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Optimization of the Drying Process for the Characteristics of Sambal Tempoyak Cube Using Response Surface Methodology

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Abstract

Sambal tempoyak is a traditional fermented food product with distinctive acidic and aromatic characteristics, but its high moisture content limits stability and practical application as an instant cube product. This study aimed to optimize drying temperature and time to obtain sambal tempoyak cubes with desirable physicochemical and microbiological characteristics. An experimental design using Response Surface Methodology with a Central Composite Design was applied to evaluate drying temperatures of 40–60°C and drying times of 2–4 hours. Moisture content, water activity (Aw), pH, and total lactic acid bacteria (LAB) were analyzed as response variables, followed by multi-response optimization and verification of the predicted optimum condition. The optimum treatment was obtained at 58°C for 2.4 hours with a desirability value of 0.894. Verification produced 32.57% moisture content, 0.69 Aw, pH 3.67, and 4.083 Log CFU/g LAB, closely corresponding to the predicted values of 30%, 0.70, 3.69, and 4.054 Log CFU/g, respectively. GC-MS analysis showed that drying modified the volatile profile, particularly reducing Butanoic acid, 2-methyl- and its ethyl ester, while these characteristic compounds remained detectable after drying. The optimized condition provides a balanced approach to moisture reduction, microbiological stability, acidity maintenance, LAB retention, and partial preservation of volatile characteristics in sambal tempoyak cubes.

Keywords: *Drying Process, Lactic Acid Bacteria, Response Surface Methodology, Sambal Tempoyak, Volatile Compound.*

INTRODUCTION

The increasing global demand for stable, convenient, and value-added traditional foods has intensified research on processing technologies capable of preserving distinctive sensory and nutritional characteristics while improving shelf life and commercial applicability. Within this development, drying has become a particularly important preservation strategy because the removal of water can suppress deterioration and transform highly perishable foods into products with improved storage stability and handling efficiency. The scientific importance of moisture reduction extends beyond simple water removal, since moisture content and water activity are recognized as critical determinants of food quality, stability, and susceptibility to physicochemical and microbiological deterioration (Sutisna et al., 2026). Tempoyak, a traditional fermented product derived from durian (*Durio zibethinus*) pulp, represents a promising raw material for such product innovation because its distinctive characteristics are closely associated with fermentation by lactic acid bacteria and provide considerable cultural as well as commercial value (Anggraini & Mustakim, 2025). The transformation of tempoyak into a sambal cube offers a potential pathway for converting a traditionally high-moisture product into a more practical, portioned, and shelf-stable food form without eliminating its characteristic fermented identity. Achieving this transformation, however, requires careful control of drying conditions because the drying process simultaneously influences water removal, structural changes, chemical composition, flavor development, texture, and other product characteristics that collectively determine final quality.

Previous studies provide substantial evidence that drying conditions are decisive determinants of food characteristics, although the direction and magnitude of these effects vary according to the material and the response being evaluated. Research on fermented durian flour showed that different drying temperatures significantly affected the physical, chemical, and hedonic characteristics of tempoyak-derived products, indicating that temperature selection must account for quality preservation rather than drying efficiency alone (Ariantika et al., 2017). A similar multidimensional response was identified in durian yoghurt chips, where variations in drying temperature and time altered chemical characteristics, demonstrating that these two operational variables may interact in shaping the quality of durian-based processed foods (Emmawati et al., 2022). Studies on traditional spicy sauce cubes further confirmed that drying time and temperature influence product quality, making these variables particularly relevant to the development of sambal tempoyak cubes as a comparable value-added product category (Masseri et al., 2021). The underlying mechanism is closely related to the simultaneous changes in moisture content and water activity during thermal dehydration, as demonstrated in drying studies of turmeric where temperature affected both parameters and consequently the condition of the dried material (Leviana & Paramita, 2017). More recent research has also shown that different drying processes can modify volatile flavor compounds, amino acids, and soluble sugars in durian, suggesting that optimization must consider quality changes generated by dehydration rather than treating drying solely as a means of extending shelf life (Yang et al., 2024). Collectively, these findings indicate that the drying of tempoyak-based products constitutes a multivariable process in which the search for appropriate operating conditions must reconcile moisture reduction with the preservation of desirable physicochemical and sensory characteristics.

Despite this growing body of evidence, the existing literature remains fragmented because many studies examine the influence of individual drying factors through limited experimental comparisons rather than systematically modelling the combined relationships among processing variables and multiple quality responses. The optimization of red ginger drying using Response Surface Methodology demonstrated that drying temperature and slice thickness can be simultaneously modelled to identify operating conditions associated with desirable process responses, illustrating the advantage of RSM over approaches that assess one factor independently (Hepi et al., 2021). Research on *Ulva lactuca* and *Gelidium* sp.-based nori similarly employed RSM to optimize drying temperature and time, confirming that statistically designed experiments can capture response patterns more efficiently than conventional trial-and-error procedures (Pramudya et al., 2022). The applicability of RSM has also expanded to fermented food systems, where Central Composite Design was used to optimize the formulation of a fermented dragon-fruit-peel beverage and establish predictive relationships between experimental factors and product responses (Fadhila et al., 2025). Nevertheless, evidence specifically addressing the optimization of drying conditions for sambal tempoyak cubes remains limited, particularly with respect to integrating the effects of major drying variables into a response-based model tailored to the characteristics of a fermented durian product. This gap is important because findings obtained from other dried foods cannot automatically be transferred to sambal tempoyak, whose composition combines fermented durian components with spices and other ingredients that may respond differently to heat and moisture removal. The absence of a systematic optimization framework therefore leaves uncertainty regarding which combination of drying conditions can produce sambal tempoyak cubes with the most desirable balance between stability and product characteristics.

The unresolved problem has both scientific and practical significance because inadequate drying conditions may create a product that is either insufficiently dehydrated for stable storage or excessively exposed to heat to the extent that desirable quality attributes are compromised. Earlier work on sambal tempoyak demonstrated that product stability and shelf life are closely related to processing and packaging strategies, confirming that the commercialization of this traditional food requires deliberate intervention to control factors associated with quality deterioration (Junita & Novitasari, 2019). Process and packaging modification studies have likewise shown that the quality and storage life of tempoyak can be improved through systematic adjustment of post-fermentation handling, reinforcing the need to treat processing conditions as controllable determinants of commercial product performance (Reli et al., 2017). The importance of optimizing processing conditions is also supported by studies showing that variations in formulation and processing parameters can alter sensory, chemical, and physical characteristics, meaning that product acceptability depends on the interaction between technological treatment and the inherent properties of the food matrix (Soetikno et al., 2018). More broadly, thermal treatment can generate measurable changes in chemical and organoleptic properties as processing intensity and duration vary, which makes the identification of an appropriate operating region more scientifically meaningful than the selection of a single arbitrary drying condition (Trissanthi & Susanto, 2016). For sambal tempoyak cubes, this issue directly affects the feasibility of developing a traditional fermented food into a standardized commercial product because inconsistent drying performance may reduce reproducibility between production batches and complicate the establishment of reliable product specifications. A scientifically grounded optimization is consequently required to convert empirical processing practice into a predictive basis for determining drying conditions that are technically effective and compatible with the intended characteristics of the final product.

Against this research landscape, the present study is positioned at the intersection of traditional fermented-food innovation, drying technology, and statistical process optimization by examining sambal tempoyak cubes as a specific food system whose characteristics emerge from the interaction between dehydration conditions and a complex fermented raw-material matrix. This position differs from previous research that has primarily investigated tempoyak preservation, evaluated the separate effects of drying variables, or optimized drying processes for other agricultural and food products without directly addressing the development of sambal tempoyak in cube form. The study adopts Response Surface Methodology as an analytical framework because the method enables the effects and interactions of experimental factors to be evaluated simultaneously while generating mathematical models that can support the prediction and optimization of relevant product responses. Its application is particularly appropriate when the objective is not merely to establish whether temperature or drying time affects product quality, but to determine the combination of processing conditions associated with the most desirable overall characteristics. The resulting approach is expected to provide a more rigorous basis for translating traditional food processing into a controlled and reproducible production system in which drying parameters are selected through quantitative relationships rather than isolated experimental observations. Such a framework also responds to the broader need for applied research that connects indigenous food resources with contemporary optimization methods capable of supporting product standardization, technological innovation, and value addition. In this sense, the study extends the existing literature by treating drying optimization as an integrated response problem in which process efficiency and the preservation of product characteristics must be evaluated within the same experimental design.

Accordingly, this study aims to optimize the drying process for sambal tempoyak cubes using Response Surface Methodology in order to determine the combination of drying conditions that produces the most desirable product characteristics. The study investigates the individual and interactive effects of the selected drying variables on the responses used to represent the quality of the resulting sambal tempoyak cubes. A response-based mathematical model is developed to characterize the relationship between process conditions and product performance and to identify an optimum operating region. The theoretical contribution of this research lies in extending the understanding of multivariable drying behavior within a fermented durian-based food system, particularly by positioning product characteristics as integrated responses to interacting processing conditions. Its methodological contribution lies in demonstrating the application of Response Surface Methodology as a structured experimental and predictive framework for optimizing the transformation of a traditional high-moisture fermented product into a standardized dried cube. From an applied perspective, the findings are expected to provide a scientific basis for establishing more consistent drying parameters and supporting the development of sambal tempoyak cubes as a stable, practical, and commercially viable value-added food product.

RESEARCH METHODS

This empirical study employed a controlled experimental design to develop and optimize sambal tempoyak cube through a systematic drying process conducted at the Agricultural Product Chemistry and Microbiology Laboratory and KAIP Laboratory, Universitas Sriwijaya. The materials consisted of tempoyak, red chili powder, shallot powder, and garlic powder, which were homogenized, subjected to designated drying treatments, and molded into 2 × 2 × 2 cm cubes following an adapted procedure for traditional spicy sauce cubes (Masseri et al., 2021). The drying process employed Response Surface Methodology (RSM) with a two-factor Central Composite Design (CCD), using drying temperature of 40–60°C and drying time of 2–4 hours as the independent variables, with the experimental matrix presented in Table 1. The measured responses were moisture content, water activity (Aw), pH, and total lactic acid bacteria (LAB), which were selected to represent dehydration performance, product stability, acidity, and the microbiological characteristics of the fermented product

(Sutisna et al., 2026). Moisture content was determined gravimetrically, Aw and pH were measured using calibrated analytical instruments, while total LAB was enumerated using the spread-plate method on MRS Agar after incubation at 37°C for 48 hours and expressed as log CFU/g (Anggraini & Mustakim, 2025). The experimental treatments were arranged to characterize the individual and interactive effects of drying temperature and time on the selected responses, providing an empirical basis for subsequent response-surface modeling and optimization (Pramudya et al., 2022).

Table 1. Central Composite Design Matrix in the Experimental Design

Std	Run	Factor 1: A – Temperature (°C)	Factor 2: B – Time (hours)	Response 1: Moisture Content (%)	Response 2: Aw	Response 3: pH	Response 4: Total LAB (Log CFU/g)
11	1	50	3				
7	2	50	1.6				
13	3	50	3				
3	4	40	4				
10	5	50	3				
8	6	50	4.4				
12	7	50	3				
2	8	60	2				
5	9	36	3				
9	10	50	3				
1	11	40	2				
6	12	64	3				
4	13	60	4				

The moisture content was calculated from the difference between the initial and dried sample weights using the following equation (AOAC, 2005).

$$\text{Moisture Content (\%)} = \frac{a - b}{a} \times 100$$

where $a$represents the initial sample weight (g) and $b$represents the dried sample weight (g), while total LAB was calculated from the number of colonies obtained at the selected dilution and expressed as colony-forming units per gram (CFU/g) using the following equation (Anggraini & Mustakim, 2025).

$$\text{CFU/g} = \frac{\text{number of colonies}}{\text{volume plated (mL)}} \times \frac{1}{\text{dilution factor}}$$

The experimental data for moisture content, Aw, pH, and total LAB were analyzed using ANOVA in Design-Expert 13 to determine the significance of drying temperature and time and to select the most appropriate regression model for each response (Pramudya et al., 2022). Model adequacy was assessed using the coefficient of determination (R^2), adjusted R^2, predicted R^2, model significance, and lack-of-fit testing to determine whether the fitted model adequately represented the experimental observations. Regression equations, contour plots, and three-dimensional response-surface plots were generated to evaluate the linear, quadratic, and interaction effects of drying temperature and time on the measured product characteristics. Multi-response optimization was performed using a desirability-function approach by establishing response criteria for moisture content, Aw, pH, and total LAB and identifying the treatment combination that produced the highest overall desirability. The predicted optimum condition was subsequently verified through an independent experiment, with the experimental responses compared with the predicted values to determine prediction error and evaluate model reliability (Ariantika et al., 2017). The integration of CCD-based experimentation, response-surface modeling, multi-response desirability optimization, and independent experimental validation provides a robust methodological framework for identifying reproducible drying conditions and establishing an evidence-based optimum process for sambal tempoyak cube.

RESULTS AND DISCUSSION

Moisture Content and Water Activity Responses

The moisture content response of the sambal tempoyak cube varied substantially across the experimental treatments, indicating that drying temperature and drying time were important process variables in determining the final water content of the product. As presented in Table 2, the measured moisture content ranged from 15.36% to 58.58%, with the highest value obtained at 40°C for 2 hours and the lowest value obtained at 60°C for 4 hours. The broad response range indicates that the selected Central Composite Design (CCD) successfully captured substantial changes in dehydration behavior within the experimental domain. At the central condition of 50°C for 3 hours, the moisture content values varied between repeated runs, ranging from 36.91% to 49.00%, indicating experimental variation around the central treatment. The reduction in moisture content under more intensive drying conditions is associated with increased heat transfer and enhanced migration of water from the product matrix toward the surface. Similar effects of drying temperature and time on moisture reduction have been reported for food materials, where greater thermal exposure accelerates moisture removal during controlled drying (Sutisna et al., 2026).

Table 2. Analysis Results of the Moisture Content Response of Sambal Tempoyak Cube

Std	Run	Factor 1: A – Temperature (°C)	Factor 2: B – Time (hours)	Response: Moisture Content (%)
11	1	50	3	36.91
7	2	50	1.6	43.56
13	3	50	3	37.61
3	4	40	4	49.16
10	5	50	3	41.88
8	6	50	4.4	28.71
12	7	50	3	39.74
2	8	60	2	29.57
5	9	36	3	56.30
9	10	50	3	49.00
1	11	40	2	58.58
6	12	64	3	17.16
4	13	60	4	15.36

The pattern in Table 2 demonstrates that increasing drying intensity promoted greater moisture removal, although the magnitude of the response depended on the combination of temperature and time. At 40°C, extending the drying period to 4 hours resulted in a moisture content of 49.16%, which was lower than the 58.58% obtained at 40°C for 2 hours. A stronger reduction was observed at 60°C, where increasing the drying time from 2 to 4 hours reduced moisture content from 29.57% to 15.36%. The treatment at 64°C for 3 hours produced a similarly low value of 17.16%, confirming the substantial contribution of elevated temperature to water removal. From a heat and mass transfer perspective, higher temperature increases the vapor pressure difference between the moist material and surrounding air, while prolonged drying provides additional time for internal moisture diffusion and surface evaporation. Comparable temperature- and time-dependent reductions in moisture have been reported during the drying of durian-based food products, demonstrating that thermal conditions strongly regulate dehydration efficiency (Emmawati et al., 2022). The response observed in the present experiment is particularly relevant to sambal tempoyak cube because moisture reduction affects not only dehydration efficiency but also the subsequent stability of a fermented food matrix.

ANOVA identified the Linear model as the appropriate model for describing the moisture content response, with a significant model probability value of $p < 0.05$ and a non-significant lack-of-fit value of $p > 0.05$. The fitted regression equation was Moisture Content = 129.80329 − 1.48488A −

5.60818B, where A represents drying temperature and B represents drying time. The negative coefficients indicate that an increase in either independent variable was associated with a reduction in predicted moisture content. The coefficient for drying time was numerically greater in absolute value than the coefficient for temperature, suggesting a substantial contribution of drying duration within the fitted regression equation, although direct comparison of raw coefficients should be interpreted cautiously because the factors are expressed in different units. The linear model indicates that the principal response tendency within the experimental region could be adequately represented without requiring interaction or quadratic terms for moisture content. This model selection is consistent with the application of RSM, in which the simplest statistically adequate model is used to represent the relationship between process variables and a measured response (Pramudya et al., 2022). The significant model and non-significant lack of fit provide empirical support for using the regression equation to describe moisture variation within the tested temperature and time ranges.

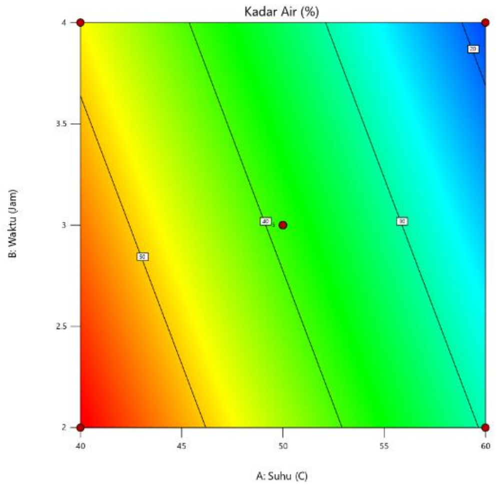

Figure 1. Contour Plot of the Moisture Content Response of Sambal Tempoyak Cube

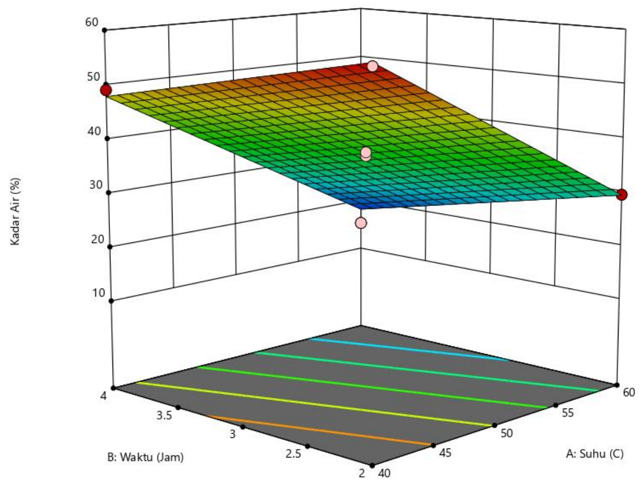

Figure 2. Three-Dimensional Graph of the Moisture Content Response of Sambal Tempoyak Cube

Figures 1 and 2 illustrate the combined influence of drying temperature and time on the moisture content response through contour and three-dimensional response-surface representations. The response surface shows a clear transition toward lower moisture content as the process moves from shorter and cooler conditions to longer and hotter conditions. The contour pattern corresponds with the negative coefficients of both temperature and time in the regression equation, confirming that the direction of the graphical response agrees with the statistical model. The low-moisture region is concentrated around the higher-temperature and longer-time combinations, with the experimental minimum of 15.36% occurring at 60°C for 4 hours. Conversely, the highest moisture region occurs under the least intensive treatment of 40°C for 2 hours, where the measured moisture content reached 58.58%. The relatively continuous surface pattern indicates that moisture removal responded systematically to changes in the two processing factors rather than showing an isolated response at a single treatment point. Similar response-surface behavior has been reported in drying optimization studies in which temperature and drying duration were used as independent variables for controlling moisture-related characteristics of food products (Pramudya et al., 2022).

Water activity exhibited a narrower response range than moisture content, with measured values between 0.61 and 0.77 across the experimental treatments. As shown in Table 3, the highest Aw value of 0.77 occurred at 40°C for 2 hours, whereas the lowest value of 0.61 was recorded at 60°C for 4 hours. The reduction in Aw under more intensive drying conditions indicates that the drying process affected not only the total quantity of water remaining in the product but also the fraction of water available for physicochemical and microbiological processes. At 50°C, increasing the drying time from 1.6 to 4.4 hours reduced Aw from 0.74 to 0.67, while the treatment at 64°C for 3 hours produced an Aw of 0.63. The response therefore followed the general direction observed for moisture content, although the relationship was more complex and was subsequently represented by a quadratic model. Water activity is a critical stability parameter because it describes the availability of water within a food matrix rather than simply its total water content, making it relevant to microbial growth and chemical reactions (Sutisna et al., 2026).

Table 3. Analysis Results of the Aw Response of Sambal Tempoyak Cube

Std	Run	Factor 1: A – Temperature (°C)	Factor 2: B – Time (hours)	Response: Aw
11	1	50	3	0.75
7	2	50	1.6	0.74
13	3	50	3	0.74
3	4	40	4	0.72
10	5	50	3	0.73
8	6	50	4.4	0.67
12	7	50	3	0.74
2	8	60	2	0.69
5	9	36	3	0.76
9	10	50	3	0.74
1	11	40	2	0.77
6	12	64	3	0.63
4	13	60	4	0.61

The ANOVA results selected the Quadratic model as the appropriate model for Aw, with a significant model value of $p < 0.05$ and a non-significant lack-of-fit value of $p > 0.05$. The resulting regression equation was $Aw = 0.199200 + 0.020948A + 0.118472B - 0.000750AB - 0.000234A^2 - 0.018293B^2$. The presence of the interaction term (AB) and quadratic terms (A^2 and B^2) indicates that the response could not be adequately represented by a simple linear relationship across the experimental region. The negative quadratic coefficients indicate curvature in the response, meaning that changes in temperature and time did not produce a constant proportional change in Aw throughout the tested range. The response surface therefore reflects a more complex dehydration process in which the availability of water changes as readily removable moisture is progressively depleted. Similar nonlinear responses have been identified in drying optimization studies using RSM, particularly when changes in processing intensity alter moisture transfer behavior across different stages of dehydration (Pramudya et al., 2022). The quadratic model provides a stronger representation of Aw behavior because it incorporates both the individual effects of the factors and their combined and curvature effects.

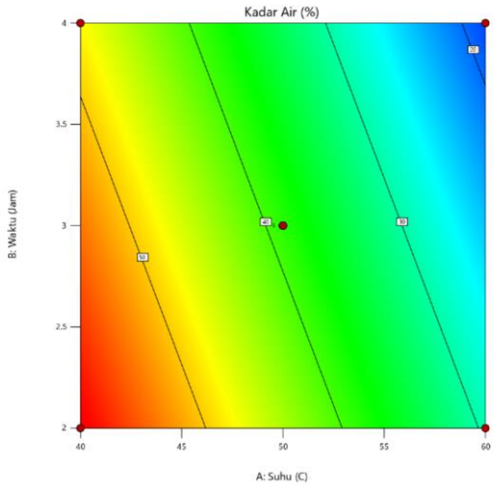

Figure 3. Contour Plot of the Aw Response of Sambal Tempoyak Cube

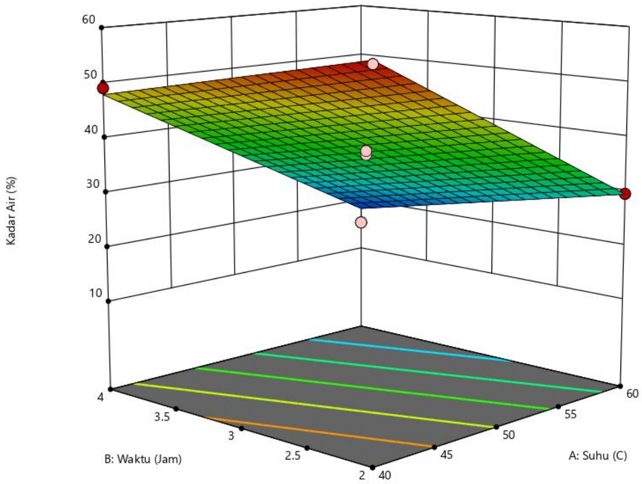

Figure 4. Three-Dimensional Graph of the Aw Response of Sambal Tempoyak Cube

Figures 3 and 4 further demonstrate the nonlinear response of Aw to drying temperature and time. The contour distribution indicates that lower Aw values were associated with more intensive drying conditions, particularly toward the higher-temperature and longer-time region of the experimental domain. The curvature visible in the three-dimensional response surface corresponds to the quadratic terms included in the fitted model and confirms that the effect of the independent variables changed across the treatment region. The experimental reduction from 0.77 at 40°C for 2 hours to 0.61 at 60°C for 4 hours provides direct evidence that intensified drying reduced water availability in the sambal tempoyak cube. This behavior is consistent with the reduction in moisture content, since evaporation removes water from the food matrix and consequently decreases the amount of water that remains available for microbial and chemical processes. A similar reduction in water activity with increasing drying temperature has been reported for turmeric dried using an electrical oven, where greater thermal exposure promoted water removal and lowered Aw (Leviana & Paramita, 2017). The joint interpretation of moisture content and Aw indicates that drying conditions influenced two related but distinct aspects of water status, providing a stronger basis for subsequent multi-response optimization of the sambal tempoyak cube.

pH and Total Lactic Acid Bacteria Responses

The pH response of the sambal tempoyak cube varied across the drying temperature and time treatments, indicating that thermal dehydration influenced the acidity characteristics of the fermented product. The lowest pH value of 3.45 was obtained at 40°C for 2 hours, whereas the highest pH value of 3.87 was recorded at 60°C for 4 hours. The experimental variation shows a gradual increase in pH as the severity of drying increased, indicating a corresponding reduction in acidity. The pH values obtained from the thirteen Central Composite Design (CCD) runs are presented in Table 4. The distribution of the observations also shows that treatments at the central condition of 50°C and 3 hours generated pH values ranging from 3.56 to 3.68, demonstrating experimental variation around the central region. This acidic pH range is consistent with the characteristics expected from fermented tempoyak, in which organic acid formation during fermentation contributes to the characteristic acidic condition of the product (Anggraini & Mustakim, 2025). The observed variation therefore provides an empirical basis for evaluating the influence of drying conditions on the acidity-related quality of sambal tempoyak cube.

Table 4. Analysis Results of the pH Response of Sambal Tempoyak Cube

Std	Run	Factor 1: A – Temperature (°C)	Factor 2: B – Time (hours)	Response: pH
11	1	50	3	3.56
7	2	50	1.6	3.49
13	3	50	3	3.61
3	4	40	4	3.58
10	5	50	3	3.64
8	6	50	4.4	3.74
12	7	50	3	3.68
2	8	60	2	3.66
5	9	36	3	3.52
9	10	50	3	3.60
1	11	40	2	3.45
6	12	64	3	3.82
4	13	60	4	3.87

The increase in pH with increasing temperature and drying time indicates that thermal treatment reduced the measurable acidity of the sambal tempoyak cube. Prolonged heating can influence organic acid stability and modify the concentration of acid compounds remaining in the food matrix, producing a shift toward higher pH values. Thermal exposure can also suppress the metabolic activity of lactic acid bacteria because elevated temperatures may damage cellular proteins and inactivate enzymes associated with lactic acid production (Reli et al., 2017). The inhibition of further acid formation is particularly relevant for tempoyak because LAB contribute to the fermentation process and the development of its characteristic acidity (Anggraini & Mustakim, 2025). Trissanthi and Susanto (2016) similarly reported an increase in pH associated with prolonged heating, indicating that thermal treatment can alter acid-related characteristics in processed food systems. Water and volatile acid components may also undergo evaporation during drying, although the extent of this mechanism depends on the composition and structure of the product matrix. The observed pH pattern therefore reflects the combined influence of thermal exposure, reduced microbial activity, and changes in the distribution or retention of acid compounds during dehydration.

ANOVA indicated that the Linear model was the appropriate model for describing the pH response of sambal tempoyak cube within the experimental range. The model was statistically significant at $p < 0.05$, while the lack-of-fit test was not significant at $p > 0.05$, indicating that the linear model adequately represented the observed response without a significant systematic deviation from the experimental data. The regression equation obtained from the analysis was

$$pH = 2.79014 + 0.011616A + 0.087121B$$

Where A represents drying temperature and B represents drying time. The positive coefficient of A indicates that increasing temperature contributed to an increase in pH, whereas the positive coefficient of B indicates that longer drying time produced the same directional response. The coefficient associated with drying time was numerically greater than that of temperature, suggesting that within the investigated range, the duration of thermal exposure had a stronger contribution to pH variation. This relationship corresponds with the experimental observations, particularly the increase from pH 3.45 at 40°C for 2 hours to pH 3.87 at 60°C for 4 hours. The linear response is also consistent with the application of RSM for identifying process-factor effects in food drying, where temperature and duration can be quantitatively related to physicochemical responses (Pramudya et al., 2022).

The response surface representation further illustrates the relationship between drying temperature, drying time, and pH of the sambal tempoyak cube. The contour plot provides a two-dimensional representation of the pH distribution, whereas the three-dimensional response surface illustrates the directional change in pH across the experimental region. The response increases toward the combination of higher drying temperature and longer drying time, corresponding to the positive coefficients of both independent variables in the fitted equation. The experimental region with lower temperature and shorter drying time is associated with lower pH values, while higher temperature and longer exposure shift the response toward higher pH. This pattern indicates that the reduction in acidity becomes more pronounced as the thermal severity of the drying process increases. Similar effects of drying temperature on the physicochemical characteristics of fermented tempoyak have been reported by Ariantika et al. (2017), demonstrating that drying conditions can modify quality attributes associated with fermentation. The response surface consequently provides a useful process map for identifying drying conditions that limit excessive increases in pH while still achieving the dehydration requirements of the cube product.

The total lactic acid bacteria (LAB) response demonstrated a treatment-dependent variation in microbial viability following drying. The highest LAB count was 5.193 Log CFU/g at 50°C for 3 hours, while the lowest count was 4.633 Log CFU/g at 60°C for 4 hours. The relatively high LAB values observed around the moderate drying conditions indicate that viable bacterial populations were retained more effectively under controlled thermal exposure. In contrast, the lower values at higher temperature and longer duration indicate that intensified drying imposed greater thermal stress on the microorganisms. The complete distribution of temperature, drying time, and total LAB values obtained from the experimental runs is presented in Table 5.

Table 5. Analysis Results of the Total Lactic Acid Bacteria Response of Sambal Tempoyak Cube

Std	Run	Factor 1: A – Temperature (°C)	Factor 2: B – Time (hours)	Response: Total LAB (Log CFU/g)
11	1	50	3	5.164
7	2	50	1.6	5.025
13	3	50	3	5.017
3	4	40	4	5.064
10	5	50	3	5.083
8	6	50	4.4	4.833
12	7	50	3	5.170
2	8	60	2	4.987
5	9	36	3	5.121
9	10	50	3	5.193
1	11	40	2	5.130
6	12	64	3	4.940
4	13	60	4	4.633

The data in Table 5 demonstrate that LAB viability was relatively stable under moderate drying conditions but decreased as thermal exposure became more intensive. The difference between the maximum and minimum LAB values reached 0.560 Log CFU/g, indicating a measurable reduction in viable cells across the investigated treatment range. Excessive thermal exposure can damage bacterial cell membranes and denature intracellular proteins, reducing the ability of LAB cells to remain viable during processing (Reli et al., 2017). The highest LAB value at 50°C for 3 hours suggests that the central processing region provided a comparatively favorable balance between moisture removal and microbial survival. This finding is relevant to fermented tempoyak because LAB constitute an important microbial component associated with its fermentation characteristics (Anggraini & Mustakim, 2025). The response also indicates that drying optimization cannot be based solely on minimizing moisture content because more intensive dehydration may compromise the viable microbial fraction of the fermented product. The preservation of LAB therefore needs to be considered simultaneously with pH and dehydration responses when determining an appropriate processing condition.

ANOVA selected the Quadratic model as the appropriate model for describing the total LAB response, with the model significant at $p < 0.05$ and the lack-of-fit test non-significant at $p > 0.05$. The fitted equation was:

$$LAB = 1.51086 + 0.065700A + 0.909475B - 0.007186AB - 0.000546A^2 - 0.106200B^2$$

Demonstrating that temperature, drying time, their interaction, and quadratic effects contributed to the response pattern. The interaction coefficient of −0.007186 indicates that the simultaneous increase in temperature and time produced a combined effect that differed from the independent contribution of each factor. The negative quadratic coefficients indicate curvature in the response, explaining why LAB viability did not continue to increase proportionally across the entire experimental region. The response-surface and contour plots in Figures 7 and 8 illustrate that relatively high LAB values occurred at approximately 40–52°C and 2–3.3 hours, whereas lower values were concentrated near the higher-temperature and longer-time region. The curved contour pattern confirms the quadratic behavior identified statistically and indicates a declining viable LAB population under intensified thermal conditions. This behavior has practical significance for process optimization because maintaining microbial viability requires limiting thermal severity while achieving sufficient dehydration, a balance that is characteristic of multi-response optimization using RSM (Fadhila et al., 2025).

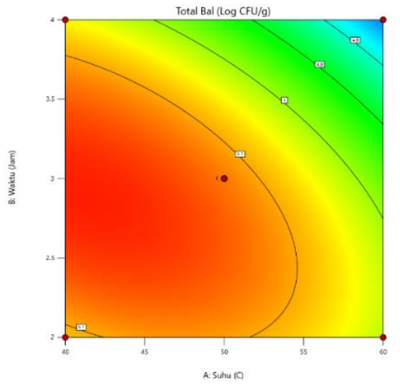

Figure 5. Contour Plot of the Total LAB Response

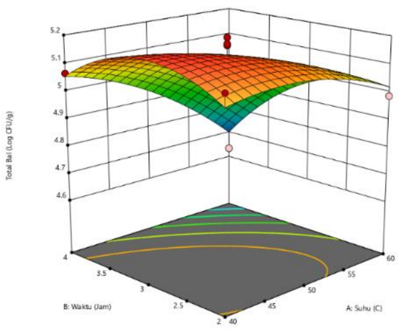

Figure 6. Three-Dimensional Graph of the Total LAB Response of Sambal Tempoyak Cube

Figures 5 and 6 illustrate the distribution of total LAB as a function of drying temperature and time. The contour pattern shows that relatively high LAB values were concentrated in the moderate-temperature region, particularly around 40–52°C with drying times of approximately 2–3.3 hours. The response surface gradually declines toward higher temperature and longer drying time, indicating reduced bacterial viability under greater thermal exposure. The curved surface also confirms the quadratic behavior represented in the regression model, where the response is influenced not only by the linear effects of temperature and time but also by their squared and interaction terms. This pattern indicates that excessive drying intensity may adversely affect the survival of LAB in sambal tempoyak cube. The graphical response is consistent with the physiological sensitivity of LAB to thermal stress, in which prolonged exposure to elevated temperatures can impair cellular structures and reduce microbial viability (Subagiyo et al., 2015).

Optimization and Verification of Drying Conditions

The optimum drying condition was determined using a multi-response desirability approach that simultaneously considered moisture content, water activity (Aw), pH, and total lactic acid bacteria (LAB). This approach was applied because the four responses represent different and partially competing quality requirements in the development of sambal tempoyak cube. Lower moisture content and Aw are desirable for improving product stability, whereas excessive dehydration may negatively affect the retention of fermentation-related characteristics. The pH response was considered to maintain the acidic characteristics of tempoyak, while total LAB was incorporated to account for the retention of viable microorganisms after drying. Multi-response optimization through desirability functions enables several response criteria to be evaluated concurrently and provides a numerical basis for selecting a balanced processing condition (Fadhila et al., 2025). The resulting optimum was selected from the combination of drying temperature and time that generated the highest overall desirability within the experimental design space.

The optimization procedure identified a drying temperature of 58°C and a drying time of 2.4 hours as the optimum processing condition, with an overall desirability of 0.894. The predicted responses under this condition were 30% moisture content, 0.70 Aw, pH 3.69, and total LAB of 4.054 Log CFU/g. The predicted and experimentally verified responses obtained under the selected optimum condition are presented in Table 6.

Table 6. Optimization Verification Results for Sambal Tempoyak Cube

Description	Independent Variable	Response	Desirability
	Temperature	Time	Moisture Content (%)
Prediction	58	2.4	30
Verification	58	2.4	32.57

The verification experiment produced 32.57% moisture content, 0.69 Aw, pH 3.67, and total LAB of 4.083 Log CFU/g at the predicted optimum condition. Compared with the predicted values, the verification moisture content was higher by 2.57 percentage points, whereas Aw was lower by 0.01 units. The experimentally measured pH of 3.67 was also close to the predicted value of 3.69, showing only a small difference in acidity. The total LAB concentration increased slightly from the predicted 4.054 to 4.083 Log CFU/g during verification. These relatively small differences indicate that the response-surface models provided a satisfactory estimation of product characteristics under the selected processing condition. The close agreement between predicted and observed responses is important for confirming that the mathematical optimization can be translated into an experimentally reproducible drying treatment (Hepi et al., 2021).

The prediction errors were calculated by comparing the predicted and verification values for each response at 58°C and 2.4 hours. Moisture content showed a difference of 2.57 percentage points, corresponding to a relative prediction error of approximately 8.57% when calculated against the predicted value. Aw differed by approximately 1.43%, while the pH difference was approximately 0.54%. Total LAB exhibited the smallest difference among the responses, with a relative prediction error of approximately 0.72%. The variation in moisture content is greater than that observed for the other responses, which may be associated with the sensitivity of water removal to material structure, moisture migration, and experimental drying conditions. Despite this variation, the verification responses remained close to the model estimates for Aw, pH, and LAB, indicating satisfactory predictive performance for the quality characteristics considered in the optimization. Hepi et al. (2021)

emphasized that verification of the predicted optimum is necessary to assess whether an RSM-derived processing condition can adequately reproduce the estimated responses experimentally.

The prediction intervals (PI) and confidence intervals (CI) provide additional evidence for evaluating the suitability of the optimized model. The predicted and verification values together with the corresponding 95% PI and CI ranges are presented in Table 7, allowing the experimental observations to be evaluated against the statistical ranges generated by the model. The moisture content verification value of 32.57% was positioned within the model's prediction interval, while the Aw value of 0.69 corresponded closely to the lower boundary of the reported interval. The pH verification value of 3.67 also remained within the model range, as did the total LAB value of 4.083 Log CFU/g. The consistency between the verification measurements and the model intervals indicates that the experimental results were compatible with the statistical predictions generated from the CCD data. Such agreement strengthens the reliability of the optimization because model validation requires the experimentally obtained responses to remain consistent with the uncertainty ranges estimated by the fitted models (Hepi et al., 2021). The statistical agreement therefore supports the use of 58°C for 2.4 hours as a practical drying condition for further evaluation of sambal tempoyak cube.

Table 7. Verification Response of the Optimum Temperature and Time Combination Model

Response	Prediction	Verification	95% PI low	95% CI low	95% CI high
Moisture Content (%)	30	32.57	23.98	25.93	49.52
Aw	0.70	0.69	0.69	0.69	0.74
pH	3.69	3.67	3.63	3.63	3.87
Total LAB (Log CFU/g)	4.054	4.083	3.93	3.959	4.466

The optimum condition of 58°C for 2.4 hours represents a process compromise among the competing effects of thermal dehydration and preservation of fermentation-related characteristics. At this condition, moisture content was reduced to 32.57% and Aw reached 0.69, indicating a substantial reduction in available water compared with the less intensive treatments. Reduced water availability is technologically important because Aw is more directly associated with the availability of water for chemical reactions and microbial growth than total moisture content alone (Leviana & Paramita, 2017; Sutisna et al., 2026). The pH of 3.67 indicates that the product retained an acidic environment despite the thermal treatment, while the LAB count of 4.083 Log CFU/g demonstrates that a measurable viable population remained after drying. The selected condition also avoids the more severe microbial reduction observed at higher temperature and longer drying times, particularly around 60°C for 4 hours. This balance is consistent with the principle of RSM-based optimization, in which the preferred solution is not necessarily the condition that maximizes or minimizes one response independently but the condition that provides the most acceptable simultaneous performance across multiple responses (Pramudya et al., 2022). The desirability value of 0.894 therefore indicates a strong overall compromise between dehydration, water-activity control, preservation of acidity, and retention of LAB, supporting 58°C for 2.4 hours as the empirically selected optimum for sambal tempoyak cube.

Changes in Volatile Compounds after Drying

The GC-MS analysis identified several volatile compounds in sambal tempoyak before the drying treatment, with the detected compounds comprising short-chain organic acid derivatives and long-chain fatty acid compounds. The volatile profile was characterized by the presence of *Butanoic acid, 2-methyl-*, its ethyl and propyl ester derivatives, as well as *Hexadecanoic acid* and its methyl and ethyl ester derivatives. Among the detected compounds, *Butanoic acid, 2-methyl-* exhibited an area of 7.03%, while *Butanoic acid, 2-methyl-, ethyl ester* accounted for 3.15% of the chromatographic area. The identification probability of these compounds ranged from 49.15% to 86.94%, indicating varying levels of spectral matching for the detected components. The complete volatile compound profile obtained before drying is presented in Table 8.

Table 8. Volatile Compound Profile of Sambal Tempoyak Before Drying

Retention Time	Probability (%)	Component	Area (%)
4.32	86.94	*Butanoic acid, 2-methyl-, ethyl ester*	3.15
20.05	78.96	*Hexadecanoic acid, ethyl ester*	8.29
25.63	78.23	*γ-Sitosterol*	1.02
19.12	76.12	*Hexadecanoic acid, methyl ester*	2.66
25.52	75.84	*γ-Sitosterol*	1.81
19.76	70.50	*n-Hexadecanoic acid*	9.99
5.06	59.01	*Butanoic acid, 2-methyl-*	7.03
5.77	49.15	*Butanoic acid, 2-methyl-, propyl ester*	0.75
26.77	40.39	*Hexadecanoic acid, 1-(hydroxymethyl)-1,2-ethanediyl ester*	1.38

The detection of *Butanoic acid, 2-methyl-* and its ester derivatives is particularly relevant to the characteristic sensory identity of fermented tempoyak. Organic acids and their ester derivatives contribute to the complex aroma profile generated during fermentation, with ester compounds generally associated with fruity and distinctive aromatic notes. In fermented durian products, ester formation is related to the transformation of organic acids and alcohols during fermentation and contributes to the characteristic flavor attributes of the product. Yuliana et al. (2011) reported that ester compounds constitute important volatile components associated with the aroma characteristics of durian and fermented tempoyak. The presence of ethyl and propyl ester derivatives in the present sample indicates that fermentation-derived volatile components remained detectable before drying. The coexistence of free butanoic acid derivatives and their ester forms also suggests that the volatile profile was chemically diverse rather than being dominated by a single compound class. This composition provides an important reference for assessing whether the subsequent drying treatment alters the characteristic aroma-related compounds of sambal tempoyak cube.

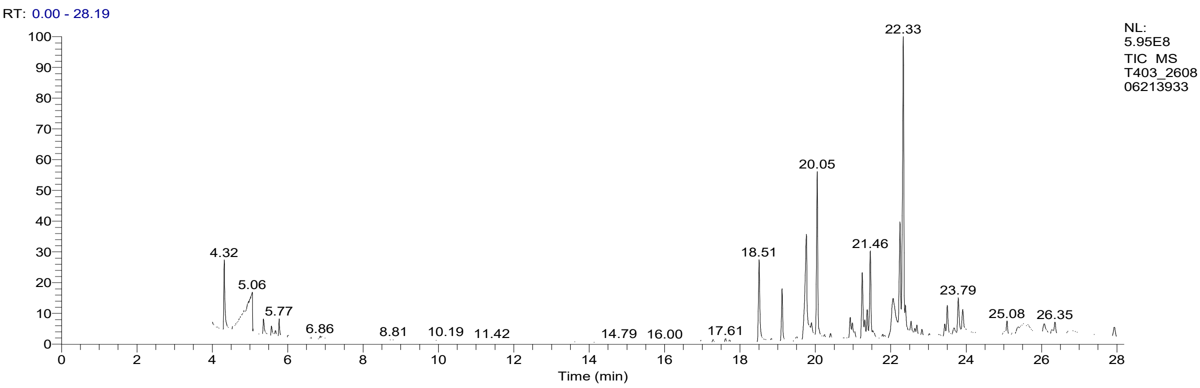

Figure 7. Chromatogram of Volatile Compounds in Sambal Tempoyak Before Drying

Figure 7 presents the chromatographic profile of volatile compounds detected in sambal tempoyak before drying and provides a visual representation of the retention-time distribution of the identified compounds. The chromatogram contains several distinct peaks corresponding to compounds identified through comparison of their mass spectra with the available spectral database. A prominent peak was detected around a retention time of 4.32 minutes and was identified as *Butanoic acid, 2-methyl-, ethyl ester* with an identification probability of 86.94%. Another relevant peak appeared at approximately 5.06 minutes and corresponded to *Butanoic acid, 2-methyl-*, which had an area of 7.03%. The distribution of peaks across the chromatogram indicates the presence of both relatively volatile short-chain compounds and less volatile long-chain fatty acid derivatives. The chromatographic pattern therefore reflects the chemical complexity of the fermented sambal matrix before exposure to thermal dehydration. This initial profile serves as a reference for evaluating changes in volatile composition following drying at the optimized temperature and time.

The GC-MS analysis after drying at 58°C for 2.4 hours showed a modified volatile compound profile compared with the undried sample. Several compounds detected before drying were no longer identified in the post-drying chromatogram, while other fatty acid derivatives remained detectable after thermal treatment. The post-drying profile included *Butanoic acid, 2-methyl-, ethyl ester*, *Butanoic acid, 2-methyl-*, *Hexadecanoic acid, methyl ester*, and several medium- and long-chain fatty acid compounds. The complete composition and chromatographic characteristics of the volatile compounds identified after the optimum drying treatment are presented in Table 9.

Table 9. Volatile Compound Profile of Sambal Tempoyak After Drying (Temperature 58°C and 2.4 Hours)

Retention Time	Probability (%)	Component	Area (%)
4.32	86.74	*Butanoic acid, 2-methyl-, ethyl ester*	0.47
19.15	85.47	*Hexadecanoic acid, methyl ester*	3.48
14.55	82.24	*Dodecanoic acid*	0.32
17.01	75.07	*Tetradecanoic acid*	0.87
17.28	68.21	*Tetradecanoic acid, ethyl ester*	0.41
18.36	67.17	*Pentadecanoic acid*	0.19
20.14	60.49	*Hexadecanoic acid, ethyl ester*	28.18
21.80	57.52	*Methyl stearate*	0.50
23.47	46.07	*n-Propyl 9,12-octadecadienoate*	0.75
4.96	43.82	*Butanoic acid, 2-methyl-*	0.99

The most notable change after drying was the reduction in the relative chromatographic area of the characteristic short-chain volatile compounds associated with tempoyak aroma. The area of *Butanoic acid, 2-methyl-, ethyl ester* decreased from 3.15% before drying to 0.47% after drying, representing a substantial reduction in its relative abundance. Similarly, *Butanoic acid, 2-methyl-* decreased from 7.03% to 0.99% following treatment at 58°C for 2.4 hours. These changes indicate that the optimized drying process caused partial loss or transformation of volatile compounds with relatively high volatility. Thermal exposure can accelerate volatilization and chemical transformation, particularly for compounds with relatively low molecular weight and high vapor pressure. Yang et al. (2024) demonstrated that drying processes can alter volatile flavor compounds in durian, including reductions in ester-related compounds and the formation of new volatile components. The persistence of both compounds in the post-drying sample, despite their reduced chromatographic areas, indicates that the optimized treatment did not completely eliminate the characteristic volatile components associated with the fermented tempoyak matrix.

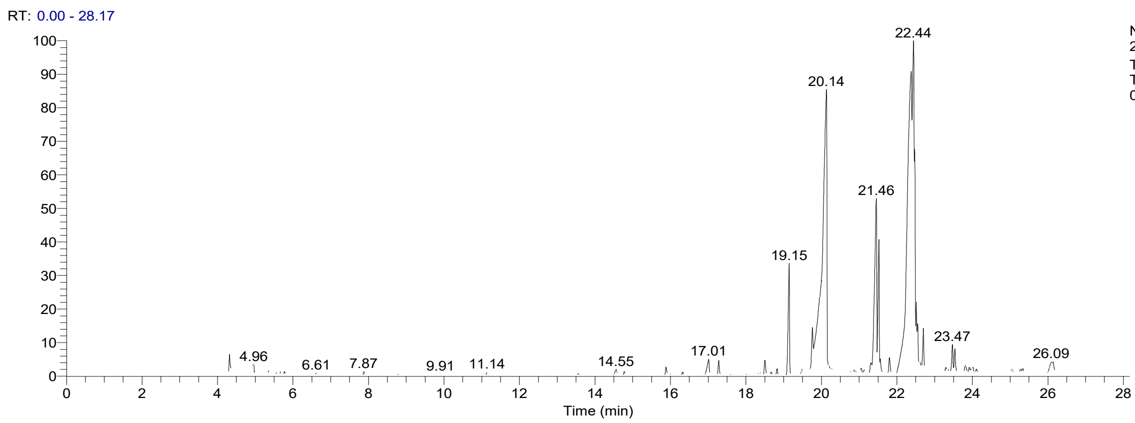

Figure 8. Chromatogram of Volatile Compounds in Sambal Tempoyak Cube (After Drying)

Figure 8 illustrates the chromatographic profile of sambal tempoyak cube after drying at the optimized condition of 58°C for 2.4 hours and can be compared directly with the pre-drying chromatogram in Figure 9. The post-drying chromatogram shows a shift in the relative distribution of volatile peaks, particularly for the short-chain butanoic acid derivative compounds. The reduction in the chromatographic area of *Butanoic acid, 2-methyl-, ethyl ester* and *Butanoic acid, 2-methyl-* indicates partial loss of aroma-active compounds during thermal dehydration. Nevertheless, the continued detection of these compounds demonstrates that the drying condition retained a fraction of the volatile components responsible for the characteristic fermented aroma of tempoyak. Yang et al. (2024) similarly found that drying can modify the volatile profile of durian through the loss of certain volatile compounds and potential formation of new compounds. Ariantika et al. (2017) also reported that differences in drying temperature affected the physicochemical characteristics of fermented tempoyak products, although differences in drying conditions did not necessarily produce significant changes in hedonic aroma attributes. The retention of characteristic volatile compounds after drying therefore suggests that the selected 58°C for 2.4 hours condition provides a reasonable balance between moisture reduction and preservation of important aroma-related constituents.

CONCLUSION

The drying process influenced the physicochemical and microbiological characteristics of sambal tempoyak cubes, including moisture content, water activity, pH, and total lactic acid bacteria (LAB). Increasing drying temperature and time reduced moisture content and Aw as a result of greater water evaporation, while pH increased with prolonged and more intense heat exposure. Moisture content and pH were adequately described by linear models, whereas Aw and total LAB were represented by quadratic models that accounted for nonlinear effects and interactions between the drying factors. Multi-response optimization identified 58°C for 2.4 hours as the optimum drying condition with a desirability value of 0.894. Verification at this condition produced 32.57% moisture content, 0.69 Aw, pH 3.67, and 4.083 Log CFU/g LAB, which were close to the predicted values. These findings indicate that the optimized drying condition provides an appropriate balance between moisture reduction, water activity control, acidity, and LAB retention in sambal tempoyak cubes.

The GC-MS analysis demonstrated that the optimized drying treatment modified the volatile compound profile of sambal tempoyak. The relative areas of *Butanoic acid, 2-methyl-, ethyl ester* and *Butanoic acid, 2-methyl-* decreased after drying, indicating partial loss or transformation of volatile compounds during thermal processing. Despite this reduction, both compounds remained detectable after treatment, indicating that important components associated with the characteristic aroma of tempoyak were retained. The optimized drying condition therefore did not completely eliminate the volatile characteristics of the fermented product. The combination of controlled dehydration, reduced water activity, maintained acidic conditions, viable LAB population, and partial retention of volatile compounds demonstrates the potential of the optimized process for producing sambal tempoyak cubes with improved processing consistency and product stability. Overall, the drying condition of 58°C for 2.4 hours can be considered an effective processing condition for obtaining sambal tempoyak cubes with balanced physicochemical, microbiological, and volatile characteristics.

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