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Evaluation of Cassava Chip Crispness Using a Fuzzy Logic System Based on Temperature and Vacuum Pressure Variables

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ABSTRACT

The study evaluates cassava chip crispness using a fuzzy logic system based on temperature and vacuum pressure variables. Fuzzy logic system is applied to objectively assess crispness, modeling the relationship between frying variables and chip texture. The application of fuzzy systems as a quality control tool can help optimize the production process so that chips meet standards. This study employs a literature review combined with an expert-based approach to design a fuzzy logic system for evaluating the crispiness of cassava chips based on temperature and pressure variables. For input and output variables, we use temperature and vacuum pressure. The temperature range used is 140-200°C and for pressure variable, we use -65, -68, -72 CmHg. Sensory values for the three crispness categories show that the undercooked category received an average score of 3.76 ± 0.52, the crisp (optimal) category received 3.72 ± 0.88, and the overcooked category received 3.85 ± 0.11. Combination of temperature 170°C and vacuum pressure -68.5 CmHg yields the best crispness result, showing that the chips reach the desired texture, not too hard and not too soft. This demonstrates that the centroid method provides a representative defuzzified value that closely reflects actual frying conditions, ensuring consistent product quality.

Keywords: cassava chips, crispness evaluation, fuzzy logic, food production

INTRODUCTION

The snack food industry is one of the fastest-growing sectors with high consumer acceptance, particularly in Indonesia. Cassava, an easily cultivated and widely available agricultural commodity, serves as the main raw material for snack food production (Hanafi & Siregar, 2025). The ease of distribution and marketing has supported the expansion of cassava chip production across various scales like large, medium, and home-based enterprises throughout Indonesia. Product quality is a key factor that differentiates cassava chips in the market (Sari & Murdani, 2024).

Vacuum frying is a frying process that can preserve nutritional value (Asmara et al., 2024). Compared to conventional frying, vacuum frying produces chips with superior crispness, color, aroma, and taste. Under vacuum conditions, the frying temperature decreases to 70–85°C due to the lower boiling point of oil, minimizing damage to color, aroma, taste, nutritional content, and crispness caused by high heat. Moreover, oil degradation and other adverse effects are reduced, maintaining the optimal texture of the chips (Tumbel & Manurung, 2017). Controlling frying temperature and time is crucial to ensure consistent product quality (Wahyuni et al., 2024).

However, many small and medium-scale cassava chip producers still lack standardized operating procedures (SOPs), particularly for the frying process. SOP implementation is essential for maintaining quality consistency, facilitating worker training, and enhancing consumer trust (Maulana et al., 2025). Without SOPs, the frying process relies on subjective visual assessments, such as color and texture changes,resulting in inconsistent product quality and reduced consumer acceptance. Inconsistent temperature and time control also pose significant challenges, as uncontrolled variations can lead to unevenly cooked chips, reduced crispiness, or excessive oil absorption, which ultimately affect company profitability (Damayanti et al., 2025). Furthermore, Evaluating crispiness is difficult since it depends on subjective human judgment, meaning the assessment results are determined by the individual conducting the evaluation (Agusman, 2013). Therefore, a decision support system is needed to evaluate chip crispiness objectively, adaptively, and flexibly. One potential solution is the application of Matlab-based software technology, which enables systematic and accurate measurement of crispiness levels.

In modern food processing, fuzzy logic has emerged as a technological approach capable of handling the uncertainty and vague values often encountered in the production process, such as "sufficiently ripe," "a bit long," or "high temperature," which are difficult to define quantitatively (Afi et al., 2022). The fuzzy logic system enables the modeling of relationships between the main input variables, namely temperature and air pressure, and the crispiness of cassava chips. By utilizing operator experience and empirical data as a knowledge base, this system is capable of performing automatic evaluations and providing more accurate results compared to subjective manual assessments (Putri et al., 2024). This approach not only improves the reliability of the evaluation process but also opens up opportunities for the development of automatic control systems in production, thereby increasing the efficiency and consistency of cassava chip quality (Asriandi *et al.*, 2024). The application of fuzzy systems as a quality control tool can help optimize the production process so that chips meet standards, because this system is easy to design without exact mathematical models, uses simple rules, and is adjusted through trial and error so that it is able to respond dynamically to changes in production variables, maintaining product quality consistency (Mahardika and Sumantri, 2022).

In addition, the application of fuzzy logic in food processing also opens up opportunities for the development of smart food processing technology in the traditional food processing industry, which has so far been heavily dependent on manual assessment and control (Ridwan, 2024). The main focus of this study is the application of a fuzzy system to evaluate the crispiness of cassava chips with two main input variables, temperature and vacuum air pressure. The output generated consists of three main categories of crispiness levels: not crispy enough, crispy, and too crispy. Thus, this system provides a quantitative overview that can be used as a basis for decision-making in the cassava chip processing process to achieve the desired quality target accurately and in a standardized manner.

METHODS

Research Approach

This study employed a qualitative descriptive methodology supported by a Systematic Literature Review (SLR) to ensure the validity of the fuzzy logic methodology for evaluating cassava chip crispiness during vacuum frying. The SLR followed a predefined protocol as outlined by Kitchenham et al. (2009), including formulating research questions, developing inclusion and exclusion criteria, conducting a systematic search in Scopus, ScienceDirect, and Google Scholar, selecting relevant studies, and extracting and synthesizing data. Inclusion criteria included peer-reviewed journal articles published between 2015 and 2025, preferably relevant to fuzzy logic, food texture evaluation, cassava chip frying processes, and crispness analysis. Studies lacking methodological rigor, incomplete crispness data, or irrelevant to frying parameters (temperature/pressure) were excluded.

The SLR approach ensured that the evidence gathered came from high-quality scientific sources. This approach was further strengthened by expert-based interpretation to assess the relevance and feasibility of applying fuzzy logic, a technique for modeling uncertain or subjective phenomena such as sensory texture. The integration of expert reviews and the literature ensures a comprehensive and evidence-based understanding of fuzzy models, particularly regarding how variables such as temperature and pressure interact (Pavani *et al.*, 2023).

The reference data for crispness scores was obtained from expert research published by Saputra (2022) and Acevedo-Correa *et al*. (2021). In Saputra (2022), three food engineering experts and two vacuum-frying practitioners assessed the effects of frying temperature and pressure on thick cassava chips. Meanwhile, in Acevedo-Correa *et al*. (2021), the crispness of cassava subjected to various frying treatments was evaluated by five food science experts and eight trained sensory panelists specializing in texture analysis and cassava processing. This experimental data provided a high-fidelity anchor point for defining the output membership function. Specifically, the average crispness values associated with undercooked, optimal, and overcooked conditions served as the basis for categorizing the fuzzy output into the sets "low," "medium," and "high."

A fuzzy inference system (FIS) was constructed with two input variables (temperature and vacuum pressure) and one output variable (crispness). Each variable is characterized by three linguistic terms, such as low, medium, and high. These membership functions are triangular or trapezoidal.

The membership function maps explicit input values to degrees of truth (0 to 1). According to Wardhani & Haerani (2011), membership functions are used to determine how accurately a data point belongs to a fuzzy set and to represent uncertainty in qualitative assessments. To construct these functions, the variable domain is defined and a threshold value for each linguistic term is determined. The membership values are then calculated using the Fuzzy Logic Toolbox in MATLAB R2025b.

Temperature (°C)
- Low: trapezoid (1, 140, 159)
- Medium: triangle (160, 170, 179)
- High: trapezoid (180, 200, 200)

Vacuum Pressure (cmHg)
- Low: trapezoid (-72, -72, -71, -69)
- Medium: triangle (-70, -68.5, -67)
- High: trapezoid (-68, -66, -65, -65)

Crispness (Sensory Scale)
- Low: triangle (3.15, 3.67, 4.19)
- Medium: triangle (2.84, 3.72, 4.60)
- Height: triangle (3.72, 3.85, 3.96)

The fuzzy inference system was developed and tested using MATLAB R2025b. This version was chosen for its improved stability, comprehensive features for fuzzy modeling, and visual support for designing membership functions and simulating defuzzification results. All modeling activities were executed using the built-in Fuzzy Logic Designer GUI.

Furthermore, to obtain sharp output values, three standard defuzzification techniques were applied: centroid, bisector, and maximum mean. Centroid calculates the center of gravity of the fuzzy output set and offers a balanced estimate, making it the most commonly used method. Bisector identifies the vertical line that divides the output membership area in half. Meanwhile, maximum mean averages all values where the output membership peaks. These methods were compared to assess their impact on the final sharpness prediction. Therefore, centroid was ultimately selected for the final results due to its continuous and stable behavior.

The fuzzy model predictions were then quantitatively validated against laboratory acuity scores from the research by Acevedo-Correa *et al.* (2021). The acuity scores predicted by the fuzzy system were compared with empirical values using the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE):

- $MAE = (1/N)\sum|\hat{y} - y|$
- $RMSE = \sqrt{[(1/N)\sum(\hat{y} - y)^2]}$

These metrics measure the system's deviation from expert-evaluated acuity scores. A low error value indicates good predictive ability and strong agreement between the fuzzy model output and direct observations. This step was taken to ensure methodological transparency and support model replication in future research.

Data Collection

This study uses a literature review combined with an expert-based approach to design a fuzzy logic system to evaluate the crispiness level of cassava chips based on temperature and pressure variables. This study is descriptive and qualitative, targeting data and insights from scientific literature and food technology experts. Data were collected from journals, books, and previous studies that discuss the relationship between temperature, air pressure, and the crispiness level of cassava chips, as well as through expert consultation to determine fuzzy sets and input variables. The Mamdani method was applied, which involves four main steps: fuzzy set formation, application of implication functions, rule composition, and defuzzification to produce numerical outputs representing the crispiness level (Kusumadewi and Hari, 2004).

Data Analysis

Data were analyzed descriptively and qualitatively by comparing the results of the fuzzy system design with existing theory and previous research. The analysis began with a literature review to identify key themes such as the relationship between temperature, frying time, and crispiness, as well as commonly used fuzzy inference methods. These findings were then validated through expert interviews to identify similarities and differences that strengthened the system design.

Fuzzy logic offers a flexible approach to decision-making under uncertain conditions. Fuzzy logic can analyze ambiguous or subjective data, enabling adaptive and dynamic evaluation and prediction of factors such as demand and stock availability (Yudha and Putra, 2024). Its application in the frying process improves efficiency and product quality consistency by effectively handling temperature and processing time uncertainty. Furthermore, fuzzy logic is recognized as a reliable control method for automation in food processing, particularly frying (Osofisan *et al*., 2007). Therefore, this qualitative descriptive analysis not only describes the results of the fuzzy system design but also evaluates its effectiveness and potential implementation in cassava chip processing.

RESULTS AND DISCUSSION

Literature Study Data

The literature study was conducted to inform decisions on optimizing the temperature and vacuum pressure in the cassava chip frying process, taking into account the crispness level parameter in the final product. The crispness level parameter in the final product will affect the quality and shelf life of the product, so control is needed to maintain quality consistency and meet consumer demands. In order to determine the optimal temperature and vacuum pressure to produce a high-quality product, it is necessary to ensure consistent use of temperature and vacuum pressure. This can be done by applying fuzzy logic, which can strengthen the validity of the approach to optimizing temperature and vacuum pressure for the crispiness parameter of the final cassava chip product.

Table 1 Data collection from literature studies

Treatment	Factor			Sample	Parameter Crispness
	T (°C)	T (s)	Vacuum Pressure (cmHg)		
1	140	180	-65	Cassava slice	3.67 ± 0.52 a
2	160	180	-68	Cassava slice	3.72 ± 0.88 a
3	180	180	-72	Cassava slice	3.85 ± 0.11 b

Source: Acevedo-Correa *et al.* 2021; Saputra 2022

The data in Table 1 is a collection of data from literature studies used as the basis for input and output variables. The data used for the analysis of chip crispness and the factors that influence it includes inputs such as frying temperature and vacuum pressure, while the output shown is the crispness level parameter. The crispness level criteria taken from the study (Correa *et al*., 2021) used control treatments with the lowest to highest crispness levels in sequence, with values of 3.67 ± 0.52, 3.72 ± 0.88, and 3.85 ± 0.11.

Input Analysis

Table 2 Variable input

Function	Variable	Fuzzy Set	Universe Set	Domain
Input	Temperature	Low	140–200	140–160°C
		Medium		140–160–180°C
		High		180–200°C
	Pressure	Low	-72–(-65)	-72
		Medium		-68
		High		-65

Input variables are factors that influence output variables. Input data includes temperature and pressure, which are control parameters of vacuum frying. These two input variables are grouped into three different fuzzy sets, namely low, medium, and high. The division of input variable sets serves to facilitate the fuzzy system in assessing conditions. In addition, this division of sets is applied to handle uncertainties that arise due to limitations in the design and technical analysis processes (Gusti *et al.*, 2025).

Output Analysis

Table 3 Variable output

Function	Variable	Fuzzy Set	Domain
Output	Crispness	Less crips	3,15 3,67 4,19
		Crispy	2,84 3,72 4,6
		Very crispy	3,74 3,85 3,96

Variable output is a variable that is influenced by input variables and shows the results and effects of these changes (Gusti *et al.*, 2025). In other words, output variables are results or outputs that show the effect of input variables on the desired end result. The variable output used is crispiness with three fuzzy set categories, namely less crispy, crispy, and very crispy.

Based Rules

Table 4 Based rules

No	Input		Output
	T (°C)	Pressure (cmHg)	Crispness
1	Low	Low	Less crisp
2	Low	Medium	Less crisp
3	Low	High	Less crisp
4	Medium	Low	Less crisp
5	Medium (170)	Medium (-68)	Crispy
6	Medium	High	Very crisp

7	High	Low	Less crisp
8	High	Medium	Very crispy
9	High	High	Very crispy

Based rules are a collection of forecasting rules based on fuzzy logic to express the conditions that occur (Siwoyo et al., 2018). Rules in fuzzy logic are connectors for inputs and outputs in making decisions based on the combinations that occur between inputs. In Table 4, fuzzy logic rules use "if-then" in placing inputs and outputs.

Temperature Input

The application of fuzzy logic to temperature and pressure inputs in a system for evaluating the crispness of fried cassava chips produced using vacuum frying is important in determining the output that will be produced. Both inputs play a role in influencing the crispness of the product and the water content in the material or solid during the vacuum frying process (Jamaluddin *et al.*, 2011). The temperature range used is 140-200°C, and the temperature membership function is illustrated using a triangular function consisting of three parameters, namely minimum, middle, and maximum values, which describe gradual changes in temperature from the smallest to the largest. This enables the evaluation process with fuzzy logic because it can describe the transition between temperatures.

$$\mu_{rendah}(x) = \begin{cases} 1, & x \leq 140 \\ \frac{160-x}{160-140}, & 140 < x < 160 \\ 0, & x \geq 160 \end{cases}$$

$$\mu_{sedang}(x) = \begin{cases} 0, & x \leq 140 \text{ atau } x \geq 180 \\ \frac{x-140}{160-140}, & 140 < x \leq 160 \\ \frac{180-x}{180-160}, & 160 < x < 180 \end{cases}$$

$$\mu_{tinggi}(x) = \begin{cases} 0, & x \leq 180 \\ \dfrac{x-180}{200-180}, & 180 < x < 200 \\ 1, & x \geq 200 \end{cases}$$

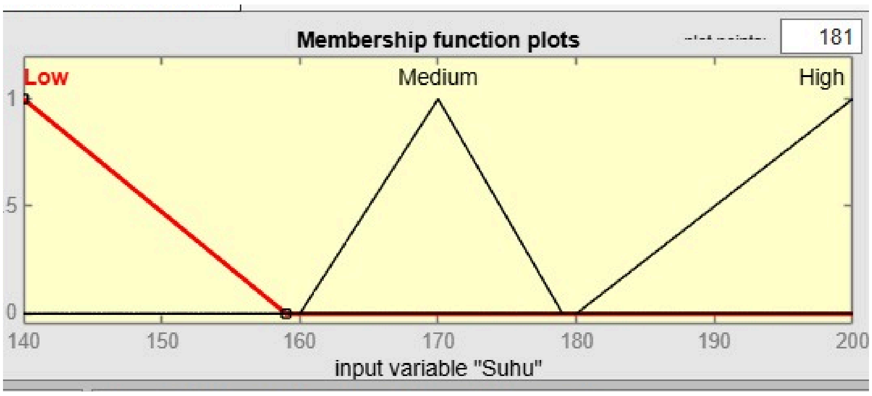

Figure 1.1 Membership function of temperature input variable

Pressure Input

The application of fuzzy logic to pressure input also plays an important role in evaluating the crispness of cassava chips produced by vacuum frying. Pressure affects the boiling point of oil and the rate of water evaporation from the material. The lower the pressure, the faster the water evaporation, thereby reducing the water content of the product and increasing its crispness. Therefore, pressure is an important parameter in determining the final quality of the product produced during the frying process (Sergovia *et al*. 2016). In its description, the pressure variable input is depicted with a trapezoidal membership function, which is commonly used to represent stable and tolerant conditions in small variations.

$$\mu_{rendah}(P) = \begin{cases} 1, & P \leq -72 \\ \frac{-68-P}{-68-(-72)}, & -72 < P < -68 \\ 0, & P \geq -68 \end{cases}$$

$$\mu_{sedang}(P) = \begin{cases} 0, & P \leq -72 \text{ atau } P \geq -65 \\ \frac{P-(-72)}{-68-(-72)}, & -72 < P \leq -68 \\ \frac{-65-P}{-65-(-68)}, & -68 < P < -65 \end{cases}$$

$$\mu_{tinggi}(P) = \begin{cases} 0, & P \leq -68 \\ \frac{P-(-68)}{-65-(-68)}, & -68 < P < -65 \\ 1, & P \geq -65 \end{cases}$$

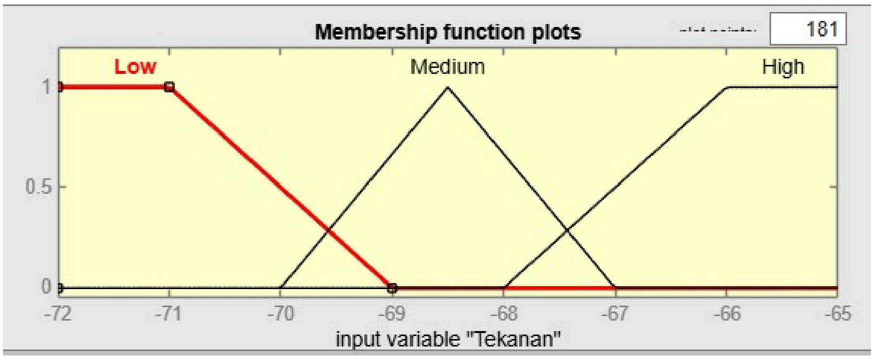

Figure 1.2 Membership function of pressure input variable

Output

Sensory values for the three crispness categories show that the undercooked category received an average score of 3.76 ± 0.52, the crisp (optimal) category received 3.72 ± 0.88, and the overcooked category received 3.85 ± 0.11. Although the average scores were not significantly different, the standard deviation values showed considerable variation in perception in the “crisp” category. Crispness is an important sensory attribute that affects consumers' level of preference for cassava chips.

The “less crispy” (undercooked) category, with a score of 3.76 ± 0.52, indicates that the frying process has not yet been fully completed. This condition may be caused by an excessively short frying time or suboptimal vacuum pressure during the vacuum frying process, resulting in a high moisture content and a less crispy texture. High moisture content can reduce the perception of crispiness because the solid structure becomes more elastic and less capable of producing the characteristic cracking sound when chewed (Tunick *et al.* 2013). Therefore, during the vacuum frying process, water evaporation must be carefully controlled to ensure sufficient moisture reduction for crispiness, while maintaining the structural stability of the chips to prevent them from breaking easily.

The crispy category, the texture of cassava chips has reached the ideal level of crispiness (sufficiently dry but not too brittle). This condition indicates that the combination of temperature and vacuum pressure has produced the right amount of water evaporation to form fine pores in the cassava tissue. During the frying process at 160°C-180°C, the microstructure of the material is preserved, resulting in a light, crispy, and non-hard texture. Additionally, vacuum frying reduces oil oxidation, so the product does not have an “oily” sensation that can reduce its sensory value (Chen et al., 2024).

The *over-crispy* (overcooked) category obtained a score of 3.85 ± 0.11, indicating chips that are nearly burnt and excessively dry. This condition may occur when the frying process lasts too long or when the vacuum temperature is set too high. An increase in temperature and frying duration accelerates moisture loss and leads to a harder texture due to the stiffening of starch and protein structures (Dangal *et al.* 2024). Although vacuum frying generally minimizes thermal damage compared to conventional frying, an excessively long process can still result in overly dry and slightly burnt textures.

Overall, the findings indicate that the adjustment of vacuum frying parameters particularly temperature, pressure, and frying time plays a crucial role in determining the level of crispness preferred by consumers. A process that is too short results in an under-dried texture, whereas an excessively long frying time leads to hardness and the loss of cassava’s natural flavor. According to (Hidayati et al., 2021), controlling the frying process is a key factor in producing crispy products with a balanced oil and moisture content. Therefore, the optimal crispy condition serves as the ideal point to maintain a balance between crispness, flavor, and overall sensory quality in vacuum-fried cassava chips.

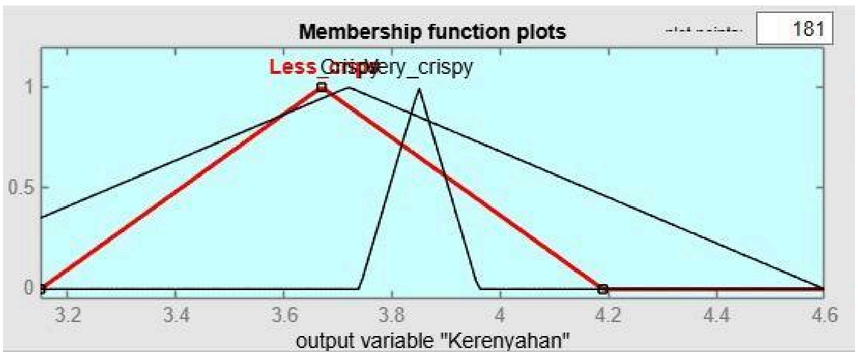

Figure 1.3 Membership function of crispiness output variable

This is an image that shows the crispiness output variable with a range 3.2 to 4.5 onto three parameters. The parameters are Less crispy, crispy, and very crispy.

Defuzzyfication

Commonly used defuzzification methods include centroid, bisector, and mean of maxima. In cassava chip production, the centroid method is often chosen because it provides more representative results for the fuzzy values generated from the temperature and vacuum pressure variables. For example, when considering the level of crispiness based on temperature and pressure data during the frying process, the fuzzy system can analyze the relationship between these variables to determine the optimal frying conditions. The analysis results are then defuzzified using the centroid method to obtain crisp values that describe the best crispness level. Thus, producers can adjust process parameters more accurately to produce crispy and consistent cassava chips according to consumer preferences (Gilda & Satarkar, 2020; Gusti *et al*., 2025).

Defuzzification is the last step of a fuzzy system that converts a fuzzy output set to a crisp value (Gilda & Satarkar, 2020) and back to its BCR (best classification result) (Hofmann, 2016). Defuzzification is characterized as the method of changing over the fluffy yields to fresh yields as an impact of the numeric fresh inputs values. A fresh numerical esteem relates to the bolster of the single fluffy yield set (Bobyr *et al.*, 2017)**.**

The final step is the calculation process, known as defuzzification, which serves as the validation that the proceeding calculation aligns closely with the anticipated outcomes. Subsequently, these manual calculations will be verified using the Matlab application to ensure their accuracy and appropriateness.

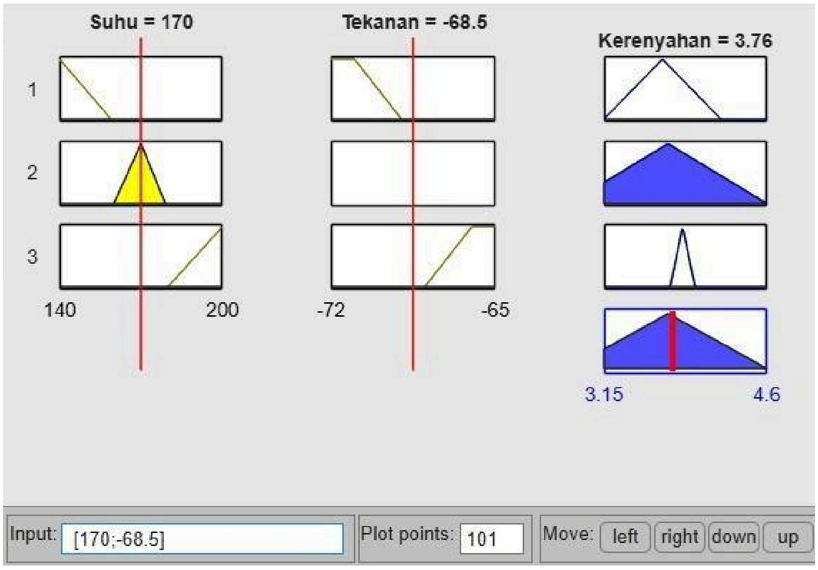

Figure 1.4 Defuzzyfication of rules result

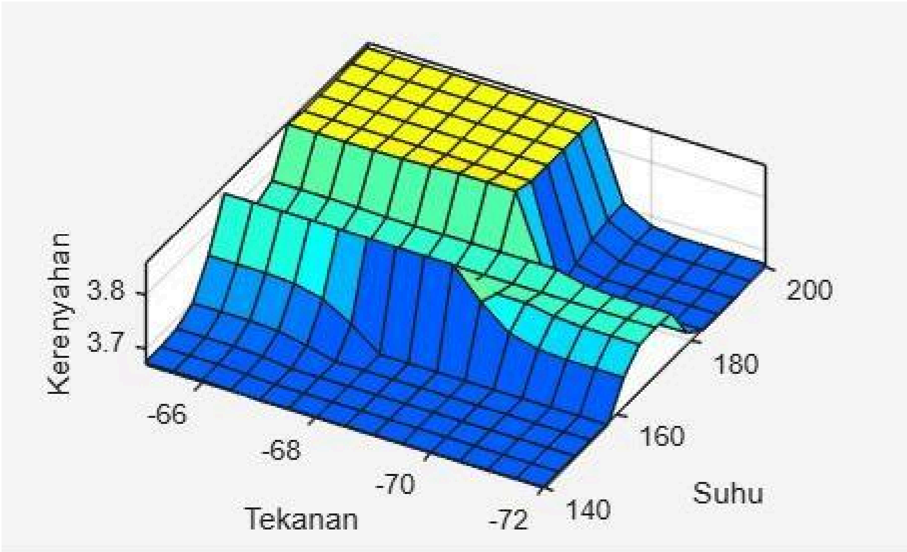

Figure 1.5 Surface of Defuzzyfication of rules result

After using the matlab application. This value is obtained from the centroid calculation, which considers the area balance of the membership functions for each variable. The input combination of temperature 170°C and vacuum pressure -68.5 cmHg yields the best crispness result, showing that the chips reach the desired texture, not too hard and not too soft. This demonstrates that the centroid method provides a representative defuzzified value that closely reflects actual frying conditions, ensuring consistent product quality. achieve a high moisture content, produce maximum results so that the chips are not too crispy or undercooked.

CONCLUSION

This study demonstrates that optimizing the vacuum frying process parameters, specifically temperature and vacuum pressure is crucial in producing cassava chips with the desired level of crispness. The application of fuzzy logic provides a systematic and reliable approach to handling the uncertainties associated with these parameters, allowing for consistent product quality. Based on the defuzzification results using the centroid method, the optimal vacuum frying conditions were identified at a temperature of 170°C and a vacuum pressure of –68.5 cmHg, which produced chips with an ideal crispness level, neither too hard nor too soft.

These findings confirm that fuzzy logic can effectively model the complex relationship between temperature, pressure, and crispness, offering a practical tool for process optimization in cassava chip production. By maintaining these optimal conditions, producers can ensure consistent texture, flavor balance, and overall sensory quality that meet consumer preferences while extending the product’s shelf life.

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