FISHERIES SCIENCE 2001; **67**: 500–505

Original Article

Optimum blends of different grades of surimi determined by non-linear programming

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SUMMARY: The texture and color properties of surimi gels consisting of pollack surimi, golden threadfin-bream surimi, and low-grade hairtail surimi in various ratios were determined based on a mixture design. Surimi gels were produced by heating at 90°C for 20 min with the addition of 2% NaCl. The texture and color properties of blended surimi from various grades can be represented as non-linear functions. Therefore, non-linear programming was found to be appropriate for determining the optimum formulation for surimi products blended from various grades of surimi. About 3.3% to 18.8% of hairtail surimi could be used when blending with high-grade surimi to produce surimi seafood.

KEY WORDS: **non-linear programming, optimization, surimi blend.**

INTRODUCTION

Surimi is a washed fish mince to which cryoprotectants, such as sorbitol and sucrose, are added, which maintain protein functionality during frozen storage. Surimi can be further processed into various surimi-based gelled products such as artificial crab legs and meats. Texture and color are the most important sensory factors affecting the consumer's acceptance of surimi seafood. However, the gelling and color properties of surimi depend strongly on the nature of the fish species used and the handling conditions during harvest and subsequent processing. For example, surimi-based products made from walleye pollack exhibit an elastic texture, whereas the surimi products made from fatty and dark-flesh species, such as mackerel and sardine, exhibit lower gelling properties.[1–3] Therefore, during the processing of surimi-based products from fatty and dark-flesh species, the addition of gel strength enhancers, such as starch, egg white, whey protein, or soybean protein, is generally required to maintain good textural characteristics. However, the addition of these texture-enhancing food additives may also change the color of the final products or result in an off-flavor, thereby reducing market acceptance.

One way to utilize low-grade surimi without using a high amount of food additives is to blend the low-grade surimi with high-grade surimi. In order to satisfy various functional and cost requirements in surimi seafood, the industry may blend different grades of surimi to produce a surimi seafood targeted for different markets based on the demands of the consumers.

When blending different grades of surimi, the use of optimization techniques, such as linear or non-linear programming, allows us to determine the ratio for each surimi that results in a minimum formulation cost while maintaining the desired level of product quality. Therefore, the development of least cost formulation could be used as a tool to evaluate the feasibility of blending low-grade surimi with higher grades of surimi. This process, which includes experiments and the application of quantitative models, establishes relationships among the cost of ingredients, the amount of ingredients in the formulation, and the quality of the final products. The development of least cost formulation using linear programming has been found to improve the profitability and/or quality for surimi products.[4–6]

When blending different grades of surimi, the assumption of linear relationships between the functionality and the amount of each surimi used

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Received 24 July 2000. Accepted 15 November 2000.

has been confirmed by Lanier and Park.[4] However, the surimi lots they used in different blends showed only small differences in textural and color properties. It is often true that linear function can describe well the mathematical relationship over a range, showing small changes in response.

In the present study, surimi made from hairtail, showing significantly low textural properties and of a dark gray appearance, was intended to blend with surimi made from light-colored flesh species such as walleye pollack. Questions arise concerning whether the assumption of linear relationships between the functionality and the amount of each surimi used is valid when blending surimi comprising both light-colored flesh and dark-colored flesh species.

The main objectives of the present study were to identify the effect of blending various grades of surimi on the texture and color properties of the formulated products and which optimization approach provides the most effective least cost formulation for surimi seafood comprising dark- and light-colored flesh species.

MATERIALS AND METHODS

Frozen high-grade walleye pollack (*Theragra chalcogramma*) surimi, golden threadfin-bream (*Nemipterus virgatus*) surimi, and low-grade hairtail (*Trichiurus lepturus*) surimi were purchased from Kasei Frozen Foods Works Co., Ltd, Keelung, Taiwan. These surimi were stored at –20°C until required for sampling.

Surimi gel preparation

Instead of being completely thawed, frozen surimi was partially thawed at room temperature for approximately 2 h to prevent the rapid increase in sample temperature during the subsequent blending procedures. A mixer (model WTI-168DX; Wang-Den Inc., Taipei, Taiwan) was used to blend approximately 600 g of surimi with 2% NaCl (weight percentage of the mixture) for 4 min, with the addition of iced water to adjust the final moisture content to 78%, while maintaining a low temperature in the range of 5–10°C. The mixture was extruded into stainless steel cooking tubes (internal diameter 3.0 cm, length 15 cm), and surimi gels were then produced by heating in a 90°C water bath for 20 min, followed by cooling in iced water at about 1°C for 10 min. Surimi gels were stored in ziplock bags and refrigerated at about 5°C. The gels were removed from refrigerated storage within 48 h, left at room temperature for 1 h and cut into small sections (diameter 3.0 cm, length 3.0 cm) for color and texture measurements.

Color measurement

The color of the surimi gels was measured using a colorimeter (model TC-1500 DX; Tokyo Denshoku Co., Ltd, Tokyo, Japan). The L* and b* values were recorded, with L* denoting lightness on a 0–100 scale from black to white and b* denoting yellow (+) or blue (–).

Gel strength measurement

The gel properties were measured by a rheometer (model CR-200D; Sun Scientific Co., Ltd, Tokyo, Japan) using a ball plunger with a diameter of 5 mm and the results were expressed as breaking force (*g*) and deformation (mm), which represent the hardness and cohesiveness of the surimi gels, respectively. A conventional folding test was also conducted by holding a 3-mm thick slice of the test sample between thumb and forefinger and folded to observe the way it breaks. Gradings were AA grade, no crack showing after folding twice; A grade, no crack showing after folding in half; B grade, cracks gradually when folded in half; C grade, cracks immediately when folded in half; and D grade, breaks with finger pressure.

Composition analysis

The analysis of the protein, fat, moisture, and ash content of each surimi was performed according to standard AOAC methods.[7]

Experimental design and modeling

Mixture design methods are often used to develop an empirical model for optimum formulations. An augmented simplex-centroid mixture design[8] was applied in the present study to develop the mathematical functions expressing texture and color as a function of the ratio of blended surimi. The combined experimental points are shown in Table 1, with three duplications in four selected experimental points for testing the lack of fit of the developed models.

A stepwise regression procedure in the SAS package (SAS Institute, Inc., Cary, NC, USA) was used to fit the texture and color data into canonical form, second order equations:

Table 1 Three-factored mixture design and experimental data

Surimi (ratio)			Color		Texture		
P	GTB	H	L*	b*	Force (*g*)	Texture deformation (mm)	Folding test
1	0	0	86.9	5.2	336	14.2	AA
1	0	0	86.3	5.6	410	11.1	AA
1	0	0	86.9	5.5	360	11.4	AA
0	1	0	87.2	7.6	444	11.7	AA
0	1	0	86.8	7.2	367	10.8	AA
0	1	0	87.4	7.7	351	12.2	AA
0	0	1	79.9	11.3	65	4.5	D
0	0	1	80.2	12.0	59	3.9	D
0	0	1	79.6	11.8	50	4.2	D
0.5	0.5	0	87.3	6.8	281	11.3	AA
0.5	0	0.5	82.7	10.1	149	7.5	B
0	0.5	0.5	82.9	10.1	179	7.6	B
0.333	0.333	0.333	83.5	9.1	196	9.3	A
0.333	0.333	0.333	83.6	9.3	174	7.8	B
0.333	0.333	0.333	83.1	9.8	135	8.5	A
0.667	0.167	0.167	84.7	7.8	235	11.3	AA
0.167	0.667	0.167	85.1	8.4	282	10.7	AA
0.167	0.167	0.667	81.5	11.1	119	6.2	C

P, pollack surimi; GTB, golden threadfin-bream surimi; H, hairtail surimi.

$$z = A_1X_1 + A_2X_2 + A_3X_3 + A_4X_1c^2 + A_5X_1X_3 + A_6X_2X_3$$

where Z is the dependent variable, A_{1-6} are the regression coefficients of the model, and X_i is the concentration (in weight ratio) of each surimi (subscripts $i = 1$, 2, and 3 and represent pollack surimi, golden threadfin-bream surimi, and hairtail surimi, respectively). An *F*-test of lack of fit was used to determine whether the regression models adequately fit the experimental data. Once the regression models were developed, six new experimental points in separate experiments were then used to test the validity of the models.

Table 2 The composition of pollack surimi, golden threadfin-bream surimi, and hairtail surimi (wt%)

	Pollack surimi	Golden threadfin-bream surimi	Hairtail surimi
Protein	16.9 ± 0.9^a	17.6 ± 0.2^a	15.0 ± 0.2^b
Moisture	73.7 ± 0.1^a	75.8 ± 0.0^b	78.0 ± 0.1^c
Fat	0.83 ± 0.00^a	1.05 ± 0.00^b	1.02 ± 0.00^c
Ash	0.70 ± 0.00^a	0.56 ± 0.01^b	0.87 ± 0.01^c

^{abc} Means of at least three determinations, expressed as mean ± SD. Values in same row with different letters are significantly different ($P < 0.05$). One way analysis of variance was conducted, and the comparison of treatment means was based on the multiple ranges test of Duncan.

Least cost model and computer package

The objective function to be minimized in the least cost model was the total cost of ingredients. Upper and lower boundaries for the parameter that defines each constraint function (i.e. texture, color, and ingredients) were used to define the quality requirement. A commercial linear and non-linear programming package 'AMPL' (The Scientific Press, San Francisco, CA, USA) was used to search for the least cost formulations of blended surimi with selected textural and color constraints.[9,10] The package implemented a primal simplex method[11] to solve the linear programming problem. In the case of solving a non-linear programming problem with non-linear constraint functions, they were transformed with the augmented Lagrangian procedures described by Robinson[12] and Murtagh and Saunders[10] into a sequence of linearly constrained subproblems that could be solved by using a reduced gradient algorithm.[13]

RESULTS & DISCUSSION

Compositional properties of surimi

The compositional properties of the three surimis used in the present study are shown in Table 2. Hairtail surimi showed the highest moisture and ash content among the three surimi samples, but the lowest protein content. It is known that the

Table 3 Regression models for the color and texture properties of blended surimi

	Color		Texture	
Variable	L*	b*	Breaking force	Deformation
P	86.6717[a]	5.4275[a]	369.6246[a]	12.0509[a]
GTB	87.1233[a]	7.4857[a]	381.6744[a]	11.4081[a]
H	79.9512[a]	11.7049[a]	51.4477[c]	3.9081[a]
P*GTB	NS	1.5539[d]	–435.4970[b]	NS
P*H	–4.1844[b]	6.5471[a]	–313.7965[c]	NS
G*H	–4.0678[b]	2.3282[c]	NS	NS
R^2	0.999	0.999	0.989	0.993
Lack of fit	Model adequate	Model adequate	Model adequate	Model adequate

[a] $P < 0.001$; [b] $P < 0.01$. [c] $P < 0.05$; [d] $P < 0.15$; NS, $P > 0.15$.
P, pollack surimi; GTB, golden threadfin-bream surimi; H, hairtail surimi.

textural properties of protein gels depend on their protein content. In general, the hardness of the protein gels tends to decrease with decreasing protein concentration. Therefore, values of lower hardness were expected in protein gels made from hairtail surimi. There were large differences in the moisture content among the three surimi selected. Thus, to compare the texture and color properties of gel samples consisting of the three types of surimi, the final moisture content was adjusted to a constant level of 78%.

Textural properties of blended surimi

Breaking force and deformation were used to indicate the hardness and elasticity of the blended surimi. There were no significant differences in either breaking force or deformation between pollack surimi and golden threadfin-bream surimi, but hairtail surimi showed a significantly lower breaking force and deformation (Table 1). The result of the folding test of hairtail surimi was grade D, further indicating that hairtail surimi had very poor gel-forming ability.

As well as the nature of the fish protein, the harvesting and subsequent processing conditions could significantly affect the quality of hailtail surimi. To improve the textural properties, the production of surimi products from hairtail surimi would require the addition of a relatively high amount of gel enhancers, such as starch and egg white. But the addition of gel enhancers may not be feasible as it may result in producing an off-flavor and/or an increase in the cost of ingredients.

An alternative for utilizing hairtail surimi without the use of gel enhancers was to blend hairtail surimi with other high-grade surimi. Both breaking force and deformation increased when the amount of pollack surimi or golden threadfin-bream surimi was increased in the formulation. It was noted that when equal amounts of pollack, golden threadfin-bream, and hailtail surimi were blended together, the folding test result of blended surimi could reach A grade.

The regression equations of breaking force and deformation are shown in Table 3. The coefficients of the determination, R^2, of the breaking force and deformation were 0.989 and 0.993, respectively. An *F*-test for lack of fit at the 0.05 significant level showed that both breaking force and deformation models adequately fit the experimental data.

Table 4 shows the validation of the regression models for breaking force and deformation using six new data points. The experimental data and the values predicted from the models showed reasonable agreement with high correlation coefficients of 0.98 and 0.92 for the breaking force and deformation, respectively. The results of the paired *t*-test further showed no significant difference ($P > 0.05$) between the experimental data and the predicted values for both the breaking force and deformation. Thus, the models were validated for predicting the textural properties of the blended surimi. It appeared that the linear model could well represent the relationships between the deformation and the ratios of blended surimi. But a non-linear model was required for the breaking force because of the interactions between each type of surimi used.

Color properties of blended surimi

Compared to the color of pollack surimi, golden threadfin-bream surimi showed a slightly higher yellow value as indicated by the high b* value, but hairtail surimi exhibited a gray color, which was identified by the relatively low L* and relatively high b* values (Table 1). The differences in the

Table 4 Regression model validation for color and texture properties using a new data set

			Color				Texture			
Surimi (ratio)			L*		b*		Breaking force		Deformation	
P	GTB	H	Exp.†	Est.‡	Exp.†	Est.‡	Exp.†	Est.‡	Exp.†	Est.‡
0.7	0	0.3	83.0	83.8	9.2	8.7	186	208	8.1	9.6
0	0.7	0.3	83.9	84.1	9.9	9.2	280	282	8.6	9.2
0.3	0.7	0	86.9	87.0	7.0	7.2	322	286	12.3	11.6
0.2	0.4	0.4	83.1	83.2	10.3	9.8	179	187	7.6	8.5
0	0.3	0.7	81.6	81.2	10.9	10.9	132	150	6.2	6.2
0.4	0.4	0.2	84.5	84.8	9.1	8.5	210	216	9.0	10.2
Correlation coefficient (*r*)			0.98		0.96		0.98		0.92	
Paired *t*-test			No difference		No difference		No difference		No difference	

† Values of experimental data.
‡ Values estimated from the regression models.
P, pollack surimi; GTB, golden threadfin-bream surimi; H, hairtail surimi.

appearance of the surimi maybe due to the variation in the nature and amount of heme pigment in the white muscle.[3] The b* value of blended surimi increased when the amount of golden threadfin-bream surimi or hairtail surimi was increased in the formulation, whereas the L* value for blended surimi decreased when the amount of hairtail surimi was increased. The coefficient of the determination was 0.999 for both models for L* and b* values, indicating a good fit to the experimental data, and the test of lack of fit also showed an adequate fit for both models (Table 3).

Model validation for L* and b* using six new data points showed no significant difference ($P > 0.05$) between experimental and predicted data, and also the correlation (correlation coefficient 0.98 and 0.96 for L* and b*, respectively) was reasonably high (Table 4). The results showed that models for the color (lightness and yellowness) and texture (hardness) properties of the blended surimi were non-linear functions.

When blending different grades of surimi lots, Lanier and Park reported that linear function can be used to describe the relationships between functionality and the amount of each surimi used.[4] The difference was that the surimi lots they used in blends showed only small differences in their textural and color properties; however, in the present study, surimi made from hairtail showed significantly low textural properties and was dark gray in appearance.

Different results have also been reported in a study by Yoon *et al.*, who stated that the texture and color properties of blended surimi (blending walleye pollack and Pacific whiting surimi) showed a linear relationship to the quantity of each surimi.[14] It was noted that walleye pollack and Pacific whiting surimi were very similar in color.

Table 5 Least cost linear models and the outcome with selected constraint targets

Objective function to be minimized	$3.1\ X_1 + 2.65\ X_2 + 1.45\ X_3$
Constraint targets for case 1	Constraint targets for case 2
$86 \leq$ Lightness (L*)	$85 \leq$ Lightness (L*)
Yellowness (b*) ≤ 7.7	Yellowness (b*) ≤ 8.7
$340 \leq$ Breaking force	$310 \leq$ Breaking force
$11 \leq$ Deformation	$10 \leq$ Deformation
Least cost for case 1	Least cost for case 2
$2.610/kg	$2.425/kg
Optimum blend	Optimum blend
$X_1 = 0$	$X_1 = 0$
$X_2 = 0.967$	$X_2 = 0.812$
$X_3 = 0.033$	$X_3 = 0.188$

X_1, weight ratio of pollack surimi; X_2, weight ratio of golden threadfin-bream surimi, and X_3, weight ratio of hairtail surimi.
The cost of surimi of pollack, golden threadfin-bream, and hairtail surimi were US$3.10, US$2.65, and US$1.45 per kg, respectively.

Optimization of least cost formulation

Because non-linear functions could be used to describe the relationships between the amount of each surimi used and the breaking force, L*, and b* of the blended surimi gels, non-linear programming was appropriate for determining the least cost formulation for the blended surimi products.

Table 5 shows the least cost of blended surimi with two sets of selected constraint targets. The constraint targets of case 1 were reasonably close to that of golden threadfin-bream surimi gel, which represented the quality constraints for high-grade surimi. The optimum blending for the least cost was 0% pollack surimi, 96.7% golden threadfin-bream surimi, and 3.3% hairtail surimi. This formulation, which used different levels of surimi, not only resulted in the least cost but also exceeded the target constraints for texture and color properties that represent high-grade surimi products. The amount of hairtail surimi in the least cost formulations would increase when the quality constraint decreased.

The constraint targets of case 2 could be used to represent the quality requirements for middle-grade surimi products. Based on the data of the present study, the deformation of surimi gels should be greater than 10 mm to pass the traditional Japanese folding test representing AA gel grade (Table 1); hence, the constraint target for the deformation in case 2 was set at 10 mm. The least cost formulation developed for middle-grade surimi products was 0% pollack surimi, 81.2% golden threadfin-bream surimi, and 18.8% hairtail surimi (Table 5). The results indicated that about 3.3–18.8% hairtail surimi could be used when blending with high-grade surimi to produce high-grade and middle-grade surimi seafood, respectively.

When blending similar grades of surimi, linear functions may be used for predicting the properties of texture and color for blended surimi products; however, non-linear functions provided better predictions because the differences in the texture and color properties of blended surimi were significant. Subsequently, non-linear programming was useful for determining the least cost formulation for surimi products adhering to predetermined required quality constraints for product texture and color. Even though hairtail surimi had very poor gel-forming ability and also showed significant discoloration, it appears that the potential for producing good quality surimi seafood by blending hairtail surimi with other high grades of surimi is promising. Making surimi seafood by blending various grades of surimi can offer a way of utilizing low-grade surimi.

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