



Effect of Lysine on Gel Properties of Reduced-Salt Surimi Prepared from Tilapia (*Oreochromis niloticus*)

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Abstract

Low-sodium surimi was prepared from tilapia (*Oreochromis niloticus*) using lysine, and the gelation properties were systematically evaluated. The primary objective of this study was to optimise the concentrations of salt and lysine using response surface methodology (RSM) with a central composite design (CCD), with salt and lysine concentrations ranging from 0.29 to 1.70% and 0.39 to 1.10%, respectively. The optimum salt concentrations were 1.00%, 1.01%, and 1.09%, with corresponding lysine concentrations of 0.71%, 0.69%, and 0.69%, respectively, to maximise gel strength and hardness and minimise expressible moisture content. The predicted maximum gel strength and hardness were 428 g cm and 6.36 N, respectively, with a predicted minimum expressible moisture content of 2.75%. In addition, the whiteness, TCA-soluble peptide content, and protein pattern of the surimi gel were assessed. Whiteness varied with both salt and lysine concentrations, with lower whiteness generally observed at higher lysine concentrations within the experimental region. The lower TCA-soluble peptide content was associated with higher gel strength, reflecting reduced proteolytic degradation and improved gel network formation. SDS-PAGE analysis revealed that the polymerisation of myosin heavy chain (MHC) was more pronounced in gels exhibiting maximal gel strength and hardness. These

findings indicate that incorporating lysine can significantly improve the gelation properties of tilapia surimi under low-salt conditions, thereby enhancing its quality as a functional food ingredient.

Keywords: Low-salt surimi, lysine, RSM, gel strength, hardness

Introduction

Texture and water-holding capacity (WHC) are critical functional properties of meat products, particularly surimi (Chen et al., 2014). Myosin, the predominant component of the myofibrillar protein matrix, plays a central role in forming a three-dimensional gel network that is essential to the texture and WHC of processed meat products. The factors influencing WHC and texture in meat products are primarily governed by molecular forces and the microstructure of salt-soluble meat protein gels, which are highly sensitive to pH and other environmental factors (Wu, Xu, Xu, & Niu, 2010; Sun & Holley, 2011).

The gelation process involves protein unfolding followed by aggregation, which can be facilitated by protein solubilisation through addition of salt. This is because myofibrillar proteins are typically extracted in buffers with intermediate to high ionic strength, classifying them as salt-soluble myofibrillar protein gels. However, excessive sodium intake, which is common in surimi products, poses a significant public health concern due to its association with increased risks of hypertension, stroke, and cardiovascular diseases (Greiff, Staurem, Nordvi, & Rusatd, 2015). Consequently, there is growing consumer awareness regarding the adverse health

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effects of high-salt diets. This has prompted a shift in the food industry, where processors are focusing on producing low-sodium surimi-based fish products to cater to this health-conscious market (Javith et al., 2023). Nonetheless, reducing sodium chloride levels can decrease WHC, texture, and juiciness, posing a challenge in maintaining product quality (Fu, Zheng, Lei, Xu, & Zhou, 2017).

In this study, lysine (Lys) was used to enhance the gelation properties of surimi with reduced salt content by promoting protein solubilisation. Lysine, an essential amino acid, contains a positively charged ϵ -amino group in its side chain, which plays a significant role in ionic interactions and hydrogen bonding. These interactions are crucial for water binding between protein chains, thereby improving the gelation properties of surimi (Sokalingam, Raghunathan, Soundarajan, & Lee, 2012). Previous studies have demonstrated that the addition of lysine enhances surimi gelation by improving water-binding capacity, texture, and microstructure, as well as increasing myosin solubility (Fu et al., 2017; Zheng et al., 2017; Li, Zheng, Xu, Zhu, & Zhou, 2018).

Tilapia, an underutilised freshwater fish, is a viable and sustainable source for surimi production due to its low cost and year-round availability. Its myofibrillar proteins exhibit acceptable gelation characteristics, making it a promising raw material for value-added surimi products. Several studies have explored the production of high-quality surimi from various tilapia species (Rawdkuen, Sai-Ut, Khamsorn, Chaijan, & Benjakul, 2009; Mahawanich, Lekhavichitr, & Duangmal, 2010; Priyadarshini, Xavier, Nayak, Dhanapal, & Balange, 2017). However, the effects of varying salt and lysine concentrations on the properties of low-salt surimi gel from tilapia have not been thoroughly investigated. Therefore, the primary objective of this study was to optimise the concentrations of salt and lysine using response surface methodology to improve the gelation properties of low-salt tilapia surimi gels formed through a two-step heating process.

Materials and Methods

Tilapia (*Oreochromis niloticus*), approximately 20 cm in length and with an average weight of 600 g, was procured from West Coast Fine Foodstuff LLP, Mumbai, Maharashtra, India. The fish were transported on ice to the laboratory within 1 hour of

procurement. Upon arrival, the fish were immediately washed with cold water; the head was removed, eviscerated, and thoroughly washed. The fish were then deboned using a mechanical deboner (Baader 694, Lubeck, Germany) equipped with a counter-rotating belt-and-drum mechanism, having a 5 mm hole diameter.

Surimi was prepared using the single washing method as described by Priyadarshini et al. (2017). The fish mince was washed with cold water (4 °C) at 3:1 (water:mince, v/w). The mixture was gently stirred for 3 minutes in a Hobart mixer (Hobart AE 200, London, England) and allowed to settle for 2 minutes. The slurry was then strained through double-layered muslin cloth, and excess water was manually squeezed out. Subsequently, the washed mince was centrifuged at 1000 rpm for 15 minutes in a basket centrifuge (Model 60-5, AIM Industries, Mumbai, India). The resulting surimi was packed in low-density polyethylene (LDPE) pouches and stored on ice until further use.

The prepared surimi was chopped using a silent cutter at low speed for 2 minutes. Salt and lysine were added at the specified concentrations (% w/w, based on the weight of surimi) according to the experimental design (as outlined in Table 2). The resulting paste was stuffed into polyvinylidene chloride casings (diameter: 2.5 cm, length: 17.5 cm) using a sausage stuffer. The casings were then tightly sealed at both ends. The gels were subjected to a two-step heating process: first, at 40 °C for 30 minutes, then at 90 °C for an additional 20 minutes, as described by Balange and Benjakul (2009a). After heating, the gels were cooled on ice and stored overnight at 4 °C before analysis.

After an equilibration period of 2 hours at room temperature (25 °C), the surimi gels were removed from the synthetic casings and cut into cylindrical samples of 2.5 cm in length. Gel strength was evaluated using a puncture test with a Rheo Tex texture analyzer (Type SD-700, Sun Scientific Co. Ltd., 4-Chome, Kamiyoga, Setagaya-KU, Japan) equipped with a 5-mm diameter, round-ended metal probe. The puncture test was conducted at a speed of 60 mm/min, and the load (as breaking force) and depth of depression (as deformation) at the point of gel rupture were recorded. All determinations were carried out in triplicate to ensure the reliability of the results.

The texture profile analysis (TPA) of the gel samples was conducted for each treatment group using a Texture Analyzer (Texan touch, Lamy Rheology, France). The cylindrical gel samples, cut into 2.5 cm segments, were placed on the flat plate of the texture analyzer. Each sample was compressed twice to 40% of its original height. The TPA parameters, including hardness, cohesiveness, adhesiveness, and elasticity, were determined from the recorded force-time curves. For simplicity, only the hardness values are reported in this study.

Expressible moisture content (EMC) was measured using the method described by Benjakul, Visessanguan, and Srivilai (2001). A gel sample, cut into 0.5-cm thick slices, was weighed (denoted as X g) and placed between three layers of Whatman filter paper No. 93 (Whatman International Ltd., Maidstone, England). A standard 5 kg weight was applied to the top of the sample for 2 minutes. After removal from the filter paper, the sample was reweighed (denoted as Y g). The expressible moisture content was calculated using the following equation:

$$\text{Expressible moisture content (\%)} = 100 \times (X - Y) / X$$

The color parameters of the surimi gels were measured using a HunterLab ColorFlex (Hunter Associates Laboratory, Reston, VA). The parameters lightness (L^*), redness (a^*), and yellowness (b^*) were determined, and the whiteness index was calculated using the following equation (Javith et al., 2022):

$$\text{Whiteness} = 100 - \sqrt{[(100 - L^*)^2 + (a^*)^2 + (b^*)^2]}$$

Approximately 2 g of the gel sample was mixed with 18 mL of 5% trichloroacetic acid (TCA) solution. The mixture was homogenised for 2 minutes at 11,000 rpm. The homogenate was then kept at 4 °C for 1 hour and centrifuged at 8000 × g for 5 minutes at room temperature. The supernatant, which contained TCA-soluble peptides, was measured according to the method described by Lowry, Rosebrough, Farr, and Randall (1951). Tyrosine was used as a standard, and the results were expressed as μmol of tyrosine per gram of sample.

The protein pattern of the surimi gel was analysed using Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE), as described by Laemmli (1970). A 3 g sample of the surimi gel was

mixed with 27 mL of 5% SDS solution and homogenised for 2 minutes at 11,000 rpm. To dissolve the proteins, the homogenate was incubated at 85 °C for 1 hour. The undissolved debris was removed by centrifugation at 3500 × g for 20 minutes. The protein concentration of the supernatant was determined using the Biuret method. Protein samples (15 μg) were loaded onto a polyacrylamide gel, which contained a 10% running gel and a 4% stacking gel, and subjected to electrophoresis at a constant current of 15 mA per gel. After electrophoresis, the gels were stained, destained, and scanned to visualise the protein bands.

The concentrations of salt (X_1) and lysine (X_2) were selected as independent variables for this experiment. The process parameters were optimised using a central composite design (CCD) with five levels for each variable, coded as -1.41 , -1 , 0 , $+1$, and $+1.41$, respectively (Table 1). The range and centre point values for these independent variables were based on preliminary experiments. The design consisted of four factorial points, four axial points, and three replicates of the central points. All experiments were conducted in triplicate, and the average values of gel strength, hardness, expressible moisture content, whiteness, and TCA-soluble peptide content were used as the response variables (Y). To minimise the effects of random variability, the experimental runs were randomised.

The relationship between the independent variables and the responses was modeled by the following equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{12} X_1 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \epsilon$$

where Y represents the predicted response; β_0 is the model intercept; β_1 and β_2 are the linear coefficients of X_1 and X_2 , respectively; β_{12} is the interaction coefficient between X_1 and X_2 ; β_{11} and β_{22} are the quadratic coefficients of X_1 and X_2 , respectively; X_1 and X_2 represent the coded levels of salt and lysine, respectively; $X_1 X_2$ represents the interaction term; X_1^2 and X_2^2 represent the quadratic terms; and ϵ represents the random error.

The statistical analysis of the experimental data was performed using Design-Expert Version 13 (Stat-Ease Inc., Minneapolis, MN, USA) to estimate the responses of the independent variables and generate response surface plots. Three-dimensional surface plots were generated to visualise the relationship

between the responses and the experimental levels of each variable. The optimal combination of the independent variables was determined, and the model's predictions were validated.

Results and Discussion

Response Surface Methodology (RSM) using Central Composite Design (CCD) was employed to investigate the impact of salt and lysine concentrations on the functional properties of surimi gel, including gel strength, hardness, and expressible moisture content. The effects of the independent variables, salt (X_1) and lysine (X_2), on the dependent variables (gel strength, hardness, and expressible moisture content) are presented in Table 2. The corresponding response surface plots illustrating the influence of the two independent variables on the response values are shown in Fig. 1. The statistical significance of the observed variations in response was

evaluated using Analysis of Variance (ANOVA), and the results are summarised in Table 3.

The ANOVA results demonstrated that the fitted quadratic models adequately described the experimental responses, with the significant effects being predominantly associated with the quadratic model terms rather than the linear or interaction terms. Therefore, the optimisation was based on the fitted response surface models rather than on the individual factor effects.

The quadratic polynomial equation developed for the maximum gel strength is $Y_1 = -1236.28 + 1007.48X_1 + 3235.73X_2 - 16.00X_1X_2 - 494.67X_1^2 - 2250.67X_2^2$. The observed gel strength values ranged from 103 to 436 g cm at design points 1 to 11. The predicted maximum gel strength was 428 g cm. The empirical model demonstrated a good fit to the experimental data, as indicated by the adjusted

Table 1. Independent variables and their coded levels used in the central composite design

Independent variables	Symbol	Coded levels				
		-1.41	-1	0	+1	+1.41
Salt (%)	X_1	0.29	0.50	1.00	1.50	1.70
Lysine (%)	X_2	0.39	0.50	0.75	1.00	1.10

Table 2. Experimental design and measured responses of tilapia surimi gels prepared with different concentrations of salt and lysine

Design points	Independent variables		Dependent variables		
	Salt (%) X_1	Lysine (%) X_2	Gel Strength (g cm) Y_1	Hardness (N) Y_2	EMC (%) Y_3
1	0.29	0.75	149	5.59	3.02
2	1.70	0.75	148	5.58	3.04
3	1.00	0.39	126	5.39	3.33
4	1.00	1.10	103	5.08	3.68
5	0.50	0.50	252	5.96	2.97
6	1.50	0.50	269	5.98	2.82
7	0.50	1.00	116	5.29	3.24
8	1.50	1.00	125	5.33	3.16
9	1.00	0.75	422	6.26	2.76
10	1.00	0.75	436	6.59	2.71
11	1.00	0.75	418	6.14	2.82

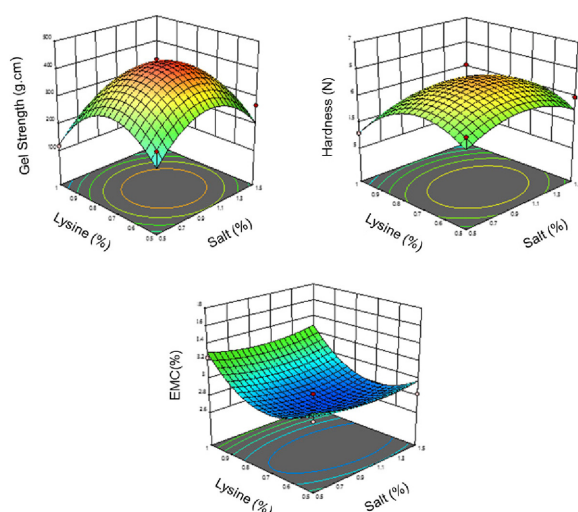


Fig. 1. Response surface plots showing the effects of salt and lysine concentrations on gel strength, hardness, and expressible moisture content of tilapia surimi gel

coefficient of determination (R^2_{adj}) value of 0.835, suggesting that approximately 84% of the variability in gel strength could be explained by the model within the range of the variables studied. The optimal conditions derived from the model corresponded to salt at 1.0% and lysine at 0.71%. Initially, when the salt concentration was 0.29% and the lysine concentration was 0.75%, the gel strength was 149 g cm. The response surface indicated a nonlinear relationship between salt and lysine concentrations and gel strength, with the highest gel strength occurring at an intermediate lysine concentration rather than at the highest concentration tested. This finding is consistent with previous research indicating that protein gelation is largely influenced by the ionic charge of molecules (Sun & Holley, 2011). At

the isoelectric point (pI), proteins have a net charge of zero, leading to minimal interactions between proteins. However, at alkaline pH, the negative charge on the protein surface increases, resulting in stronger electrostatic repulsion between proteins, subsequently enhancing protein-water interactions and facilitating solubilisation (Zhu, Li, Li, Ning, & Zhou, 2019). This process may improve protein aggregation or entanglement, leading to a stronger gel network (Buamard, Javith, Balange, Krishna, & Benjakul, 2020). The improvement in gel strength at the intermediate salt and lysine concentrations may be associated with enhanced protein solubilisation and subsequent protein-protein interactions during heating.

The ANOVA results indicated that the quadratic effects of salt (X_1^2) and lysine (X_2^2) were highly significant (Table 3), demonstrating that gel strength was primarily governed by the nonlinear relationship between the two variables rather than by their individual linear effects. The linear and interaction terms were not statistically significant within the investigated experimental range. These findings suggest that optimisation of gel strength depends on achieving an appropriate combination of salt and lysine concentrations rather than continuously increasing either factor. The fitted quadratic model successfully predicted the optimum formulation, yielding a maximum gel strength of 428 g cm at approximately 1.0% salt and 0.71% lysine.

The quadratic polynomial equation developed to predict maximum hardness is $Y_2 = 1.34 + 2.50X_1 + 10.84X_2 + 0.04X_1X_2 - 1.26X_1^2 - 7.84X_2^2$. The observed hardness values ranged from 5.08 to 6.59 N at design points 1 to 11. The predicted maximum hardness was 6.36 N. The empirical model demonstrated a

Table 3. Coefficient of variables in the model and their significance

Parameters	Gel Strength	Hardness	EMC
β_0	-1236.28	1.34	5.66
X_1	1007.48	2.50	-0.78
X_2	3235.73	10.84*	-7.17*
X_1X_2	-16.00	0.04	0.14
X_1^2	-494.67***	-1.26*	0.31
X_2^2	-2250.67***	-7.84***	5.05***

* = significant at 95%, ** = significant at 99%, *** = significant at 99.9%, β_0 = Model constant, Coefficient of X_1 = Salt and X_2 = Lysine

good fit to the experimental data, as indicated by the adjusted coefficient of determination (R^2_{adj}) value of 0.720, suggesting that 72% of the variability in hardness could be explained by the model within the range of the variables studied.

The optimal conditions derived from the model were a salt concentration of 1.1% and a lysine concentration of 0.69%. The addition of lysine appears to enhance protein refolding, which facilitates the formation of a more uniform and compact gel structure. This could contribute to the increased gel hardness, thereby improving its texture.

According to the ANOVA results (Table 3), the quadratic terms, particularly X_2^2 , significantly influenced hardness, whereas the linear and interaction terms were not statistically significant. This indicates that hardness was predominantly governed by nonlinear responses to lysine concentration within the experimental region. The fitted quadratic model adequately described the experimental data and predicted the optimum hardness (6.36 N) at approximately 1.01% salt and 0.69% lysine.

The quadratic polynomial equation developed for the maximum expressible moisture is $Y_3 = 5.66 - 0.78X_1 - 7.17X_2 + 0.14X_1X_2 + 0.31X_1^2 + 5.05X_2^2$. The measured response EMC values ranged from 2.71% to 3.68% at design points 1 and 11. The predicted minimum EMC was 2.75%. The empirical model demonstrated a good fit to the experimental data, as indicated by the adjusted coefficient of determination (R^2_{adj}) value of 0.730, suggesting that 73% of the variability in EMC could be explained by the model within the experimental range.

The optimal conditions for minimizing EMC, as determined by the model, were a salt concentration of 1.09% and a lysine concentration of 0.69%. The minimum EMC was observed at 1% salt and 0.75% lysine, while the highest value was obtained at 1% salt and 1.1% lysine. The expressible moisture content is a critical indicator of the water-holding capacity of protein gels, directly related to the ability of the protein network to trap water. In this study, the lower EMC observed at the intermediate lysine concentration suggests improved water retention within the protein network. However, the increase in EMC at the highest lysine concentration indicates that the effect of lysine was nonlinear.

The regression analysis demonstrated that the quadratic effect of lysine concentration (X_2^2) was

highly significant, while the linear term of lysine was significant at the 95% confidence level. In contrast, the linear effect of salt and the interaction term were not statistically significant (Table 3). These results indicate that the reduction in expressible moisture content was mainly associated with the nonlinear response of lysine concentration. The fitted RSM model effectively predicted the optimum processing conditions, resulting in a minimum EMC of 2.75% at approximately 1.09% salt and 0.69% lysine, consistent with previous findings reported by Zhou, Li, and Tan (2014) and Zhu et al. (2018).

The measured whiteness values of surimi gel ranged from 57.39 to 62.80, with the lowest value recorded at 0.29% salt and 0.75% lysine concentration (design point 1) and the highest value observed at 1.5% salt and 0.5% lysine concentration (design point 6). The optimal conditions for whiteness were achieved with 1.5% salt and 0.5% lysine, resulting in the highest whiteness value.

The observed decrease in whiteness with the addition of lysine is consistent with findings from previous studies. According to Hong, Park, Kim, and Min (2006), changes in the whiteness of meat products are often associated with variations in moisture content, with higher water retention generally resulting in lower whiteness values. In the present study, addition of lysine reduced the expressible moisture content, indicating enhanced water-holding capacity, which may have contributed to the slight reduction in whiteness.

In addition, lysine possesses a highly reactive ϵ -amino group that readily participates in the Maillard reaction with reducing sugars during thermal processing. The two-step heating process employed in this study (40 °C followed by 90 °C) may have promoted the formation of brown-coloured Maillard reaction products (melanoidins), thereby reducing the whiteness of the surimi gel. The high reactivity of lysine makes it one of the amino acids most susceptible to Maillard browning, which has been widely reported in thermally processed protein-rich foods (Martins, Jongen, & van Boekel, 2001; Nursten, 2005). Similar reductions in whiteness following lysine incorporation have also been reported in fish mince and surimi gels (Zhou et al., 2014; Buamard et al., 2020). Therefore, the decrease in whiteness observed in the present study can be attributed to the combined effects of enhanced moisture retention and lysine-induced

Maillard browning during heat-induced gelation.

The TCA-soluble peptide content of surimi gel with varying concentrations of salt and lysine is presented in Table 5. The presence of soluble peptides suggests that proteolytic degradation occurred during the setting and gelation stages of surimi preparation, as noted by Rawdkuen et al. (2009). The TCA-soluble peptide content ranged from 2.13 to 4.00 μmol tyrosine/g, with the minimum and maximum values observed at design points 10 and 3, respectively, indicating variation in the degree of protein degradation under the experimental conditions.

The minimum TCA-soluble peptide content was observed at 1% salt and 0.75% lysine concentration, while the highest value was found at 1% salt and 0.39% lysine. The results demonstrated an inverse relationship between TCA-soluble peptide content and gel strength. Samples with lower TCA-soluble peptide content consistently showed higher gel strength, indicating that reduced proteolytic degradation favoured the formation of a stronger and more stable protein network. The experimental conditions associated with lower TCA-soluble peptide contents were also associated with higher gel strength, suggesting that reduced proteolytic degradation may have contributed to improved gel formation. These findings are consistent with previous reports demonstrating that reduced proteolysis improves gel quality in surimi products (Zheng et al., 2017; Li et al., 2018).

The protein patterns of surimi gels with varying salt and lysine levels are shown in Fig. 2. Among the myofibrillar proteins, myosin, actin, and actomyosin are the key components that play a crucial role in the functional properties of meat products, particularly in gel formation (Priyadarshini et al., 2017). Myosin heavy chain (MHC) is one of the major myofibrillar proteins involved in heat-induced gel

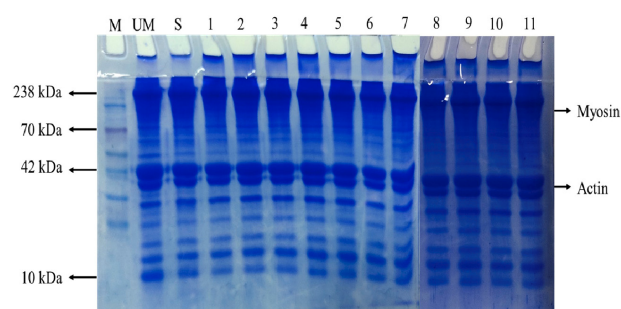


Fig. 2. SDS-PAGE profiles of surimi gels prepared with different concentrations of salt and lysine

formation. Changes in MHC band intensity and the appearance of high-molecular-weight protein species can provide evidence of protein aggregation or polymerisation during gelation.

The SDS-PAGE profiles showed differences in the MHC band pattern among the formulations. The formulations associated with higher gel strength showed a greater reduction in MHC band intensity and/or an increase in high-molecular-weight material, suggesting greater MHC aggregation or polymerisation. Overall, the protein pattern analysis suggests that the changes in MHC observed among the formulations may be associated with differences in gel strength. However, the SDS-PAGE results alone do not establish the specific mechanism by which lysine affects protein polymerisation.

Interestingly, the intensity of the actin band remained unchanged across all experimental conditions. This indicates that actin did not undergo significant polymerisation during gelation, possibly due to its resistance to proteolysis. The relatively unchanged actin band intensity across the formulations suggests that no substantial change in actin was detected under the experimental conditions, as also reported by Balange and Benjakul (2009b). This

Table 4. Individual optimum conditions predicted by the RSM models for gel strength, hardness, and expressible moisture content

Independent variables	Gel Strength (g cm)	Hardness (N)	EMC (%)
Salt (%)	1.00	1.01	1.09
Lysine (%)	0.71	0.69	0.69
Maximum/Minimum predicted point	428	6.36	2.75

Table 5. Effect of salt and lysine concentrations on TCA-soluble peptide content and whiteness of tilapia surimi gels

Design points	Independent variables		Dependent variables	
	Salt (%) X_1	Lysine (%) X_2	TCA soluble peptide content (μmol tyrosine/g) Y_1	Whiteness Y_2
1	0.29	0.75	3.63	57.39
2	1.70	0.75	3.58	62.08
3	1.00	0.39	4.00	60.84
4	1.00	1.10	3.73	59.81
5	0.50	0.50	3.47	60.07
6	1.50	0.50	3.40	62.80
7	0.50	1.00	3.96	58.84
8	1.50	1.00	3.95	58.33
9	1.00	0.75	2.28	62.19
10	1.00	0.75	2.13	62.19
11	1.00	0.75	2.33	62.50

resistance to proteolysis further supports the notion that lysine may help preserve the integrity of certain protein structures, contributing to the overall quality of the surimi gel.

Overall, the protein pattern analysis indicates that lysine enhances myosin polymerisation, while actin remains relatively unaffected, contributing to a stable and strong gel network. This observation aligns with the findings of previous studies, which suggest that lysine can improve the gelation properties of surimi by promoting cross-linking of myofibrillar proteins.

The individual response models predicted optimum conditions of 1.00% salt and 0.71% lysine for gel strength, 1.01% salt and 0.69% lysine for hardness, and 1.09% salt and 0.69% lysine for EMC. The corresponding levels of the independent variables (salt and lysine concentrations) for these optimal predictions are provided in Table 4.

To validate the predictions, experimental trials were conducted under the optimised conditions, and the actual measured values for gel strength, hardness, and EMC were 418 g cm, 6.29 N, and 3.09%, respectively. These experimental values were in close agreement with the predicted values, confirming the reliability and repeatability of the optimised conditions.

This validation demonstrates the robustness of the developed model and its ability to predict the functional properties of surimi gel under the given experimental conditions, further supporting the effectiveness of using RSM for optimising the formulation of low-salt surimi with lysine enhancement.

Under the selected optimised conditions, the experimentally validated gel strength, hardness, and expressible moisture content were 418 g cm, 6.29 N, and 3.09%, respectively. The results of this study indicate that incorporating lysine was associated with improved gel properties under the conditions investigated. However, adding lysine at the optimised salt and lysine concentrations reduced the gel whiteness.

These findings suggest that lysine can serve as a promising functional additive to enhance the gelation properties of tilapia surimi under reduced-salt conditions, thereby facilitating sodium reduction while maintaining desirable product quality. The incorporation of lysine may contribute to the development of healthier low-sodium surimi products without compromising their functional properties. This study provides a practical approach in developing low-sodium surimi products with improved gel properties using lysine, which can help

the seafood industry meet consumer demand for healthier products.

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