**Journal of Applied Science, Technology & Humanities**
Volume 2, Issue 1, January, 2025, Pages 119-135

**ISSN 3032-5765**
**DOI : https://doi.org/10.62535/2mzdar32**

# Implementation of Fuzzy Logic in Temperature and Fermentation Time Control System on Alcohol Content of Cassava Tape Product

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**Abstract**

The fermentation process of cassava tape involves complex biochemical reactions and requires careful attention to various factors. Temperature and fermentation time are crucial parameters that significantly affect the final quality of cassava tape. Along with the development of artificial intelligence (AI), the fermentation process can be controlled and monitored more precisely, thereby increasing the efficiency and consistency of the final product. This study aims to determine the Mamdani fuzzy logic approach in the temperature control system and fermentation duration in the cassava tape production process to optimally regulate the alcohol content of cassava tape. The research method is a literature study, testing Mamdani fuzzy logic using Matlab software, and analyzing input variables manually. The results of the study showed that the optimal temperature for cassava tape fermentation was between 25°C - 30°C and the optimal time for cassava tape fermentation was with a "long" duration. From the defuzzification results, the final results showed an alcohol content of 15.9% at a temperature of 29°C and a fermentation time of 80 hours so that the alcohol content of cassava tape was in accordance with the specifications.

**Keywords:** cassava, fermentation, fuzzy logic, temperature

## INTRODUCTION

In the modern era, humans increasingly rely on technology to optimize various processes across different sectors, including food production and manufacturing. Technological advancements have enabled more precise control, monitoring, and automation of industrial processes, leading to improved efficiency, consistency, and product quality (Kasnawati *et al.*, 2024) The integration of smart systems and sensors has revolutionized how we approach process control and optimization. These technological solutions have become essential in maintaining product quality while reducing human error and operational costs. The demand for automated systems continues to grow as industries seek more efficient and reliable production methods (Saputra, 2023).

Indonesia, as one of the largest agricultural countries in Southeast Asia, has abundant natural resources, particularly in agricultural products (Radhiana *et al.*, 2023). The country's diverse agricultural sector plays a crucial role in its economy, providing employment and sustaining food security for its large population. Cassava, locally known as singkong, is one of the major agricultural commodities in Indonesia, with annual production reaching millions of tons (Yudha *et al.*, 2023). The cultivation of cassava is widespread across various regions in Indonesia, from Java to Sumatra and beyond. This abundant availability of cassava has led to the development of numerous traditional food products, including fermented foods that are deeply rooted in Indonesian culture, especially cassava tape (Purnamasari *et al.,* 2024).

The fermentation process of cassava tape involves complex biochemical reactions where microorganisms convert carbohydrates into simpler compounds, producing alcohol as one of its byproducts (Susilawati *et al.*, 2024). Traditional fermentation methods have been practiced for centuries, utilizing natural microorganisms and environmental conditions. The process requires careful attention to various factors, including cleanliness, raw material quality, and environmental conditions (Setiarto, 2020). While these traditional methods have sustained production for generations, they often lack precision and scientific control. The variability in environmental conditions and processing methods frequently results in inconsistent product quality and unpredictable fermentation outcomes (Yuwono *et al*., 2022).

Research by Susilawati *et al.,* (2024) mentioned that temperature and fermentation time are crucial parameters that significantly influence the final quality of cassava tape, particularly its alcohol content. The temperature directly affects the growth rate and metabolism of the microorganisms responsible for fermentation. Maintaining optimal temperature ranges is essential for ensuring proper fermentation progression and preventing unwanted microbial growth. The duration of fermentation must be carefully monitored as it determines the extent of substrate conversion and final product characteristics. Variations in these parameters can lead to significant differences in product quality, taste, and alcohol content, making their control essential for consistent production.

As artificial intelligence (AI) continues to revolutionize various industries (Javaid *et al.,* 2022), its application in food processing and fermentation control systems presents promising opportunities. AI-based systems can analyze multiple process variables simultaneously and make real-time adjustments to maintain optimal conditions (Karim *et al.,* 2023). The implementation of AI in fermentation processes allows for more precise control and monitoring than traditional manual methods. These systems can learn from historical data and adapt to changing conditions, improving process efficiency over time (Augustin *et al.,* 2024). The integration of AI technology also enables predictive maintenance and quality control, reducing production losses and ensuring consistent product quality.

According to Garcia *et al.,* (2018) Fuzzy logic as a branch of artificial intelligence (AI), offers a practical approach to handling the inherent uncertainties and complexities in fermentation processes. This mathematical framework can effectively process imprecise input data and implement human-like reasoning in decision-making processes. Unlike conventional control systems that operate on binary logic, fuzzy logic can handle partial truths and gradual transitions between states. The flexibility of fuzzy logic makes it particularly suitable for controlling biological processes where exact mathematical models may be difficult to establish. This approach allows for more nuanced control decisions based on multiple input parameters and their complex interactions.

The implementation of fuzzy logic in controlling temperature and fermentation time for cassava tape production represents a significant advancement in traditional food processing. This intelligent control system can continuously monitor and adjust critical parameters based on predefined rules and real-time conditions. The system's ability to handle multiple inputs and make sophisticated decisions helps maintain optimal fermentation conditions throughout the process. The integration of fuzzy logic control provides a more reliable and consistent approach to achieving desired alcohol content levels in the final product. This technological solution not only improves product quality but also increases production efficiency and reduces the dependence on operator expertise. The adaptability of the fuzzy logic system makes it suitable for various production scales and environmental conditions.

## METHODS

The method used in this research is a literature study or literature review. Literature study is a process of searching and researching literature by reading and reviewing various journals, books, and other published manuscripts related to research topics in order to compile articles on certain topics or issues (Pratiwi *et al*., 2020).

This research includes methods of processing research data objectively, systematically, analytically and critically for the purposes of collecting literature data, reading and recording, and monitoring using fuzzy techniques in testing alcohol content in cassava tapai using alcohol refractor. Fuzzy logic is a system of reasoning that handles gradual transitions between states. Instead of rigid categories, it operates with a spectrum of possibilities, where variables can take on values between 0 and 1, representing varying degrees of truth or falsehood (Wawan *et al.*, 2021)

The fuzzy method used in this research is the mamdani method. This method has advantages, namely being more intuitive, accepted by many parties, can be applied to the field of statistics, is flexible, produces outputs that are closer to the actual situation, and has tolerance for data that has a more efficient approach using numbers than other methods. The mamdani method is often used in cases because it has a simple structure, which uses min-max or max-product operations (Muntahanah *et al.*, 2021). Mamdani fuzzy method which is implemented with an application system designed using Matlab software (Surbakti *et al.,* 2020).

The initial step in compiling a fuzzy system is to identify the variables needed for problem analysis and calculation of the final results. The variables used consist of input and output variables. Each variable, both input and output, will have several fuzzy sets. This fuzzy set is in a certain range of values that will determine the mathematical equation to produce output in the form of fuzzy membership values (Rifanti *et al*., 2023). The input variables used in this study are 2 (two) elements contained in the assessment component, consisting of time and temperature, while the output variable used is alcohol content.

After the process of determining the input and output variables, the next step is to determine the rules used as a reference for determining the assessment output. In the fuzzy system defined, there are several rules that connect temperature and time with alcohol content. The linguistic value uses colloquial language as its value such as high, moderate, and low (Wawan *et al.,* 2021). The first rule states that if the temperature is low or the time is short, then the alcohol content will be low. Furthermore, if the temperature is low or the time is medium, then alcohol content remains low. Similarly, if the temperature is low or the time is long, then alcohol content will also be low. When the temperature is moderate or the time is short, then the alcohol level is still low. However, if the temperature is moderate or the time is medium, then the alcohol level will be at a moderate level. If the temperature is moderate and the time is long, then the alcohol level increases to high. On the other hand, if the temperature is high or the time is short, then the alcohol level is low again. However, if the temperature is high or the time is medium, then the alcohol level is at a moderate level. Finally, if the temperature is high or the time is long, then the alcohol level will reach a high level.

Furthermore, the process of using the implication function depends on the fuzzy method applied. In this research, the method used is Mamdani, so the implication function applied is the minimum function. The input of the defuzzification process comes from the fuzzy set generated through the composition of several fuzzy rules (Darani *et al.,* 2019). The output of this affirmation process is a number obtained from a fuzzy set in a certain interval. Therefore, it is necessary to determine a firm (crisp) value as the final output (Rifanti *et al*., 2023).

## RESULTS AND DISCUSSION

As we know, fermentation is a process of chemical change that occurs in an organic substance. Involving microorganisms in the process such as the use of bacteria and enzymes (Meliana and Rizaldi, 2024). These microorganisms will produce enzymes that can change organic substances. According to Firdausi (2023), the fermentation process is a way of processing food ingredients with the aim of increasing the shelf life. Microorganisms that play a role in the food fermentation process can be yeast, bacteria and mold. Meanwhile, the microorganisms used in the tape making process are the genus Saccharomyces, namely a type of yeast which is usually called Saccharomyces cerevisiae. The tapai fermentation process will produce a sour taste which is given by the lactic acid content produced from the fermentation process.

During the fermentation process, temperature and time become one of the important factors in the tapai making process. If the temperature of the incubation room is too low it can inhibit the growth of yeast. Meanwhile, if the temperature in the incubation room is too high, it can stop the performance of the bacteria. This can result in failure during the fermentation process. Likewise with the influence of the fermentation time used. If the incubation time is short or too short, it will not produce a tapai product that is as expected. On the other hand, if the incubation time is long or too long, it will produce tapai products that are damaged and are not good for consumption. Based on literature studies that we use input and output variables as attached in the tables and calculations.

**Creating Fuzzy Sets**

The first stage in designing a fuzzy system is to determine the variables. In a fuzzy system there are two types of variables used, namely input and output. In the tapai fermentation case study, there are two input data used, namely temperature input during the fermentation process and input for the length of time the fermentation process lasts. In fuzzy logic, true and false statements cannot represent the results of every human thought (Nisa et al., 2020). Basically, a fuzzy variable is a variable value that is not clear or uncertain. In other words, it can be said to be partly right or partly wrong.

In its application using MATLAB (Matrix Laboratory), the temperature input variable has three assessment levels, namely low, medium and high. Where in one level of assessment there are four parameter values when using the trapmf type or trapezoidal graph. These four parameters are number points to explain the data from the input. The use of the mf code provides a sign of the existence of a membership function which can represent a fuzzy set with a value between 0 and 1.

Fuzzy sets themselves are a branch of understanding of mathematics that studies random numbers such as their probability, systematics, and information theory (Nisa et al., 2020). In a fuzzy set there is a membership function which functions as a provider of information by showing the mapping of points where the input data is placed into its membership value. By referring to the theory of fuzzy linguistic variables, it becomes more expressive with the use of natural language because it is felt to be easier to understand (Davvaz et al., 2021).

Just like the temperature input variable, the time input variable also uses three assessment levels, namely short, medium and long. However, there is a difference between the temperature input variable and the time input variable. The membership function used for the time input variable is the trimf type or triangular graph. The parameters used are only three points. Just like the trapezoidal membership function, the triangular membership function also has a value between 0 and 1. Meanwhile, the output result is the amount of alcohol produced. Using a trimf type membership function which has three assessment levels, namely low, medium and high.

As previously explained, one input variable and another input variable are closely related to each other. The length of fermentation time will have a significant influence on tapai fermented products (Kusuma et al., 2020). Where bacteria or fungi are used with an incubation period that is too long, it will damage the tapai product, such as the taste of the tapai becoming too sour with an alcohol content that is too high. Changes in the quality of tapai products can cause disease for the body's health.

Likewise, if the temperature in the incubation room is too high, it can trigger the growth of abnormal bacteria and fungi. This will result in tapai products that are unfit for consumption. The normal temperature that can be used for the fermentation process is around 25°C to 30°C (Gres, 2023). Therefore, the application was made based on this case example using the help of technology in order to prove whether the statement as previously mentioned was true. And can provide information about what temperature and time to achieve success in the fermentation process.

Table 1. Input and Output of Cassava Product

| Variables | Parameters | Parameters Values |
|---|---|---|
| Temperature (°C) | Low | [10 10 15 22] |
| | Moderate | [20 24 27 30] |
| | High | [28 35 40 40] |
| Time (hour) | Short | [0 24 48] |
| | Medium | [48 60 72] |
| | Long | [72 96 120] |
| Alcohol content (%) | Low | [0 5 10] |
| | Moderate | [10 15 20] |
| | High | [20 26 32] |

Based on the table above, the membership function of the temperature variable can be illustrated using a trapezoidal membership function type. The four parameter points are as clearly illustrated in Figure 1 below.

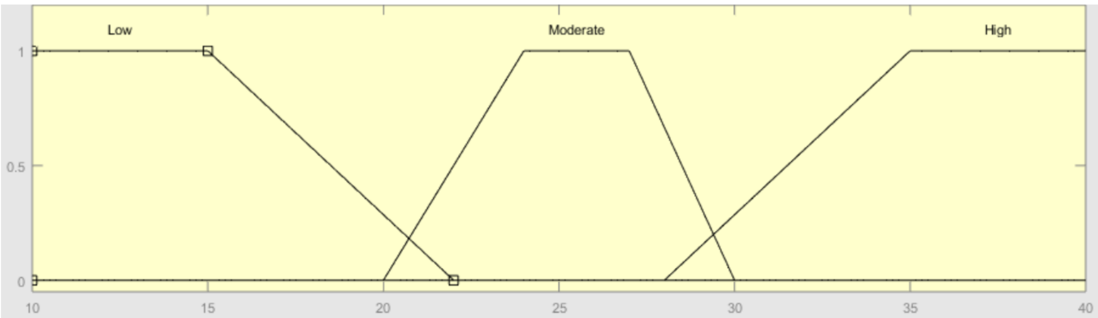

Figure 1. Temperatur Input Variable Membership Set Graph

From this image, membership function values are obtained through manual calculation results. Based on three levels of temperature assessment that can have an impact on the final result of the tapai product as follows:

$$
Temperature \left( {}^{\circ}C \right) \begin{cases} \mu low\ (x) = \begin{cases} 0, & x \le 10 \\ \frac{x-10}{10-10}, & 10 \le x \le 10 \\ 1, & 10 \le x \le 15 \\ \frac{22-x}{22-15}, & 15 \le x \le 22 \\ 0, & 22 \le x \end{cases} \\ \mu moderate\ (x) = \begin{cases} 0, & x \le 20 \\ \frac{x-20}{24-20}, & 20 \le x \le 24 \\ 1, & 24 \le x \le 27 \\ \frac{30-x}{30-27}, & 27 \le x \le 30 \\ 0, & 30 \le x \end{cases} \\ \mu high\ (x) = \begin{cases} 0, & x \le 28 \\ \frac{x-28}{35-28}, & 28 \le x \le 35 \\ 1, & 35 \le x \le 40 \\ \frac{40-x}{40-40}, & 40 \le x \le 40 \\ 0, & 40 \le x \end{cases} \end{cases}
$$

Figure 2. Parameter Input Value (Temperature [°C])

For time variables, the membership function can be illustrated using a triangular membership function type. The three parameter points are as clearly illustrated in Figure 3 below.

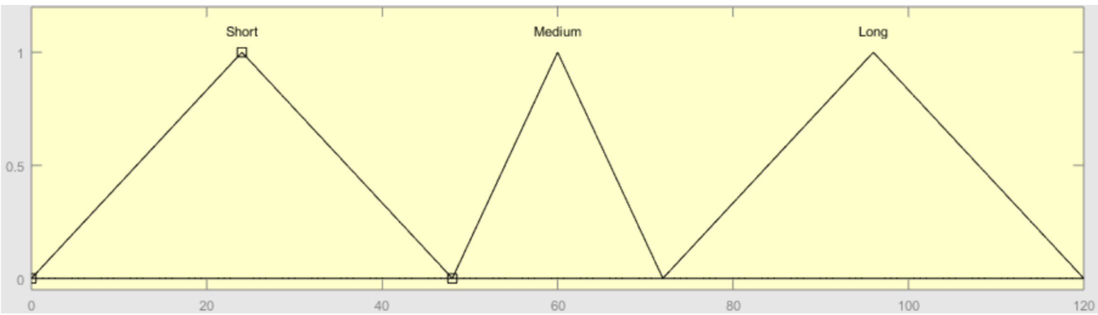


Figure 3. Time Input Variable Membership Set Graph

From this image, membership function values are obtained through manual calculation results. Based on the three levels of time assessment which are closely related to the final results of the tapai product as follows:

$$
Time \left( hour \right) \begin{cases} \mu short\ (x) = \begin{cases} 0, & x \le 0 \\ \frac{x-0}{24-0}, & 0 \le x \le 24 \\ \frac{48-x}{48-24}, & 24 \le x \le 48 \\ 0, & 48 \le x \end{cases} \\ \mu medium\ (x) = \begin{cases} 0, & x \le 48 \\ \frac{x-48}{60-48}, & 48 \le x \le 60 \\ \frac{72-x}{72-60}, & 60 \le x \le 72 \\ 0, & 72 \le x \end{cases} \\ \mu long\ (x) = \begin{cases} 0, & x \le 72 \\ \frac{x-72}{96-72}, & 72 \le x \le 96 \\ \frac{120-x}{120-96}, & 96 \le x \le 120 \\ 0, & 120 \le x \end{cases} \end{cases}
$$

Figure 4. Parameter Input Value (Time [hour])

The amount of alcohol produced during the tapai fermentation process comes from yeast and yeast. Yeast and yeast will both change the carbohydrate or starch content into glucose. After turning into glucose, the glucose will turn into alcohol (Islami, 2019). In the output variable, namely the amount of alcohol content, the membership function can be illustrated using a triangular membership function type. The three parameter points are as clearly illustrated in Figure 5 below.

Figure 5. Alcohol Content Output Variable Membership Set Graph

From this image, membership function values are obtained through manual calculation results. Based on the three levels of assessment of the amount of alcohol content produced in tapai products as follows:

$$
\textit{Alcohol content} \left( \% \right) \left\{
\begin{array}{l}
\mu low\,(x) = \begin{cases} 0, & x \le 0 \\ \frac{x-0}{5-0}, & 0 \le x \le 5 \\ \frac{10-x}{10-5}, & 5 \le x \le 10 \\ 0, & 10 \le x \end{cases} \\
\mu moderate\,(x) = \begin{cases} 0, & x \le 10 \\ \frac{x-10}{15-10}, & 10 \le x \le 15 \\ \frac{20-x}{20-15}, & 15 \le x \le 20 \\ 0, & 20 \le x \end{cases} \\
\mu high\,(x) = \begin{cases} 0, & x \le 20 \\ \frac{x-20}{26-20}, & 20 \le x \le 26 \\ \frac{32-x}{32-26}, & 26 \le x \le 32 \\ 0, & 32 \le x \end{cases}
\end{array}
\right.
$$

Figure 6. Parameter Output Value (Alcohol Content [%])

**Membership Degrees**

Membership degrees are a fundamental concept in fuzzy logic that indicate the degree to which a value belongs to a fuzzy set (Xie et al., 2021). Membership degrees are used to describe how "true" or "false" a given temperature or fermentation time is classified as "low," "moderate," or "high." Figures 8 and 9 present the graphs of membership degrees for the variables of temperature and fermentation time, which warrant further analysis.

On the X-axis, the numerical values of the variables (temperature or time) are displayed, while the Y-axis represents the membership degree (a value between 0 and 1), where a value of 1 indicates full membership and 0 indicates no membership at all. Each curve in these graphs corresponds to a specific fuzzy set (low, moderate, or high), with common shapes for these curves including triangular or trapezoidal forms.

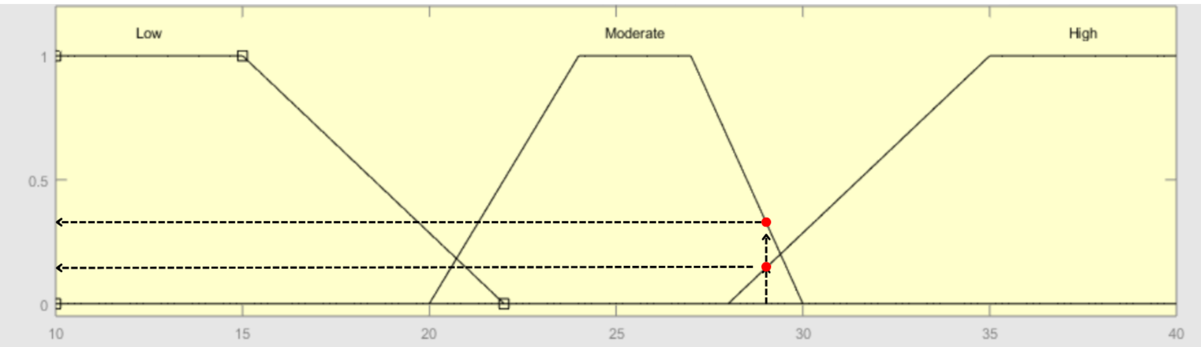

Figure 7. Membership Set Graph of Moderate Temperature Variable Parameters 29°C

At a temperature of 29°C, the membership degree for the "medium" set approaches 1, while the degrees for the "low" and "high" sets approach 0. This suggests that a temperature of 29°C is more likely to be classified as "moderate." The overlapping shape of the curves indicates a zone of uncertainty; for instance, at around 25°C, the membership degrees for both the "low" and "moderate" sets hover close to 0.5. This indicates that this temperature could be considered a transition point between "low" and "moderate".

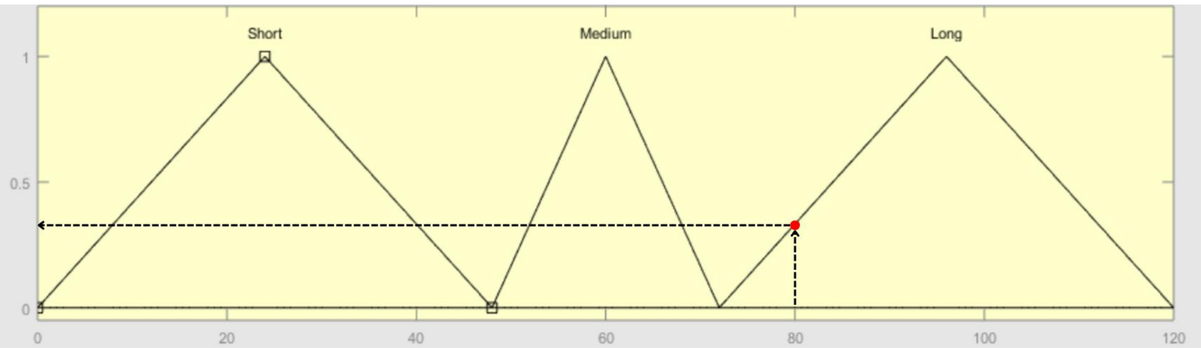

Figure 8. Membership Set Graph of Long Time Variable Parameters 80 hours

For a fermentation time of 80 hours, the membership degree for the "long" set is close to 1, while the degrees for the "short" and "medium" sets approach 0. This implies that an 80-hour fermentation period is predominantly classified as "long." Similar to temperature, certain time periods exhibit zones of uncertainty, illustrating the complexities of categorization within the fuzzy framework.

**Applying Fuzzy Operators**

After converting the input values into fuzzy form, the next step is to formulate fuzzy rules for decision-making. Figure 9 shows nine fuzzy rules (A1 to A9) based on the combinations of fuzzy values from two main variables: temperature and time. These combinations are used to determine the categories of alcohol content levels (Low, Moderate, High). These fuzzy rules are crucial for mapping the relationships between temperature, fermentation time, and alcohol content levels in cassava tape products, allowing the system to make more accurate predictions based on fermentation conditions.

1. If (Temperature is Low) or (Time is Short) then (AlcoholContent is Low) (1)
2. If (Temperature is Low) or (Time is Medium) then (AlcoholContent is Low) (1)
3. If (Temperature is Low) or (Time is Long) then (AlcoholContent is Low) (1)
4. If (Temperature is Moderate) or (Time is Short) then (AlcoholContent is Low) (1)
5. If (Temperature is Moderate) or (Time is Medium) then (AlcoholContent is Moderate) (1)
6. If (Temperature is Moderate) or (Time is Long) then (AlcoholContent is High) (1)
7. If (Temperature is High) or (Time is Short) then (AlcoholContent is Low) (1)
8. If (Temperature is High) or (Time is Medium) then (AlcoholContent is Moderate) (1)
9. If (Temperature is High) or (Time is Long) then (AlcoholContent is High) (1)

Figure 9. Fuzzy Rule Base of Cassava Tape Product

In a fuzzy logic-based decision-making system, operators are crucial for combining membership values from various variables, allowing for flexible handling of uncertainty in input data (Judijanto & Riandari, 2024). By combining values from variables such as temperature and time in the fermentation of cassava tape, the fuzzy system can map input combinations to the desired output results.

The two common operators used are Max and Min. The Max operator, or "OR," selects the highest membership value from several values, while the Min operator, or "AND," takes the lowest value (Tsiakmaki et al., 2021). The use of the Max operator helps the fuzzy system provide optimal results by being more sensitive to relevant conditions, thus achieving flexibility in determining output levels from various input combinations, which is especially useful in the fermentation process of cassava tape.

A1 $\max(\mu T\_low[29], \mu S\_short[80]) = \max(0,0) = 0$
A2 $\max(\mu T\_low[29], \mu S\_moderate[80]) = \max(0,0) = 0$
A3 $\max(\mu T\_low[29], \mu S\_long[80]) = \max(0,0.33) = 0.33$
A4 $\max(\mu T\_moderate[29], \mu S\_short[80]) = \max(0.33,0) = 0.33$
A5 $\max(\mu T\_moderate[29], \mu S\_moderate[80]) = \max(0.33,0) = 0.33$
A6 $\max(\mu T\_moderate[29], \mu S\_long[80]) = \max(0.33,0.33) = 0.33$
A7 $\max(\mu T\_high[29], \mu S\_short[80]) = \max(0.14,0) = 0.14$
A8 $\max(\mu T\_high[29], \mu S\_moderate[80]) = \max(0.14,0) = 0.14$
A9 $\max(\mu T\_high[29], \mu S\_long[80]) = \max(0.14,0.33) = 0.33$

The fuzzy rules in this system are established based on the combinations of temperature and fermentation time, aimed at determining the alcohol content in cassava tape products. These combinations reflect the relationship between environmental variables and the fermentation process that affects the final alcohol content. Each fuzzy rule is designed to provide prediction results that align with actual conditions, ensuring that the system can accommodate variations in temperature and time during fermentation (Moya-Almeida et al., 2024).

In rules A1 to A3, low temperatures result in consistently low alcohol content, regardless of the fermentation duration, as they inhibit the activity of the involved microorganisms. In rules A4 to A6, moderate temperatures allow for an increase in alcohol content, especially with longer fermentation times, creating a better environment for microorganisms. Conversely, in rules A7 to A9, high temperatures significantly enhance alcohol content, particularly with extended fermentation, as microorganisms become more active in converting sugars to alcohol. High temperatures and sufficiently long fermentation times create optimal conditions for maximum alcohol production.

**Applying the Implication Function**

The implication function is a crucial component in fuzzy systems that connects conditions (antecedents) with outcomes (consequents) of fuzzy rules (Lughofer, 2022). In this context, the implication function is used to calculate the degree of membership of a specific value within a fuzzy set (Zhou et al., 2020). This enables the system to interpret how input values, such as temperature and time,

The data indicates that the analyzed temperature is 29°C. This temperature is evaluated to determine its degree of membership in two fuzzy sets: "moderate" and "high." The results show that 29 degrees has a degree of membership of 0.33 in the "moderate" category and 0.14 in the "high" category, suggesting it is more likely to fall into the "moderate" category. This information is significant as a "moderate" temperature can influence the behavior of microorganisms during the fermentation process.

$$\mu moderate\ (x) = \frac{30-x}{30-27}, 27 \leq x \leq 30$$

$$= \frac{30-29}{30-27}$$

$$= \frac{1}{3}$$

$$= 0{,}33$$

$$\mu high\ (x) = \frac{x-28}{35-28}, 28 \leq x \leq 35$$

$$= \frac{29-28}{35-28}$$

$$= \frac{1}{7}$$

$$= 0{,}14$$

The analyzed time is 80 minutes, with a degree of membership of 0.33 in the fuzzy set "long." This indicates that 80 minutes falls into the "long" category. A longer fermentation time can increase the alcohol content, depending on the previously analyzed temperature conditions.

$$\mu long\ (x) = \frac{x-72}{96-72}, 72 \leq x \leq 96$$

$$= \frac{80-72}{96-72}$$

$$= \frac{8}{24}$$

$$= \frac{1}{3}$$

$$= 0{,}33$$

The degree of membership is a value from the membership function that indicates the extent to which a value belongs to a specific fuzzy set, ranging from 0 to 1 (Khairuddin et al., 2021). A value of 1 reflects perfect fit, while a value of 0 indicates complete mismatch (n Pla et al., 2020). Thus, the degree of membership is essential for understanding the relationship between a value and the established categories.

$$A1 = 0$$

$$A2 = 0$$

$$\begin{aligned} A3 &= 0.33 = \frac{x-0}{5-0} \\ &= 0.33 \times (5-0) = x-0 \\ &= 1.65 = x-0 \\ &= x = 1.65 \end{aligned} \quad \text{or}: \quad \begin{aligned} A3 &= 0.33 = \frac{10-x}{10-5} \\ &= 0.33 \times (10-5) = 10-x \\ &= 1.65 = 10-x \\ &= x = 8.35 \end{aligned}$$

$$\begin{aligned} A4 &= 0.33 = \frac{x-0}{5-0} \\ &= 0.33 \times (5-0) = x-0 \\ &= 1.65 = x-0 \\ &= x = 1.65 \end{aligned} \quad \text{or}: \quad \begin{aligned} A4 &= 0.33 = \frac{10-x}{10-5} \\ &= 0.33 \times (10-5) = 10-x \\ &= 1.65 = 10-x \\ &= x = 8.35 \end{aligned}$$

$$\begin{aligned} A5 &= 0.33 = \frac{x-10}{15-10} \\ &= 0.33 \times (15-10) = x-10 \\ &= 1.65 = x-10 \\ &= x = 11.65 \end{aligned} \quad \text{or}: \quad \begin{aligned} A5 &= 0.33 = \frac{20-x}{20-15} \\ &= 0.33 \times (20-15) = 20-x \\ &= 1.65 = 20-x \\ &= x = 18.35 \end{aligned}$$

$$\begin{aligned} A6 &= 0.33 = \frac{x-20}{26-20} \\ &= 0.33 \times (26-20) = x-20 \\ &= 1.98 = x-20 \\ &= x = 21.98 \end{aligned} \quad \text{or}: \quad \begin{aligned} A6 &= 0.33 = \frac{32-x}{32-26} \\ &= 0.33 \times (32-26) = 32-x \\ &= 1.98 = 32-x \\ &= x = 30.02 \end{aligned}$$

$$\begin{aligned} A7 &= 0.14 = \frac{x-0}{5-0} \\ &= 0.14 \times (5-0) = x-0 \\ &= 0.7 = x-0 \\ &= x = 0.7 \end{aligned} \quad \text{or}: \quad \begin{aligned} A7 &= 0.14 = \frac{10-x}{10-5} \\ &= 0.14 \times (10-5) = 10-x \\ &= 0.7 = 10-x \\ &= x = 9.3 \end{aligned}$$

$$\begin{aligned} A8 &= 0.14 = \frac{x-10}{15-10} \\ &= 0.14 \times (15-10) = x-10 \\ &= 0.7 = x-10 \\ &= x = 10.7 \end{aligned} \quad \text{or}: \quad \begin{aligned} A8 &= 0.14 = \frac{20-x}{20-15} \\ &= 0.14 \times (20-15) = 20-x \\ &= 0.7 = 20-x \\ &= x = 19.3 \end{aligned}$$

$$\begin{aligned} A9 &= 0.33 = \frac{x-20}{26-20} \\ &= 0.33 \times (26-20) = x-20 \\ &= 1.98 = x-20 \\ &= x = 21.98 \end{aligned} \quad \text{or}: \quad \begin{aligned} A9 &= 0.33 = \frac{32-x}{32-26} \\ &= 0.33 \times (32-26) = 32-x \\ &= 1.98 = 32-x \\ &= x = 30.02 \end{aligned}$$

The interpretation of the results from the membership function can be illustrated with an example. For instance, the equation A1 = 0 indicates that a temperature of 0 has a membership degree of 0 in the fuzzy set "low," meaning that this temperature does not fall into the "low" category. Additionally, each membership function equation has a different range of values, determining the relevant intervals of temperature or time for that fuzzy set.

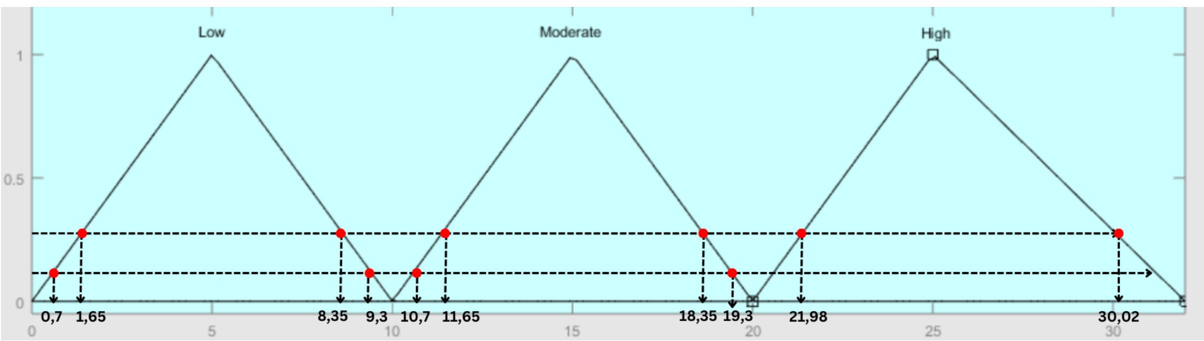


Figure 10. Fuzzy Set Area

Figure 10 illustrates the fuzzy sets used to predict the alcohol content in cassava tape. The intersection points between the curves and the horizontal line at the value of 1 indicate the definitive boundaries of the sets, while the overlapping areas demonstrate that a value can have a non-zero membership degree in multiple fuzzy sets, creating uncertainty in classification (Raut & Pal, 2022).

**Composing All Outputs**

The stages of composing output in fuzzy logic involve rule determination, fuzzy inference, aggregation, and defuzzification (Shoaip et al., 2024). After the rules are applied to the input, the output values from each rule are combined into a single composite result. Figure 11 illustrates this process, where the X-axis represents the output variable range, and the Y-axis shows the membership degree from 0 to 1. The triangular curves represent fuzzy sets such as "Low," "Moderate," and "High," while the red points indicate the output values from each rule, combined to form the final curve, which depicts the output distribution of the composition.

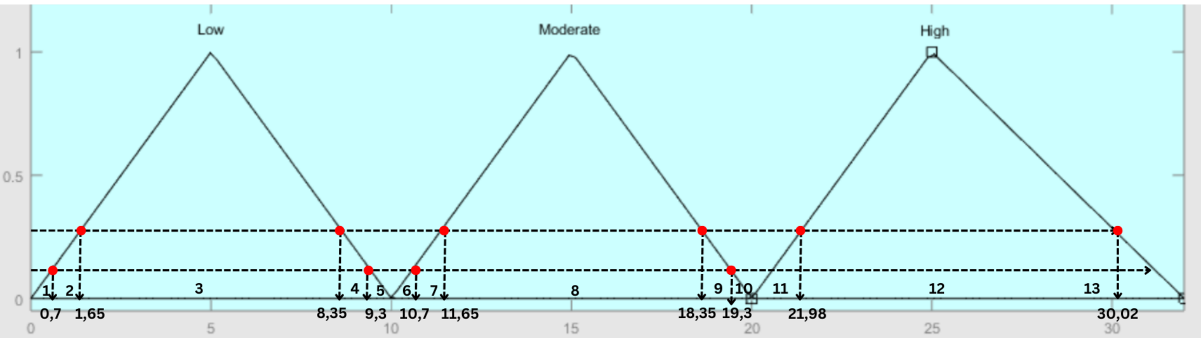

Figure 11. Output Composition Result

The resulting equations mathematically define the membership function for each fuzzy output set, which is generally in the shape of a triangle or trapezoid. The final output value can be obtained by finding the x-value on the X-axis with the highest membership degree on the output curve.

$$\mu_{\mathrm{SF[z]}} = \begin{cases} 0, \quad x \le 0 \\ \frac{x-0}{5-0}, 0 \le x \le 5 \\ \frac{10-x}{10-5}, 5 \le x \le 10 \\ 0, \quad 10 \le x \\ 0, \quad x \le 10 \\ \frac{x-10}{15-10}, 10 \le x \le 15 \\ \frac{20-x}{20-15}, 15 \le x \le 20 \\ 0, \quad 20 \le x \\ 0, \quad x \le 20 \\ \frac{x-20}{26-20}, 20 \le x \le 26 \\ \frac{32-x}{32-26}, 26 \le x \le 32 \\ 0, \quad 32 \le x \end{cases}$$

The uncertainty in the output curve, which appears vague, reflects the characteristic nature of fuzzy systems in modeling complex and uncertain systems (Zheng et al., 2024). Each fuzzy rule contributes to the shape of the final output curve, with higher-weighted rules having a greater influence.

**Defuzzification**

The simplification of the composition function aims to transform complex membership functions into a more easily calculable form, particularly by breaking down complicated functions into linear segments defined by straight line equations (Ferrer-Comalat et al., 2020). This process simplifies further calculations, including moment calculations, thereby facilitating analysis and data processing in fuzzy systems.

$$\mu_{\mathrm{SF}[z]} \begin{cases} 0, & x \leq 0 \\ 0.2x, & 0 \leq x \leq 5 \\ 2 - 0.2x, & 5 \leq x \leq 10 \\ 0, & 10 \leq x \\ 0, & x \leq 10 \\ 0.2x - 2, & 10 \leq x \leq 15 \\ 4 - 0.2x, & 15 \leq x \leq 20 \\ 0, & 20 \leq x \\ 0, & x \leq 20 \\ 0.16x - 3.33, & 20 \leq x \leq 26 \\ 5.33 - 0.16x, & 26 \leq x \leq 32 \\ 0, & 32 \leq x \end{cases}$$

Moment calculation aims to determine the characteristics of the distribution, such as the center (centroid) of the fuzzy distribution (Cerqueti et al., 2021). In fuzzy systems, moments are calculated by integrating the simplified membership function multiplied by a power of the independent variable. The first moment (M1) indicates the average location or center of mass of the distribution, while the second moment (M2) is related to inertia or the spread of data around the mean. Higher moments provide information about the shape of more complex distributions.

$$\mathrm{M1} = \int_0^5 (0.2z)z\,dz = 8.33$$
$$\mathrm{M2} = \int_5^{10} (2 - 0.2z)z\,dz = 16.66$$
$$\mathrm{M3} = \int_{10}^{15} (0.2z - 2)z\,dz = 33.33$$
$$\mathrm{M4} = \int_{15}^{20} (4 - 0.2z)z\,dz = 41.66$$
$$\mathrm{M5} = \int_{20}^{26} (0.16z - 3.33)z\,dz = 51.18$$
$$\mathrm{M6} = \int_{26}^{32} (5.33 - 0.16z)z\,dz = 117.18$$
$$\mathrm{M7} - \mathrm{M12} = 0$$

Calculating the centroid aims to find a representative value of the fuzzy distribution by dividing the first moment by the total area under the membership function curve (Ma et al., 2024). This centroid reflects a weighted average value, where the weights are determined by the degree of membership. The calculation of the centroid indicates a representative value of the fuzzy distribution of 30.61, reflecting the weighted average based on the degree of membership.

$$z^* = \frac{(M1 + M2 + M3 + M4 + M5 + M6 + M7 + M8 + M9 + M10 + M11 + M12)}{(A1 + A2 + A3 + A4 + A5 + A6 + A7 + A8 + A9 + A10 + A11 + A12 + A13)}$$

$$= \frac{(8.33 + 16.66 + 33.33 + 41.66 + 51.18 + 117.18 + 0 \ldots 0)}{(0.049 + 0.1567 + 2.211 + 0.0665 + 0.049 + 0.049 + 0.1567 + 2.211 + 0.133 + 0.049 + 0.3267 + 2.6532 + 0.6534)}$$

$$= 30.61$$

Figure 12 displays the results of calculations using MATLAB, illustrating the fuzzy inference process where input values (temperature and fermentation time) are mapped to output values (alcohol content) based on predetermined fuzzy rules. To find the appropriate point, it is necessary to identify the row with the most active fuzzy rule at a temperature of 29°C and a fermentation time of 80 hours. This point is then projected onto the response surface shown in Figure 13, indicating that the Z value at this projection approaches an alcohol content of 15.9%. Although the centroid calculation indicates an alcohol content of 30.61%, this discrepancy may be attributed to variations in the parameters used in the calculations, even though the same method and parameters should ideally produce consistent values (Zamzoum et al., 2020).

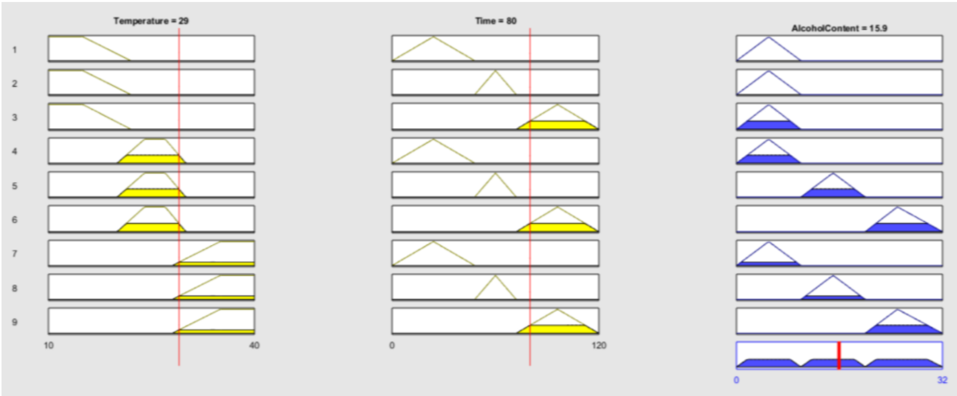


Figure 12. Matlab Result Calculation

Figure 13 presents a three-dimensional visualization of the response surface of the fuzzy system, illustrating the relationship between temperature, fermentation time, and the resulting alcohol content. This graph depicts how variations in temperature and fermentation duration can affect the alcohol level. The curved shape of the surface indicates that the relationship between the inputs (temperature and time) and the output (alcohol content) is non-linear, which is a characteristic feature of fuzzy systems (Thakur et al., 2021). By analyzing this response surface, combinations of temperature and fermentation time can be identified to achieve the desired alcohol content.

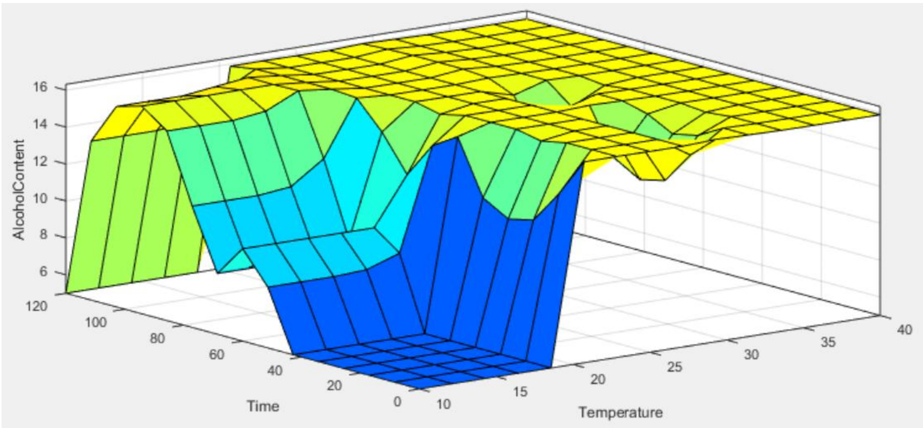


Figure 13. Matlab Surface Data Result

Defuzzification is a process used in fuzzy systems to convert fuzzy values into crisp or more concrete numerical values, allowing them to be applied in practical decision-making (Rudnik et al., 2024). This process occurs after all fuzzy outputs have been combined, resulting in a fuzzy distribution. One common method for defuzzification is to use the centroid of the output distribution (Jain et al., 2022). Analysis in MATLAB shows that the calculated alcohol content from the fuzzy inference indicates an alcohol level of 15.9% at a temperature of 29°C and a fermentation time of 80 hours. Although the centroid calculation previously yielded a value of 30.61, the MATLAB analysis demonstrates that a more accurate alcohol content is produced from the defuzzification method, confirming the relationship between temperature and fermentation time that affects the final alcohol content.

**CONCLUSION**

Based on the literature, the length of fermentation time and fermentation temperature significantly affect the final results and alcohol content of cassava tape. The implementation of fuzzy logic helps handle uncertainty so that the desired alcohol content is easier to achieve. In this study, nine fuzzy rules were created that allow the system to make more accurate predictions based on fermentation conditions and produce consistent and appropriate alcohol levels. From the results and discussion of this study, it can be concluded that the optimal temperature for cassava tape fermentation ranges from 25°C - 30°C. This temperature control is then used in the fuzzy membership degree to identify the "moderate" temperature as the right point to produce quality tape. From this fuzzy system, it can also be concluded that the optimal fermentation time to produce cassava tape with an alcohol content that meets the specifications is a "long" duration. From the defuzzification results, the final results showed an alcohol content of 15.9% at a temperature of 29°C and a fermentation time of 80 hours which is close to the target in this study.

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