Design and Development of the Fermented Fish Chopper Machine using the Design of Experiments Method

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ABSTRACT

The objective of this research is to design and develop a fermented fish chopper machine to provide support to community enterprises in Phetchabun province in Thailand. A full factorial design of experiments was employed for the purpose of evaluating and optimizing manufacturing parameters. The experiment involved varying the knife chopping speed, the chopping block speed, and the press distance of the knife from 250 to 280 rpm, 50 to 70 rpm, and 1 to 3 mm, respectively. The Analysis of Variance (ANOVA) was employed to analyze the variation in the experimental data. The main effects and interaction effects were found to be significant ($p < 0.05$), indicating their influence on chopping time. The results demonstrated the optimal operating conditions for minimizing chopping time and improving machine performance.

Keywords-fish chopper machine; full factorial design of experiments; ANOVA; chopping time

I. INTRODUCTION

Fermenting fish is a traditional culinary technique observed in diverse cultural contexts across the globe. It entails the preservation and transformation of fish through the process of fermentation. The popularity of fermented fish products can be attributed to their flavor and texture. Indeed, it has been reported that production in Thailand increases by more than 40,000 tons each year [1]. The province of Phetchabun, situated in the northern region of Thailand, is a prominent producer of fermented fish and a major processing center for these products destined for the market. However, the processing of fermented fish in community enterprises in Phetchabun province has encountered some challenges, including the use of traditional methods. The process of chopping is conducted manually with a knife by workers, which affects both productivity and safety, resulting in low output. Consequently, the implementation of technology in the aforementioned processes can enhance productivity and augment the value of the product while simultaneously offering a cost-effective solution. The utilization of a fermented fish chopper machine represents a viable alternative that facilitates the processing.

Prior research on fermented fish chopper machines has not provided comprehensive data. However, similar devices, such as meat and pork chopper machines, are commercially available. Authors in [2] investigated the impact of chopping time and rotational speed of the cutter knives and bowl on the structure of meat batter. The experiment employed a range of rotational speeds, including 1500/10 rpm, 1500/20 rpm, 3000/10 rpm, and 3000/20 rpm. The chopping times were 5, 6, 8, and 10 minutes, respectively. The findings indicated that the optimal speed for the cutter knives and bowl was 3000/20 rpm, resulting in a reduction in chopping time from 10 to 8 minutes.

Authors in [3] designed, fabricated, and conducted a performance evaluation of a semi-automatic fish cutting machine utilizing a 1400 rpm, 1 hp electric motor. The machine was tested with five major types of fish. The results demonstrated that the machine is capable of processing an average of 21 fish per minute, with an average time of 47 minutes to complete the cutting of 1,000 fish, resulting in an 81.2% reduction in processing time. The objective of the machine's development was to evaluate its operational performance based on durability, functionality, efficiency, energy consumption, and safety [4, 5]. Moreover, the machine is capable of enhancing production benefits in comparison to traditional choppers [6]. Design of Experiment (DOE) is a statistical modeling approach that may be defined as an analysis procedure encompassing a structured approach to experimentation. This facilitates a systematic exploration of factors and their interactions, with the aim of enhancing processes or products [7-9]. Authors in [5] developed the machine using the DOE Response Surface Methodology (RSM) to optimize the kernel-free digester machine for evaluating factors such as rotational speed (RPM), separation time (*s*), and nut categories (%). The results obtained under these conditions revealed that the *p*-value model was statistically significant ($p < 0.05$) and that the R^2 value for separation efficiency was 97.73%, indicating that the machine exhibited high efficiency for high-capacity operations. The objective of this research is to design and develop a fermented fish chopper machine that meets the needs of community enterprises and business purposes. The primary goal is to develop a novel fermented fish chopper machine that is straightforward to operate, dependable, safe, and cost-effective. The optimization of the factors is controlled by an experimental design employing a full factorial design of experiments [10-13].

II. EXPERIMENTAL DESIGN

A. Mechanical Design

Figure 1 presents the general features of the machine's components. The dimensions of the machine are 600 mm in width, 800 mm in length, and 1,170 mm in height, indicating a relatively simple design comprising eight main parts:

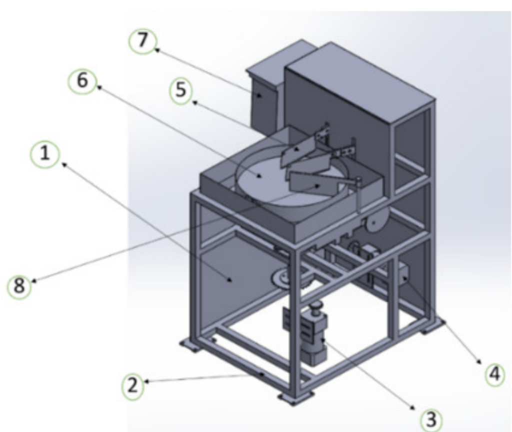

Fig. 1. Main parts of the fermented fish chopper machine.

(1) the machine cover, which is designed with the objective of safeguarding the machinery from various external factors, thereby enhancing the safety and longevity of the equipment, (2) the frame, which is a pivotal component, providing indispensable support, stability, and protection for the machine's operational integrity, (3) the motor, which is responsible for transferring power to the chain, therefore facilitating the rotation of the knife set, (4) the motor, which is tasked with transferring power to the chopping block set, (5) the knife set, which is utilized for the purpose of chopping fermented fish, (6) the chopping block set, which serves to support the fermented fish during the chopping operation, (7) the control panel, which is a vital component, typically comprising an on-off breaker and an emergency stop, and (8) the control plate, which is employed for the regulation of the position of the fermented fish throughout the knife set chopping operation.

B. Manufacturing

A fermented fish chopper machine, constructed following a comprehensive design process, was locally manufactured in workshops, as shown in Figures 2 and 3. As the initial phase in the preparation of all the primary components, the frame should be assembled in accordance with the specifications delineated in the accompanying drawing. The two motors are to be installed in the frame, along with the requisite accessories, including the gear, chain, crank, and bearing and the chopping block set too. Subsequently, the knife set and control plate are to be installed on the chopping block set. The control panel should be installed, and a trial run of the machine should be conducted. Ultimately, it is essential to ascertain the overall completeness of the machine and to install the machine cover on the frame.

Fig. 2. A machine frame.

Fig. 3. A prototype of the fermented fish chopper machine.

C. Design of Experiments (DOE)

Experimental design and statistical analysis using Minitab® 21 software were performed based on a 2^k full factorial design to evaluate the influence of a fermented fish chopper machine. 2k denotes the number of standard two-level factorial points (low: L, high: H) [14-15]. Two levels were specified for each factor in the factorial design. The performance of the machine was tested based on three factors: (A) knife cutting speed, (B) chopping block speed, and (C) knife pressure distance, as evidenced in Table I. According to the full factorial design, 10 trials, including two center points, were performed to study the effects and provide a measure of process stability, as observed in Table II. The sample trial used 10 kg of fermented fish each time.

TABLE I. FACTORS AND EXPERIMENTAL OF FULL FACTORIAL DESIGN 2^K

Coded	Factor	Experimental value	
		Low level (-1)	High level (+1)
A	Knife chopping speed (rpm)	250	280
B	Chopping block speed (rpm)	50	70
C	Press distance of the knife (mm)	1	3

The response variable for the first-order model of all factors in the general form can be expressed as [16]:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ij} X_i X_j \quad (1)$$

where Y is the predicted response, β_0 is the model constant, β_i is the main effect of the factors, β_{ij} is the interaction coefficient, X_i and X_j are the variable effects, respectively. Statistical analysis using ANOVA was carried out to analyze the main effects and interaction effects of the response variables [17-18].

TABLE II. FULL FACTORIAL DESIGN RESULTS

Run	Factors			Chopping time (s)
	Knife chopping speed (rpm)	Chopping block speed (rpm)	Press distance of the knife (mm)	
1	250	50	1	1,180
2	280	50	1	635
3	250	70	1	1,416
4	280	70	1	650
5	250	50	3	1,080
6	280	50	3	602
7	250	70	3	1,150
8	280	70	3	620
9	265	60	2	850
10	265	60	2	845

III. RESULTS AND DISCUSSION

In this study, the fermented fish chopping machine was designed and manufactured, optimizing the chopping time. ANOVA was utilized to evaluate the significance and adequacy of the model at the 95% confidence level ($\alpha = 0.05$) for the factors and their interactions [11, 17, 1-24].

A. Analysis of Variance (ANOVA) of Chopping Time

Table III displays the summarized statistical results for the overall responses of the experimental data on chopping time. The results indicate that the model is statistically significant because the f-value of the model is 7449.19, and the probability value (p-value) is 0.009, which is less than 0.05, indicating the significance of the model. As can be observed, the linear (A, B, C), 2-way interactions (A×B, A×C, B×C), and 3-way interactions (A×B×C) coefficients of the three factors, based on a P-value of less than 0.05, were all significant for chopping time. The R-squared value ($R^2 = 0.9999$) for the responses indicates that the model is very close to 100%. The adjusted R-squared value ($R^2_{Adj} = 0.9995$) for the responses indicates that the model has a good correlation between the factors and the responses [18-19].

TABLE III. ANOVA FOR RESPONS OF THE CHOPPING TIME

Source	DF	Adj SS	Adj MS	f-Value	p-Value
Model	8	744,919	93,115	7,449.19	0.009
Linear	3	709,590	236,530	18,922.41	0.005
A (Knife chopping speed)	1	672,220	672,220	53,777.61	0.003
B (Chopping block speed)	1	14,365	14,365	1,149.21	0.019
C (Press distance of the knife)	1	23,005	23,005	1,840.41	0.015
2-Way Interactions	3	24,113	8,038	643.02	0.029
A*B	1	9,316	9,316	745.29	0.023
A*C	1	11,476	11,476	918.09	0.021
B*C	1	3,321	3,321	265.69	0.039
3-Way Interactions	1	3,570	3,570	285.61	0.038
A*B*C	1	3,570	3,570	285.61	0.038
Curvature	1	7,645	7,645	611.62	0.026
Error	1	12	12		
Total	9	744,932			
Model Summary	S = 3.53553; R^2 = 99.99%; R^2_{Adj} = 99.95%				

Pareto charts, as illustrated in Figure 4, show the effectiveness of the analyzed factors that are statistically significant. The final empirical regression model of the actual significant factors for the chopping time is:

$$Y = -1111 + 6.17\,A + 143.24\,B + 1639\,C - 0.5092\,A \times B - 5.925\,A \times C - 39.36\,B \times C + 0.14083\,A \times B \times C - 69.13 \quad (2)$$

In Figure 5, the main effects plot for each factor in the model is plotted to minimize the chopping time, using the means of the data. The lines in the main effects plot provide information about the differences between the level means for each factor. As knife cutting speed increases from low to high levels, chopping time decreases. Conversely, as the chopping block speed increases, the chopping time also increases. The previous Pareto chart analysis indicates that the chopping block speed factor is significant with a p-value of less than 0.05 [7]. According to Figure 5, the main effect plot for knife pressure distance shows that increasing the distance from low to high level significantly decreases the chopping time, while the main effect of knife pressure distance has a lower impact.

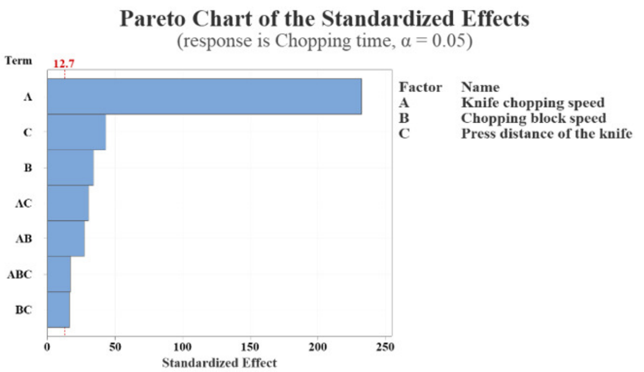

Fig. 4. Pareto chart of the standardized effects of each factor on chopping. time.

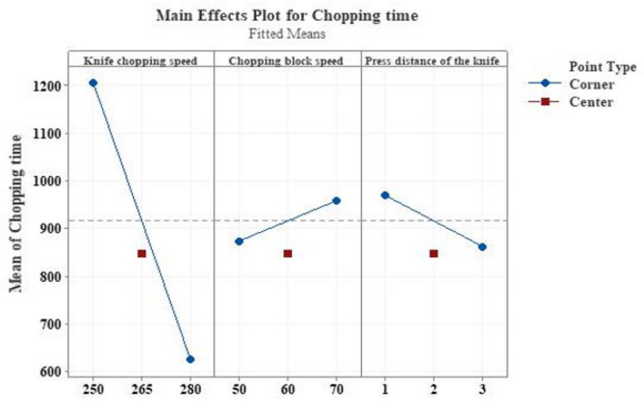

Fig. 5. Main effects plots of the fitted mean chopping time.

B. *Response Surface Analysis and Contour Plots of Chopping Time*

The 3D response surface and 2D contour plots offer a visual representation of the relationship and effects of different variables on the considered responses, allowing for a comprehensive evaluation of the data [10, 19-20]. In this study, the combined effects of three independent variables - (A) applied knife chopping speed, (B) chopping block speed, and (C) press distance of the knife - on chopping time were examined. Figure 6 shows that the contour plots that minimize chopping time are achieved at (A) higher knife chopping speed and (B) lower chopping block speed in the top left and right quadrants. Similarly, lower chopping times were achieved with (A) a knife chopping speed and (C) press distance of the knife around the top left and right, with values below 750 seconds. An analysis of the contour plot reveals that the optimal combination for minimizing chopping time is (B) a chopping block speed above 55 rpm and (C) a press distance of the knife above 1.2 mm, resulting in values below 750 seconds.

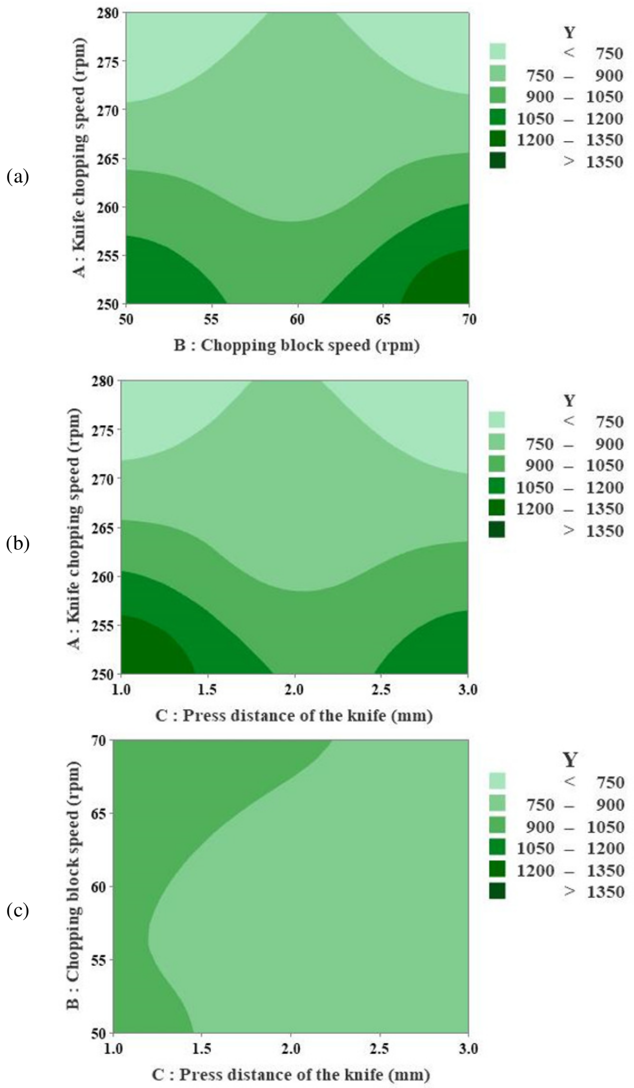

Fig. 6. 2D contour plots showing the effects of (a) A and B, (b) A and C, and (c) B and C on chopping time.

Figure 7 depicts the response surface plots, which exhibit the impact of factors A and B on chopping time when factor C is maintained at a value of 3 mm. It was observed that the chopping time was minimized, and an increase in chopping time was noted at (A) low knife chopping speed and (B) high chopping block speed. Therefore, the interaction between factors A and B had an impact on the chopping time. Additionally, the impact of factors A and C on chopping time when factor B is maintained at a constant value of 50 rpm, is presented. The chopping time exhibited a decreasing trend with increasing values of A and C, reaching a minimum value. When compared to the trend of chopping time, the trends with constant value B demonstrated similar patterns but with higher magnitudes. While factor A was held at 280 rpm, the effects of factors B and C were examined. It can be observed that a decrease in factor B and an increase in factor C had a significant impact on minimizing the responses.

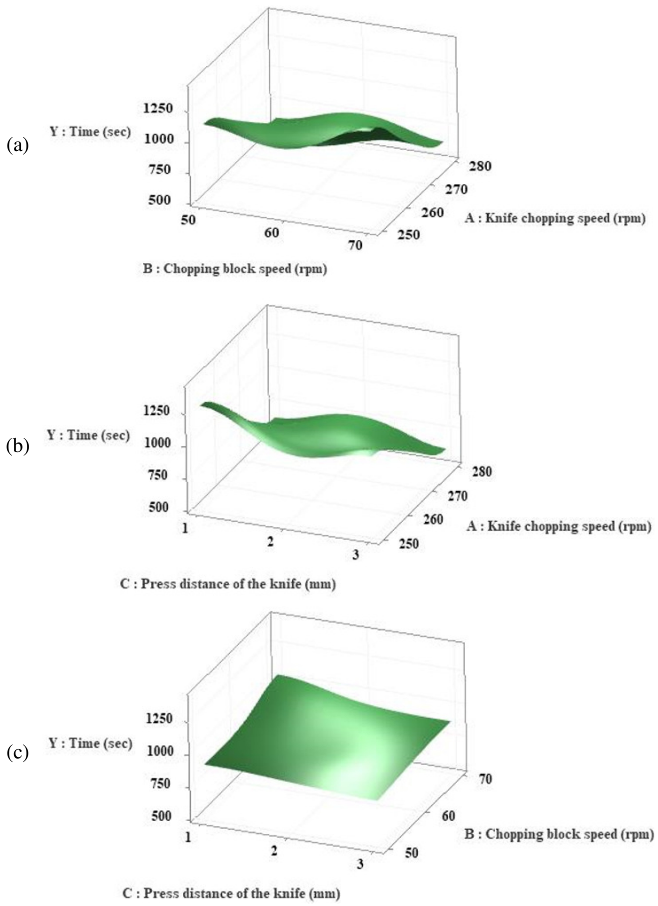

Fig. 7. 3D surface plots showing the effects of (a) A and B, (b) A and C, and (c) B and C on chopping time.

C. *Response Optimizer Plots analysis of Chopping Time*

The optimization plot can be a valuable tool for optimizing responses in product or process development, demonstrating how different operating conditions and experimental settings can be used to predict responses for factorial designs [11]. Figure 8 presents the optimization of the responses for chopping time. The graph illustrates the variables within the three columns, designated as A, B, and C factors. The columns represent the range of response variables as each factor is varied. The current variable settings, indicated at the top of each column, are represented by red numbers. Moreover, the numerical values and horizontal blue lines represent the current factor levels, while the vertical red lines demonstrate the current factor settings. The three points in each column represent the effect of the independent variables. The desirability function is a measure that ranges from low to high on a scale from zero to one. As presented in Figure 8, the predicted conditions of the independent variables for achieving the lowest chopping time are 280 rpm, 50 rpm, and 3 mm, resulting in a composite desirability function of 1.000. This indicates that lower values are preferable, as previously discussed in [21]. It is predicted that the optimal chopping time of 602.0 seconds will be achieved when the lower factor setting is applied to variable B.

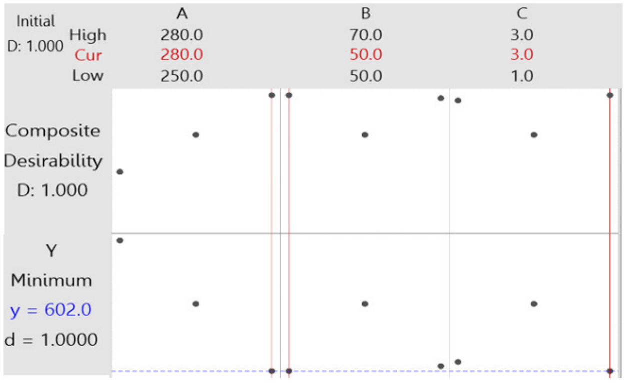

Fig. 8. Response optimizer plots for chopping time.

IV. CONCLUSION

The objective of this study was to examine the impact of specific parameters on the design and development of a fermented fish chopper machine process, utilizing the Design of Experiments (DOE) methodology. The optimization of the process parameters with three independent variables was identified and analyzed using a full factorial design. A statistical analysis was conducted to predict the optimal combination of chopping time, as summarized in the following section:

- The analysis of variance results indicated that the three parameters, namely (A) knife chopping speed, (B) chopping block speed, and (C) press distance of the knife, significantly affected chopping time.
- The results of the response surface analysis indicated that the optimal combination of factors minimizes chopping time. Specifically, the analysis demonstrated that increasing factors A and C, and decreasing factor B, minimize chopping time.
- The optimized values for the machine's chopping time settings are: knife chopping speed at 280 rpm, chopping block speed at 50 rpm, and press distance of the knife at 3 mm, resulting in a predicted chopping time of 602.0 seconds.

- The fermented fish chopper is manufactured with the objective of providing a cost-effective alternative to similar products, such as those used for chopping fresh fish, meat, and pork of various sizes, and to support community enterprises. Nevertheless, it is possible that certain parameters may require modification in accordance with the particular operational requirements.

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