination, type of microorganism, and the test medium used (Utah *et al.*, 2021).

### 3.5. Relationship and Modeling of Smoked Catfish Quality Parameters

Pearson's correlation analysis ($r$) was used to assess the strength and direction of the linear relationship between the quality parameters of smoked catfish. The r value ranges from -1 to +1, with values close to -1 indicating a strong negative correlation and values close to +1 indicating a strong positive correlation. In this study, Pearson's correlation was used to evaluate the linear relationship between smoked catfish quality parameters, color changes, sensory evaluation, and microbial contamination of smoked catfish. The results of Pearson's correlation analysis are presented in Table 6. The table indicates that some parameter pairs exhibit a robust and significant correlation ($p < 0.05$), while other variables do not show a significant relationship. Significant relationships were found between pH and overall hedonic (HKS), hedonic hardness (HKN), and HKS, as well as $C^*$ and $a^*$. The correlation values of pH–DWR were ($r$ = -0.965; $p$ = 0.035), DKN–HKS ($r$ = -0.954; $p$ = 0.046), HKN–HKS ($r$ = 0.970; $p$ = 0.030), and $C^*$–$a^*$ (r = 0.961; $p$ = 0.039). Based on the classification by Wiendarlina & Sukaesih (2019), $r$ value between 0.91 and 0.99 indicates a robust correlation. Hence, the results of this study show a close relationship between the quality parameters of smoked

Table 6. Pearson's correlation between pH extract, color, and sensory parameters of smoked catfish

| | | DWR | HKS | $a^*$ |
|---|---|---|---|---|
| pH | Pearson Correlation | -0.965* | -0.216 | 0.485 |
| | Sig. (2-tailed) | 0.035 | 0.784 | 0.515 |
| | N | 4 | 4 | 4 |
| DKN | Pearson Correlation | -0.385 | -0.954* | -0.433 |
| | Sig. (2-tailed) | 0.615 | 0.046 | 0.567 |
| | N | 4 | 4 | 4 |
| HKN | Pearson Correlation | 0.612 | 0.970* | 0.129 |
| | Sig. (2-tailed) | 0.388 | 0,030 | 0.871 |
| | N | 4 | 4 | 4 |
| $C^*$ | Pearson Correlation | -0.641 | -0.062 | 0.961* |
| | Sig. (2-tailed) | 0.359 | 0.938 | 0.039 |
| | N | 4 | 4 | 4 |

*Significant correlation at a confidence level of 0.05 (2-tailed); pH = pH value, DWR = descriptive color, DKN = descriptive hardness, HKN = hedonic hardness, HKS = Hedonic overall, $C^*$= chroma difference index, $a^*$= red-green color index

catfish. The negative correlation between pH and DWR ($r$ = -0.965) suggests that a decrease in pH is typically accompanied by a decrease in color intensity, as observed by the panelists. This correlation suggests that changes in chemical conditions during storage affect pigment stability and non-enzymatic browning reactions, which the panelists subsequently perceive as visual color changes. The negative correlation between DKN and HKS ($r$ = -0.954) indicates that an increasingly hard texture tends to decrease overall liking, thus requiring an optimal hardness of smoked catfish. The overly hard texture of smoked catfish reflects changes in the muscle tissue structure of the fish during storage and is a major limiting factor in product acceptance.

The significant positive correlation between HKN and HKS ($r$ = 0.970) indicates that the assessment of hedonic hardness greatly influences the overall sensory evaluation of smoked catfish. The higher the preference for hardness, the higher the overall acceptance preference. The attribute of hedonic hardness functions synergistically with other parameters, thereby strengthening or weakening the overall perception. Texture control is a key factor in extract formulation because the texture that is positively accepted by panelists significantly contributes to product acceptance. The positive correlation between $C^*$ and $a^*$ ($r$ = 0.961) indicates that an increase in chroma color is related to red color intensity, making dark brown color an indicator of the quality and visual appeal of smoked catfish. The increase in color intensity measured by instruments is in line with changes in visual hue, allowing instrumental parameters to serve as objective indicators of changes in the color perception of smoked catfish during storage.

A quadratic regression model was used to evaluate the non-linear relationship between variables because it is capable of capturing complex patterns by considering quadratic effects. A high coefficient of determination ($R^2$) indicates good prediction, while a low residual sum of squares (RSS) indicates minimal prediction error. The modeling results for detecting the optimum point are presented in Table 7 and Figure 5. Table 7 illustrates a significant quadratic relationship between extract pH, sensory attributes (both descriptive and hedonic), and color ($C^*$ and $a^*$) and smoked catfish quality, characterized by high $R^2$ and low RSS values. The DWR model with pH is presented mathematically as DWR = -95.790 + 35.693(pH) - 3.086(pH$^2$) ($R^2$ = 0.965; RSS = 0.026), indicating that an increase in pH can increase the color intensity, but decrease the descriptive color ratings. The model describes the direction and limits of color

Table 7. Quadratic regression model parameters for the relationship of extract pH, sensory evaluation, and color of smoked catfish

| | | Intercept | $\beta_1$ | $\beta_2$ | RSS | $R^2$ |
|---|---|---|---|---|---|---|
| pH | DWR | -95.790±116.991 | 35.693±38.160 | -3.086±3.109 | 0.026 | 0.965 |
| DKN | HKS | 11.957±1.221 | 0 | -0.124±0.027 | 0.012 | 0.912 |
| HKN | HKS | -0.735±1.245 | 0 | 0.195±0.034 | 0.008 | 0.943 |
| $C^*$ | $a^*$ | 7.796±1.079 | 0 | 0.021±0.004 | 0.018 | 0.927 |

$y = \text{intercept} + \beta_1 x + \beta_2 x^2$; y = dependent variable (DWR, HKS, $a^*$), x = independent variable (pH, DKN, HKN, $C^*$), $\beta_1$ = linear regression coefficient, $\beta_2$ = quadratic regression coefficient. pH = pH value, DWR= descriptive color, DKN= descriptive hardness, HKN= hedonic hardness, HKS= hedonic overall, $C^*$= chroma difference index, $a^*$= red-green color index

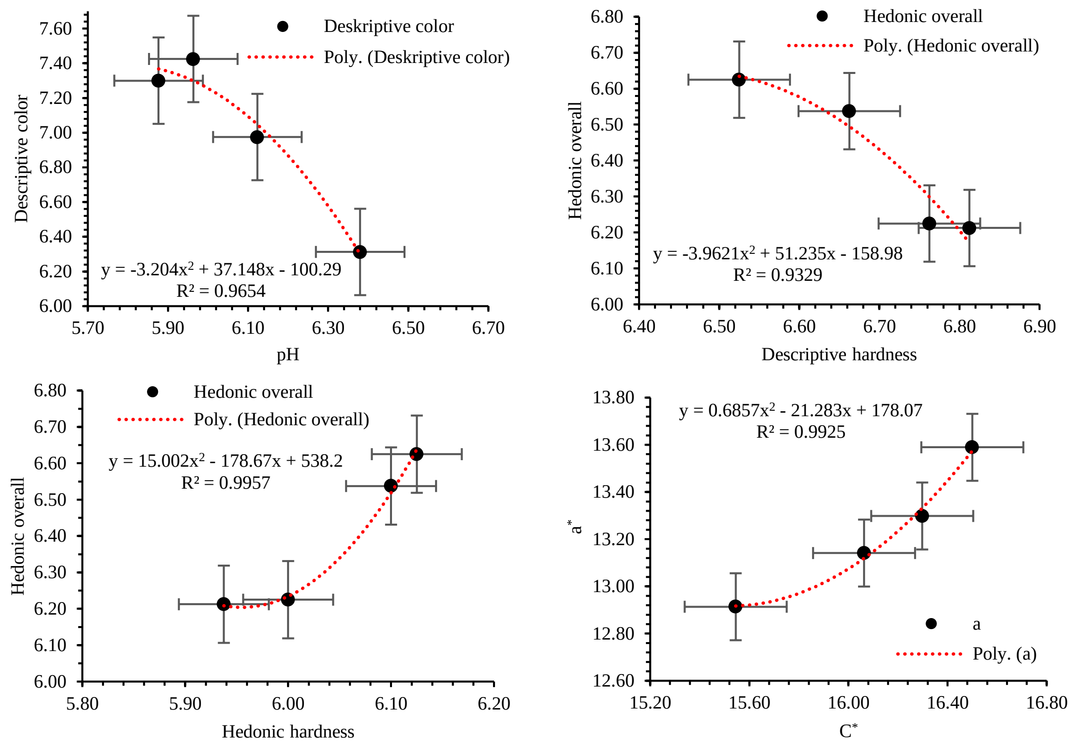



Figure 5. Quadratic regression model for the relationship between extract pH, sensory assessment, and smoked catfish color

description response, characterized by an increase in color description perception up to a certain point, followed by a decline. This quadratic pattern reflects that chemical conditions affect the color intensity of smoked catfish non-linearly due to the limitations of pigment stability and non-enzymatic browning reactions during storage.

The HKS model with DKN is HKS = 11.957 - 0.124(DKN$^2$) ($R^2$ = 0.912; RSS = 0.012, indicating that an increase in descriptive hardness tends to decrease overall consumer acceptance. The model illustrates that the hedonic response of overall acceptance decreases after exceeding a certain hardness, making the model helpful in identifying the acceptance limit of smoked catfish texture. This quadratic pattern confirms that excessive hardness reduces overall preference, even though this change is still acceptable to panelists. The HKS model with HKN is mathematically formulated as HKS = -0.735 + 0.195(HKN$^2$) ($R^2$ = 0.943; RSS = 0.008), confirming that an increase in hedonic hardness leads to an increase in overall hedonic ratings. The model describes an increase in overall hedonic liking for hedonic hardness, which becomes evident after a certain level of perception is reached. This quadratic pattern indicates that there is a threshold for overall hedonic perception; an increase in hedonic hardness does not occur immediately from the start of storage, but rather after storage on the fifth day. Model $a^*$ with $C^*$ is mathematically presented as $a^*$ = 7.796 + 0.021($C^{*2}$) ($R^2$ = 0.927; RSS = 0.018), indicating that high chroma enhances the red color and visual appeal of smoked catfish. The model demonstrates that changes in a$^*$ become apparent at a specific chroma level, making it a valuable indicator of non-linear visual changes. This quadratic pattern reflects the interaction of smoked catfish pigments with bioactive compounds in the extract during storage, resulting in a gradual color response rather than an immediate change.

The $R^2$ values (0.912-0.965) and RSS (0,008-0,026) indicate that the quadratic regression model effectively describes the variability of the data and the complex interactions of the quality parameters of smoked catfish. The regression model involving pH shows relatively high variability in the intercept coefficient. This condition is a common characteristic of quadratic regression when the data range does not include the zero point, resulting in an intercept value that falls outside the observation domain. The results of this study indicate that the extract pH falls within the acidic to neutral range. Therefore, the analysis focuses on the linear and quadratic coefficients to describe the direction of changes in smoked catfish quality, which includes color stability, sensory perception, and microbial contamination, during a five-day storage period. This approach allows for a more accurate understanding of the interaction between parameters within the scope of the experimental data. Thus, despite the variability in the intercept, the quadratic regression model remains effective in describing the trend of changes in the quality of smoked catfish.

Figure 5 shows the quadratic relationship between the pH of the extract and DWR, DKN, and HKS, as well as the color parameters $C^*$ and $a^*$, with $R^2 > 0.93$. An increase in pH tends to decrease the color descriptors of smoked catfish ($R^2 = 0.9654$), an increase in hardness descriptors actually decreases overall acceptance ($R^2 = 0.9329$), an increase in preference for hardness is followed by an increase in overall preference ($R^2 = 0.9957$), and an increase in the $C^*$ value also increases the $a^*$ value, which enhances the visual appeal of smoked catfish ($R^2 = 0.9925$).

The regression coefficient of extract pH with DWR indicates that pH changes have a substantial effect on the color perception of smoked catfish. The regression coefficient shows an increase in color intensity to a peak point, followed by a decrease, reflecting the limited stability of pigments during storage. This pattern indicates that pH can be used as an indicator of chemical changes that affect the visual perception of smoked catfish in a non-linear manner. The regression coefficient of DKN with HKS indicates that there is a tolerance limit for hardness that affects consumer preferences in a quadratic manner. The regression coefficient of HKN with HKS indicates that the overall hedonic assessment is primarily determined by the hedonic hardness preferred by the panelists, with this factor being the dominant influence. The regression coefficients of $C^*$ and $a^*$ indicate that the interaction between pigments and extract compounds during storage results in gradual, rather than immediate, changes in visual color.

## 4. CONCLUSION

This study proves that the combination of botanical extracts as a coating on smoked catfish not only functions as a natural preservative but also maintains quality and microbiological safety during storage. The main contribution of this study lies in the finding that the extract formulation has a significant effect on color stability, sensory acceptance, and reduction of microbial contamination, thus providing new insights into the interaction of bioactive components in smoked food systems. The preservative treatment of 25% garlic, 50% red ginger, and 25% red galangal was the best because it achieved a balance between color stability, consumer acceptance (sensory color, aroma, hardness, and overall acceptance), and suppressed the growth of pathogenic microbes (*E. coli*, *S. aureus*, and *Salmonella*) without reducing the distinctive characteristics of smoked fish products. Practically, these findings are relevant for application on an UMKM scale as a safe and easy-to-apply natural preservative alternative that aligns with the principles of sustainable food processing. Further research is recommended to evaluate the effectiveness of the extract formulation over more extended storage periods and larger production scales, as well as to integrate model validation to improve the reliability of smoked catfish quality predictions.

## AUTHOR CONTRIBUTION STATEMENT

| Author | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ES | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | |
| RH | | | | ✓ | | | | | | ✓ | ✓ | ✓ | | |
| ED | | | | ✓ | | | | | | ✓ | ✓ | ✓ | | |
| MN | | | | ✓ | | | | | | ✓ | ✓ | ✓ | | |

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

## ACKNOWLEDGMENTS

The author would like to thank the Indonesian Education Scholarship (Decree Number 00302/J5.2.3./BPI.06/9/2022), the Center for Higher Education Funding and Assessment, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, and the Endowment Fund for Education Agency, Ministry of Finance of the Republic of

Indonesia, for providing financial support that enabled this research to be completed successfully (BPI ID: 202209090788).

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