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Implementation of Fuzzy Logic to Control Temperature and Incubation Time for the pH of Yoghurt

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Abstract

This research develops a fuzzy logic-based yoghurt production model by considering incubation temperature and incubation time as the main variables that influence the final pH of yoghurt. In this study, 49 yoghurt samples were produced and tested in two replications to obtain pH data which was then processed through fuzzy modeling. This fuzzy model is for determining fuzzy rules and membership functions. By using two fuzzy sets for each parameter and the Mamdani method, a total of 49 fuzzy logic rules were built to describe the relationship between incubation variables and final pH. Matlab 2015a software was used to process data and assess model accuracy. The results showed that this model was effective for predicting the final pH of yoghurt, which is important for maintaining product quality. In the future, it is hoped that this model can be applied to automated production lines, thereby supporting yoghurt production on an industrial scale with greater consistency and efficiency, especially in the food sector.

Keywords: yoghurt, incubation, fuzzy logic, pH

INTRODUCTION

Yogurt is a dairy product made from pasteurized milk, which is then fermented with specific bacteria to develop its distinctive acidity, aroma, and taste. This process may include the addition of permitted additives or none at all (Latifasari *et al*., 2023). Yoghurt is well known as a sort of fermented drain that contains lactic acid–producing microscopic organisms (LAB) and gives dietary benefits for human wellbeing in progressing gastroin testinal function and expanding longevity. Yoghurt on the market is formed like porridge with a sour taste. The characteristic of yoghurt is that it is formed like mash with a slightly sour taste. Yoghurt is ordinarily made utilizing two types of LAB, specifically Streptococcus thermonhilus and Lactobacilius hulgaricus as a starter. Separated from that, there are moreover yogurt included with LAB which has probiotic properties such as acidophilus, Lactobacillus casei and Bifidabacterium (Widiyanto *et al* 2019). This microscopic organisms plays a part in breaking down the lactose in milk into lactic acid. During the yoghurt incubation process, temperature and incubation time are very important factors. Lactobacillus bulgaricus bacteria grow optimally at a temperature of 42 to 45°C, while Streptococcus thermophilus thrives at a temperature of 38 to 42°C (Widiani *et al.*, 2017).

Yoghurt contains total nutrients and is good for wellbeing. Expending yoghurt has benefits for the body, specifically controlling the stomach related tract, anti-diarrhea, anti-cancer, expanding development, and many more. In making yoghurt there are many variables can influence the quality of yoghurt, counting incubation temperature and incubation time. Temperature is the foremost critical figure in incubation and will impact the growth of acid lactate from yoghurt (Adiputra *et al., 2022*). At the proper temperature, these bacteria will increase well, producing lactic acid which gives yoghurt its particular taste and thick surface. In the event that the temperature is too low, the fermentation process will slow down, so the yoghurt will not reach the specified thickness and taste. On the other hand, temperatures that are too high can kill these great bacteria, causing fermentation to fall flat and the quality of the yoghurt to decrease. In expansion, the length of incubation time also plays an critical part; As well short a time can create yoghurt that's less thick and less acrid, while too long can make it too acrid and change the expected taste.

Fuzzy logic was utilized to model yoghurt production process with the utilize of last pH values of incubation impacted by incubation temperature, incubation time (Akgul *et al.,* 2022). Fuzzy logic is connected to model the yoghurt production prepare, by combining the impact of temperature and incubation time on the ultimate pH value of the yoghurt. By analyzing past pH data, fuzzy logic is able to set up connections between these variables, allowing more exact control of the fermentation process.

This innovative approach permits a deeper understanding of how varieties in temperature and time affect the sharpness level of yoghurt, as pH is an critical parameter that determines the texture, taste and generally quality of the ultimate product. Fuzzy logic scientifically describes the level of truth and falsity of a value in stages. Unlike classical logic which only provides two possibilities, a value is completely in a set or completely outside a set, fuzzy logic uses degrees of membership to indicate the level of association of a value with a particular set. A membership value of 0 indicates a total disconnection from the set, while a value of 1 indicates a full association (Kurniati *et al.*, 2017).

By utilizing fuzzy logic, the model can successfully handle the uncertainty and complexity of the fermentation process, permitting producers to optimize conditions for desired yoghurt characteristics. This includes dynamically adjusting temperature and time based on real-time pH readings, guaranteeing that the fermentation process remains within the ideal range for the growth of beneficial bacteria. Eventually, this modeling technique improves the capacity to predict and control yoghurt quality. By analyzing using fuzzy logic, this approach improves the consistency and quality of the final yoghurt product so that it can satisfy consumers.

METHODS

In this study, the method used is a literature review. In (Putrihapsari and Fauziah, 2020) defines literature studies as research conducted by examining various literature studies needed in research. The use of the literature study method in this study is as the first step in planning the research by utilizing literature to obtain data in the field without the need to jump in directly. The main reference in this study is related literature, which includes primary data in the form of other research results, research reports, and scientific publications, as well as secondary data consisting of government regulations and relevant books. By collecting studies on temperature control and the length of incubation time on the pH of yogurt and applying fuzzy logic to build a mathematical model.

A Mamdani fuzzy inference system based approach is proposed for performance measurement of manufacturing systems. The main consideration in designing this model is the fuzzy rule formation process (Pourjavad and Mayorga, 2019). In the context of fuzzy sets, each element in the universe of talk (X) is assigned a membership value that ranges from 0 to 1. A value of 1 indicates full membership or absolute certainty, while a value of 0 indicates no membership at all. This mapping process is carried out through the membership function specified at the initial stage. In this study, membership functions and fuzzy rules were used to model the influence of input variables such as temperature and incubation time on the pH of yoghurt (Akgul *et al.,* 2022). Based on an in-depth literature review, the data that has been collected allows the determination of fuzzy operators that will connect inputs and outputs that represent the knowledge of experts as well as the results of observations. Commonly used fuzzy operators include negation (NOT), disjunction (OR), and conjunction (AND), which respectively represent denial, separation, and merger. The combination of these operators will ultimately produce an output that matches the fuzzy model that has been built.

The implementation of the fuzzy logic system is carried out in several stages, starting with fuzzification, which is converting crisp input data into fuzzy values based on membership functions. After that, the fuzzy inference process is carried out using methods such as Mamdani or Sugeno to produce fuzzy output based on predetermined rules. The results of this inference are then defuzzified using methods such as Centroid, resulting in crisp values that can be used as a reference to control temperature and incubation time. After the fuzzy logic system was successfully implemented, tests were carried out for various temperature scenarios and incubation times to ensure that the system was able to maintain the desired pH of the yoghurt (Rahman *et al.,* 2020).

RESULTS AND DISCUSSION

Based on the system development methodology previously outlined, this section presents the results of the analysis concerning the application of fuzzy logic for controlling the pH quality of yogurt, specifically utilizing the Mamdani fuzzy logic approach. The primary inputs for this system consist of temperature and incubation time values utilized during the yogurt production process. These data points serve as the foundation for computational analysis aimed at identifying the optimal combinations of temperature and incubation time. This approach facilitates the production of yogurt that meets the specified and desired pH quality parameters, thereby enhancing the consistency and overall quality of the final yoghurt product.

1. Data Preparation

After conducting an in-depth analysis of relevant literature studies, namely in research conducted by Akgul *et al.*, (2022). In their research, the optimal incubation temperature range used was between 33-53°C. For other input parameters, namely the incubation time in the yoghurt making process, it was obtained from 0-7 hours. During the yoghurt fermentation process, temperature and incubation time are determining factors for the quality of the final yoghurt results. The results showed that temperature and time treatments can provide different levels of final acidity. The longer the fermentation time, the acidity of yoghurt tends to increase in accordance with the increase in acid production during fermentation which is followed by the growth phase of lactic acid bacteria until optimum growth (Tursina, 2019). The treatment of incubation time can affect the acidity level of the yoghurt produced where the longer the fermentation time, the more acidic the yoghurt formed will be. The final pH value that will be produced is 3.75 after the optimal incubation time which is identified as 3 out of 24 hours, depending on the fermentation conditions applied (Adiputra *et al.*, 2022). In this study, fuzzy logic is used to model the yoghurt production process which results in the final pH value of yoghurt incubation being influenced by the incubation temperature and incubation time.

Fuzzy logic is a computational approach that imitates human thinking by dealing with uncertainty and imprecision, especially in complex systems. In contrast to traditional binary logic which only recognizes true or false values (0 or 1), fuzzy logic allows degrees of truth with membership values between 0 and 1 (Wawan *et al.*, 2021). In this research, the fuzzy logic used is mamdani logic, this is applied to optimize the fermentation process yoghurt by controlling two main factors, namely temperature and incubation time, which greatly influence the final pH of the yoghurt as the main determinant of quality. Input data in the form of temperature (33–53°C) and incubation time (0–7 hours) are converted into a fuzzy set via a membership function, where temperature is categorized into "Very Low," "Normal," or "High," while time is classified as "Poor," "Normal," or "High." The fuzzy inference process then uses predetermined rules, such as if the temperature is Normal and the time is High, then the pH is Low, to model the relationship between temperature, time, and pH. The resulting fuzzy output, such as "Low pH" or "Normal pH," is then converted back to an appropriate numerical value, such as pH 3.75, through a defuzzification process. The application of this fuzzy logic allows adaptive control of conditions in real time, keeping the yoghurt acidity level within the optimal range. Thus, fuzzy logic helps manage the variability and complexity of the fermentation process, improving product consistency and quality, making it suitable for industrial-scale production applications.

2. **Variable Definition**

Variable definition is the process of determining and grouping input and output variables that will be used in a fuzzy system. This process includes providing descriptions, value ranges, and linguistic categories for each variable, so that the fuzzy system can process uncertain data and make inferences more accurately.

Table 1 Types, variables and ranges used

Type	Variable	Range
Input	Incubation temperature	[33 53]
	Incubation time	[0 7]
Output	pH yoghurt	[0,5 7,5]

Table 1 provides information on the types, variables, and ranges used in this study. In the incubation temperature variable, it was found that the optimal temperature for the yoghurt making process in this study was in the range of 33-53°C. The incubation temperature variable with the range calculation was expanded to very low temperatures of 33-39°C, low temperatures of 36-41°C, slightly low temperatures of 40-42°C, warm temperatures of 41-43°C, normal temperatures of 42.5-45°C, slightly high temperatures of 44-49°C, and high temperatures of 46-53°C.

Meanwhile, the variables also use ranges that are in accordance with the references contained in the literature study conducted. In the incubation time variable used 0-7 hours with the calculation of the range expanded to insufficient time in the range of 0-1.9 hours, very low time in the range of 1.6-2.4 hours, low time in the range of 2.1-3.5 hours, slightly low time in the range of 3-4.4 hours, normal time in the range of 4.1-4.9 hours, slightly high time in the range of 4.6-5.9 hours, and high time in the range of 5.1-7.0 hours. In the outcome variable, namely yogurt pH, it was found that the pH was in the range of 0.5-7.5 for the final product. The calculation of the expanded range became low pH from 0.5-3.5, normal pH from 2-5.5, and high pH from 4-7.5.

3. **Fuzzification**

Fuzzy Logic Modelling

The modeling endeavor was conducted in a two-part approach. The first part involved the formulation of fuzzy rules and membership functions, while the second part focused on the application of defuzzification techniques. In modeling with fuzzy logic, there are fuzzy control input parameters (incubation temperature and incubation time) which will later produce pH output.

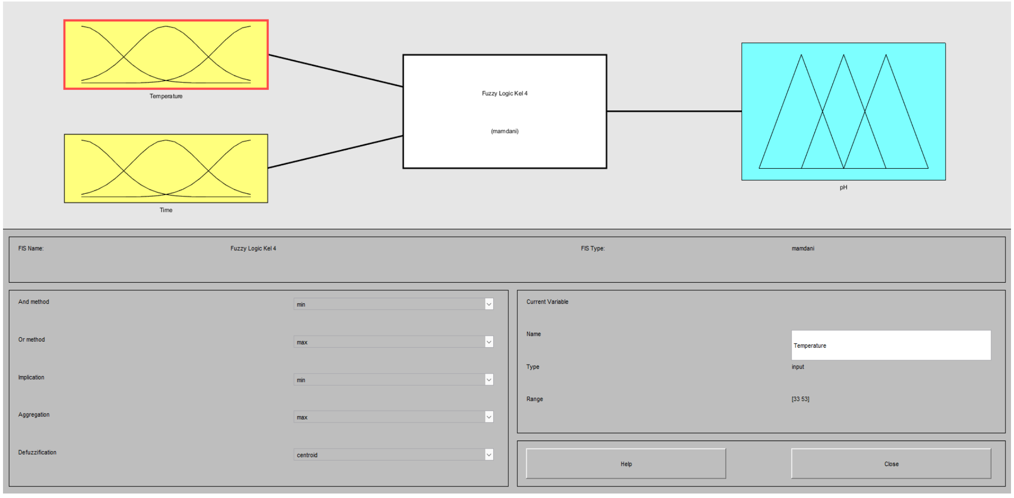


Figure 1 Modeling with fuzzy logic

Based on the provided diagram, the fuzzy logic model for controlling the pH value is designed with two primary input variables: *temperature* and *time*. Both inputs use membership functions to categorize values into linguistic terms, such as "low," "medium," and "high," which correspond to various ranges of temperature and time. This linguistic categorization allows the fuzzy system to interpret the input data in a way that aligns with human understanding, enhancing the accuracy of process control (Feng, 2018). Research has shown that the use of fuzzy approaches in biological process control can improve adaptability and precision, as demonstrated by Ahmadi *et al*., (2018) in their work on optimizing microbial growth conditions by considering environmental parameters.

In this setup, the fuzzy inference process applies established fuzzy rules to link the inputs (temperature and time) to the output (pH). The diagram shows that the rules are processed using the specified parameters: the "min" method for AND operations, "max" for OR operations, and "min" for implication, all of which influence how inputs are combined and evaluated within the fuzzy system. Aggregation also uses the "max" method, determining how the output is consolidated from the fuzzy rule results. This configuration aligns with research from Zhang *et al*. (2020), who demonstrated that fuzzy systems could optimize biological processes by adapting to multiple input conditions.

Once the fuzzy inference is complete, a defuzzification method is used to convert the fuzzy output into a specific numerical value for pH. Here, the Centroid method is selected, which calculates the center of gravity of the output distribution to yield a stable and consistent pH value. This approach has been shown to provide reliable outputs in complex systems, as discussed by Khan et al. (2022), who highlighted the stability provided by the Centroid method. In a similar study, *Rani et al.,* (2019) applied defuzzification to the control of incubation processes and demonstrated that it yielded consistent output values, proving the effectiveness of this approach in real-world applications.

Overall, this fuzzy modeling approach not only addresses the inherent uncertainty in input variables but also enhances the efficiency and accuracy of the entire process control system. Bhat *et al.,* (2023) confirmed the advantages of fuzzy logic in biotechnology, noting that such systems could quickly adapt to real-time changes, ensuring consistent quality and performance. This makes fuzzy logic modeling an ideal tool for biotechnology applications and other areas requiring precise control in the face of variable and uncertain conditions.

Membership Function

Table 2 Input incubation temperature (°C) in yoghurt making

Condition	Temperature Range
Very low	33-39℃
Low	36-41℃
Little low	40-42℃
Warm	41-43℃
Normal	42,5-45℃

Condition	Temperature Range
Little high	44-49℃
High	46-53℃

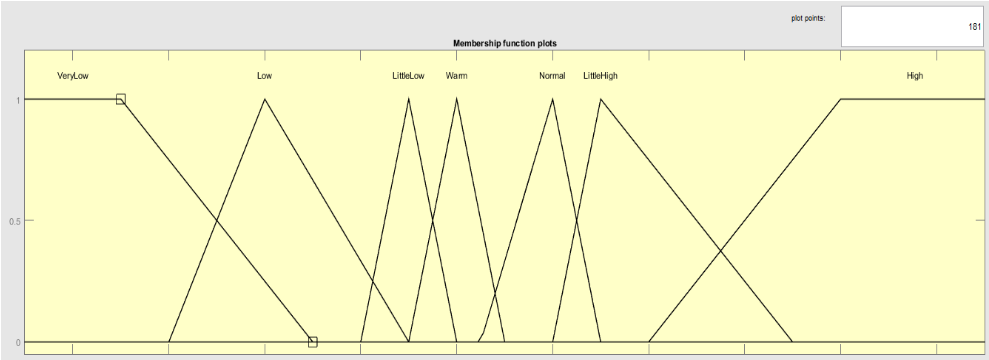


Figure 2 Graphic incubation temperature (°C) input

In Figure 2, the membership functions for incubation temperature are divided into seven categories: very low, low, little low, warm, normal, little high, and high. Each temperature category represents a different temperature level, which is important for ensuring an optimal incubation process. In yogurt production, temperature is a critical factor because it affects the activity of bacterial cultures necessary for fermentation. Bacteria such as *Lactobacillus delbrueckii subsp. bulgaricus* and *Streptococcus thermophilus* work most effectively at a certain temperature, generally around 42-44 °C, to achieve the desired acidity and texture characteristics (Freitas, 2017).

A fuzzy logic system is applied in this study to manage temperature variability that may occur during the production process. By using fuzzy sets, temperature is interpreted not only as a single value but as a range with different degrees of membership. For example, a temperature around 42.5 °C may have the highest degree of membership in the normal category and also a slight degree in the little high category. This approach allows greater flexibility in managing incubation temperature, leading to more consistent yogurt quality.

Additionally, the fuzzy logic modeling follows several stages. In the initial stage, fuzzy rules are set, and membership functions for each parameter (incubation temperature, incubation time, and culture inoculum ratio) are arranged in a triangular shape. These membership functions are then combined with fuzzy rules to generate a variety of decisions about the final pH outcome. A total of 343 fuzzy rules are applied in this system, derived from the combination of the three parameters, each with seven membership functions. To translate the fuzzy output into a final useful numerical decision, a defuzzification process is carried out using the weighted average method, which yields the final pH value of the yogurt based on the degree of membership across various pH classes (Freitas, 2017).

Furthermore, through this approach, researchers can optimize the ideal incubation temperature to control the final pH, which is an important indicator in yogurt fermentation. For example, if the incubation temperature falls within the normal range but the incubation time is insufficient, the fuzzy system will indicate that fermentation may be incomplete, resulting in a higher final pH, or a yogurt that isn't sufficiently acidic. Conversely, if the temperature is too high or the incubation time is too long, this can lead to excessive acidification, negatively affecting the taste and texture of the yogurt**.**

Using this fuzzy logic method, yogurt production is expected to be more stable in terms of quality, as this model allows responsive adjustments to minor changes in incubation temperature. This also demonstrates the potential for broader automation applications in the food industry, where production parameter variability is often difficult to control precisely with conventional methods.

Table 3 Input of incubation time (hours) in yogurt production

Condition	Time Range (hours)
Not enough	0-1,9

Condition	Time Range (hours)
Very low	1,6-2,4
Low	2,1-3,5
Little low	3-4,4
Normal	4,1-4,9
Little high	4,6-5,9
High	5,1-7

Each time range provides an overview of how the incubation level affects the condition of the resulting yogurt, where a longer incubation time can reach higher category levels, from "not enough" to "high." (Setianingrum, 2017).

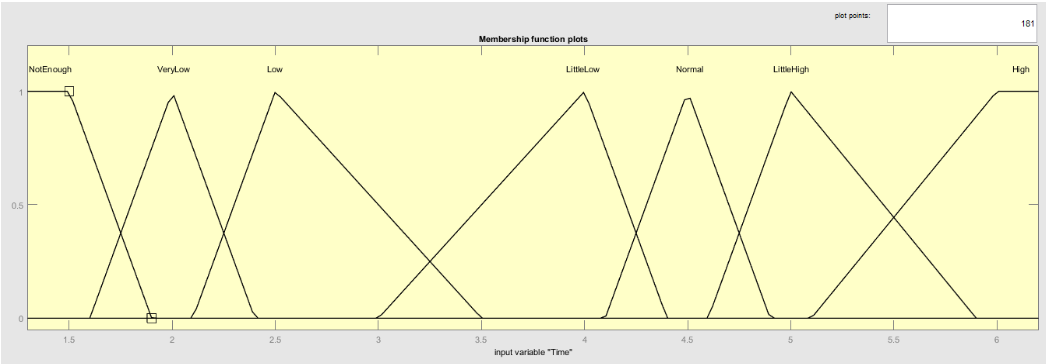


Figure 3 Graphic incubation time (hour) input

The figure displays a membership function graph for incubation time across several categories, such as "Very Low," "Low," "Normal," "Likely," and "High." This graph represents the degree of membership for each category based on incubation time in hours, with the horizontal axis as time and the vertical axis indicating membership values. Incubation time in yogurt production and other fermented products plays a crucial role in determining the final product's physical and sensory properties. Studies show that increased incubation time can influence viscosity and water-holding capacity in yogurt, ultimately enhancing texture stability (Krisnaniangsih *et al.,* 2019). Conversely, research by Dennis *et al.*, (2021) suggests that overly long incubation times may raise acidity levels excessively, which can reduce consumer acceptance due to an overly sour taste.

Other studies have also found that incubation duration impacts the probiotic content in yogurt. Adequate incubation can increase the number of beneficial probiotic microorganisms that support digestive health, although overly long incubation may result in an overly thick consistency and an undesirable taste (Anderson *et al.,* 2020; Zhao *et al.,* 2018). Furthermore, a study by Hassan and Sultana (2022) recommends optimizing incubation time to balance viscosity and taste in the resulting yogurt.

Table 4 Output of yogurt pH values

Condition	pH Range
Low	0,5-3,5
Normal	2-5,5
High	4-7,5

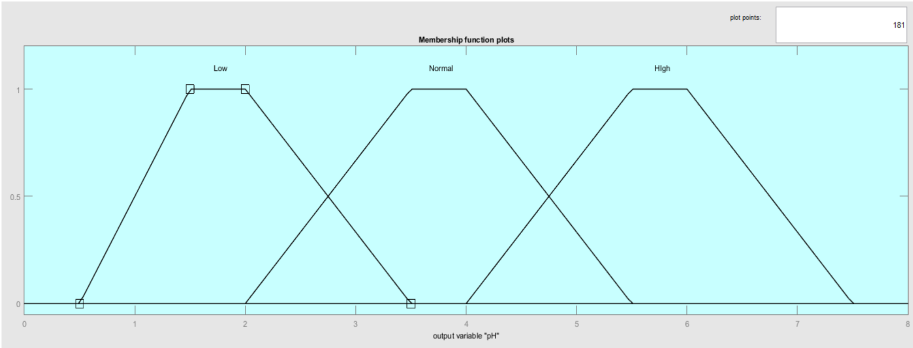


Figure 4 Graphic pH of yoghurt output

Figure 4 presents a graph illustrating the membership degree of yogurt pH across three main categories: Low, Normal, and High. This graph demonstrates how the fuzzy logic system classifies the acidity levels of yogurt during the incubation process, a critical indicator in determining the final quality of the product. According to the literature, the pH range of 0.5–3.5 is categorized as Low, indicating high acidity or yogurt in the initial stages of fermentation, where lactic acid bacteria are just beginning to break down lactose into lactic acid. At this stage, the fuzzy membership degree assigns a higher weight to lower pH values, reflecting the progressive increase in acidity (Akgul *et al.,* 2022). Trapezoidal membership function is a membership function in fuzzy logic that is defined by four main parameters, namely {a, b, c, d}. These four parameters determine the shape and boundaries of the trapezoid, which significantly affect the membership value in a certain interval, and provide flexibility in representing data with various fuzzy values (Al Riza *et al.*, 2014).

Meanwhile, the pH range of 2–5.5 is considered Normal, reflecting the optimal acidity level where yogurt achieves the desired texture and flavor quality suitable for consumption (Wu *et al.,* 2024*)*. In this range, the fuzzy system maximizes the membership degree to indicate that the pH is in an ideal condition, signifying that the fermentation process has reached an optimal point (Deshwal *et al.*, 2021). According to the literature, this condition is highly influenced by precise incubation duration and temperature, where optimal fermentation results in a pH within this range, ensuring a stable and high-quality product. On the other hand, the High category with a pH range of 4–7.5 indicates low or near-neutral acidity, occurring when fermentation has not proceeded optimally or has stopped prematurely (Do *et al.*, 2019). In this category, the fuzzy membership degree tends to decrease as the pH approaches a more neutral value, suggesting that the yogurt may not have reached the expected acidity standard, potentially affecting the quality of taste and texture.

Through the application of this fuzzy logic system, the yogurt fermentation process can be more controlled and consistent, as the system is able to provide real-time assessments of pH conditions based on slight changes occurring during incubation (Akgul *et al.* 2022). This approach, as described in the literature, enables more responsive decision-making in managing the variability of production parameters, ensuring that the resulting yogurt meets the desired quality standards and reducing the risk of inconsistency in the final product.

Membership Degree

Membership Degree is a graph that represents the degree of membership of each input variable in the interval 0 and 1. Where the degree of membership of a variable is characterized by μ(x). rules using membership values are then used to determine the effect when inference is carried out and conclusions can be drawn (Syahputra *et al.* 2022). The membership function used in this test is the trapezoidal membership function.

Trapezoidal membership

$$\mu[x,a,b,c,d] \begin{cases} 0; & x \le a \\ (x-a)/(b-a); & a \le x \le b \\ 1; & b \le x \le c \\ (d-x)/(d-c); & c \le x \le d \\ 0; & x \ge d \end{cases}$$

Explanation:
a = the smallest domain value with a membership degree of zero
b = the smallest domain value with a membership degree of one
c = the largest domain value with a membership degree of one
d = the largest domain value with a membership degree of zero
x = the input value to be converted into a fuzzy number

Based on the trapezoidal membership function, the membership set value µx(a,b,c) is obtained. The incubation temperature (℃) membership set model can be described as follows:

$$Temperature(℃) \begin{cases} Very\ low \begin{cases} 0, x \le 0 \\ \frac{x-0}{20-0}, 0 \le x \le 20 \\ 1, 20 \le x \le 35 \\ \frac{39-x}{39-35}, 35 \le x \le 39 \\ 0, 39 \le x \end{cases} \\ Low \begin{cases} 0, x \le 36 \\ \frac{x-36}{38-36}, 36 \le x \le 38 \\ \frac{41-x}{41-38}, 38 \le x \le 41 \\ 0, 41 \le x \end{cases} \\ Little\ low \begin{cases} 0, x \le 40 \\ \frac{x-40}{41-40}, 40 \le x \le 41 \\ \frac{42-x}{42-41}, 41 \le x \le 42 \\ 0, 42 \le x \end{cases} \\ Warm \begin{cases} 0, x \le 41 \\ \frac{x-41}{42-41}, 41 \le x \le 42 \\ \frac{43-x}{43-42}, 42 \le x \le 43 \\ 0, 43 \le x \end{cases} \\ Normal \begin{cases} 0, x \le 42{,}5 \\ \frac{x-42{,}5}{44-42{,}5}, 42{,}5 \le x \le 44 \\ \frac{45-x}{45-44}, 44 \le x \le 45 \\ 0, 45 \le x \end{cases} \\ Little\ high \begin{cases} 0, x \le 44 \\ \frac{x-44}{45-44}, 44 \le x \le 45 \\ \frac{49-x}{49-45}, 45 \le x \le 49 \\ 0, 49 \le x \end{cases} \\ High \begin{cases} 0, x \le 46 \\ \frac{x-46}{50-46}, 46 \le x \le 50 \\ 1, 50 \le x \le 53 \\ \frac{54-x}{54-53}, 53 \le x \le 54 \\ 0, 54 \le x \end{cases} \end{cases}$$

Figure 5 Parameter input value (incubation temperature (℃))

Based on the trapezoidal membership function, the membership set value µx(a,b,c) is obtained. The incubation time (hour) membership set model can be described as follows:

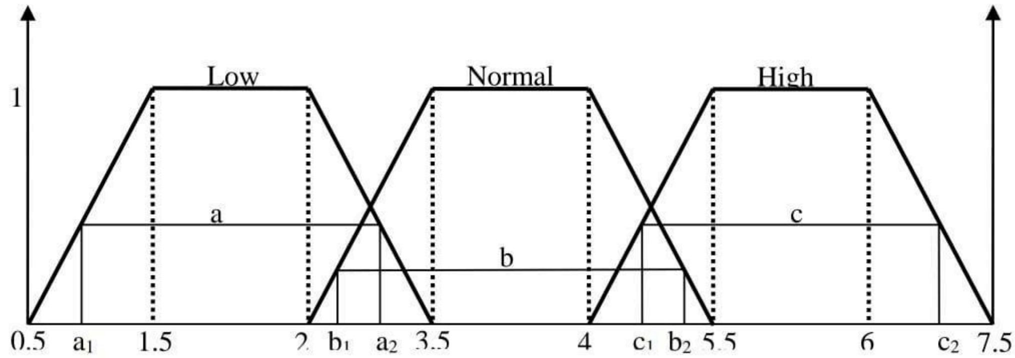
$$
Time(hour)\begin{cases}
Not\ enough\begin{cases} 0, x \le 0 \\ \dfrac{x-0}{1-0}, 0 \le x \le 1 \\ 1, 1 \le x \le 1{,}5 \\ \dfrac{1{,}9-x}{1{,}9-1{,}5}, 1{,}5 \le x \le 1{,}9 \\ 0, 1{,}9 \le x \end{cases} \\
Very\ low\begin{cases} 0, x \le 1{,}6 \\ \dfrac{x-1{,}6}{2-1{,}6}, 1{,}6 \le x \le 2 \\ \dfrac{2{,}4-x}{2{,}4-2}, 2 \le x \le 2{,}4 \\ 0, 2{,}4 \le x \end{cases} \\
Low\begin{cases} 0, x \le 2{,}1 \\ \dfrac{x-2{,}1}{2{,}5-2{,}1}, 2{,}1 \le x \le 2{,}5 \\ \dfrac{3{,}5-x}{3{,}5-2{,}5}, 2{,}5 \le x \le 3{,}5 \\ 0, 3{,}5 \le x \end{cases} \\
Little\ low\begin{cases} 0, x \le 3 \\ \dfrac{x-3}{4-3}, 3 \le x \le 4 \\ \dfrac{4{,}4-x}{4{,}4-4}, 4 \le x \le 4{,}4 \\ 0, 4{,}4 \le x \end{cases} \\
Normal\begin{cases} 0, x \le 4{,}1 \\ \dfrac{x-4{,}1}{4{,}5-4{,}1}, 4{,}1 \le x \le 4{,}5 \\ \dfrac{4{,}9-x}{4{,}9-4{,}5}, 4{,}5 \le x \le 4{,}9 \\ 0, 4{,}9 \le x \end{cases} \\
Little\ high\begin{cases} 0, x \le 4{,}6 \\ \dfrac{x-4{,}6}{5-4{,}6}, 4{,}6 \le x \le 5 \\ \dfrac{5{,}9-x}{5{,}9-5}, 5 \le x \le 5{,}9 \\ 0, 5{,}9 \le x \end{cases} \\
High\begin{cases} 0, x \le 5{,}1 \\ \dfrac{x-5{,}1}{6-5{,}1}, 5{,}1 \le x \le 6 \\ 1, 6 \le x \le 6{,}5 \\ \dfrac{7-x}{7-6{,}5}, 6{,}5 \le x \le 7 \\ 0, 7 \le x \end{cases}
\end{cases}
$$

Figure 5 Parameter input value (incubation time (hour))

Based on the trapezoidal membership function, the output using µx(a,b,c) is obtained. The parameter output value (pH) set model can be described as follows:

$$
pH\begin{cases}
Low\begin{cases} 0, x \le 0{,}5 \\ \dfrac{x-0{,}5}{1{,}5-0{,}5}, 0{,}5 \le x \le 1{,}5 \\ 1, 1{,}5 \le x \le 2 \\ \dfrac{3{,}5-x}{3{,}5-2}, 2 \le x \le 3{,}5 \\ 0, 3{,}5 \le x \end{cases} \\
Normal\begin{cases} 0, x \le 2 \\ \dfrac{x-2}{3{,}5-2}, 2 \le x \le 3{,}5 \\ 1, 3{,}5 \le x \le 4 \\ \dfrac{5{,}5-x}{5{,}5-4}, 4 \le x \le 5{,}5 \\ 0, 5{,}5 \le x \end{cases} \\
High\begin{cases} 0, x \le 4 \\ \dfrac{x-4}{4-5{,}5}, 4 \le x \le 5{,}5 \\ 1, 5{,}5 \le x \le 6 \\ \dfrac{7{,}5-x}{7{,}5-6}, 6 \le x \le 7{,}5 \\ 0, 7{,}5 \le x \end{cases}
\end{cases}
$$

Figure 5 Parameter output value (pH)



4. **Fuzzy Rules**

Fuzzy rules are representations of the variables and linguistics used in fuzzy. The rules used consist of "if" "then" rules that can be connected with the operators "or", "and", and "not". In the research conducted there were only 3 rules used. The input variables consist of incubation temperature and incubation time, each of which has 7 linguistic variables. The incubation temperature variable has linguistic values of very low, low, slightly low, warm, normal, slightly high, and high. While the incubation time variable has linguistic values of very low, low, slightly low, warm, normal, slightly high, and high. The output variable is a pH value with linguistic variables of low, normal, and high (Asrianto and Effendi 2021).

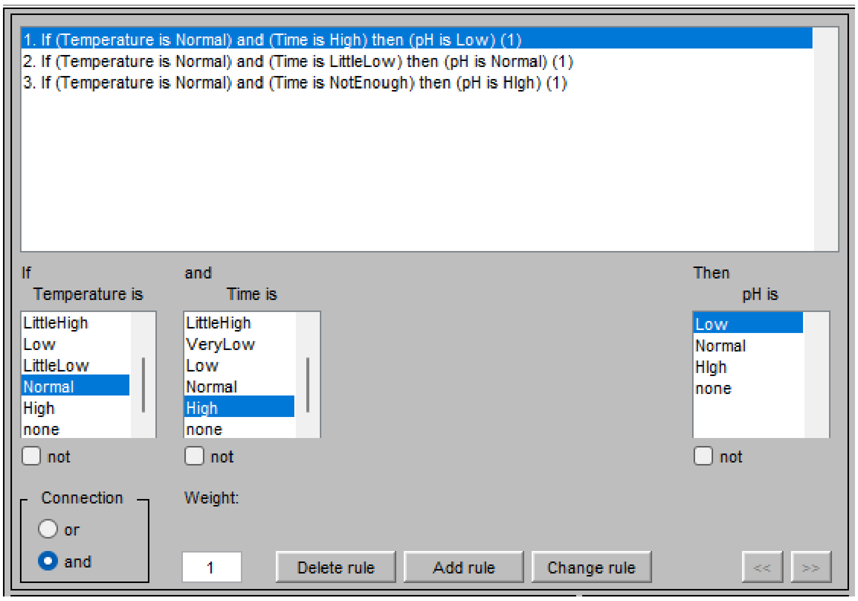


Figure 5 Fuzzy rule base of temperature and incubation time for the pH of yoghurt

Figure 5 Fuzzy rule base of temperature and incubation time for the pH of yoghurt shows the rules used in fuzzy modeling. There are three rules used, namely, if the incubation temperature is normal and the incubation time is high, it will produce a low pH. The second rule is if the incubation temperature is normal and the incubation time is low, it will produce a normal pH. The third rule is if the incubation temperature is normal and the incubation time is not enough, the resulting pH will be high or no fermentation occurs.

Table 5 Fuzzy rules

No.	Incubation Temperature	Incubation Time	pH Level
1.	Normal	High	Low
2.	Normal	Little low	Normal
3.	Normal	Not enough	High

The following are the rules that are used :

1. If “Temperature is Normal” and “Time is High” then “pH is Low”
2. If “Temperature is Normal” and “Time is LittleLow” then “pH is Normal”
3. If “Temperature is Normal” and “Time is NotEnough” then “pH is High”

Rules :

1. (µT_normal[43], µS_high[3,75]) = min(0.33,0) = 0.33
2. (µT_normal[43], µS_littlelow[3,75]) = min(0.33,0.75) = 0.33
3. (µT_normal[43], µS_notenough[3,75]) = min(0.33,0) = 0.33

5. Fuzzy Inference System

The fuzzy inference system in the figure shows the application of fuzzy logic in determining the temperature and incubation time conditions for the yoghurt fermentation process. The membership function (µ) is used to group the temperature and incubation time into fuzzy categories such as "normal," "high," "low," or "little low" based on the calculated membership degree values.

Incubation temperature

$$\mu T\_normal = \frac{x-a}{b-a}$$

$$\frac{43-42{,}5}{44-42{,}5} = \frac{0{,}5}{1{,}5}$$

$$= 0{,}33$$

Incubation time

$$\mu T\_high = 0$$

$$\mu T\_littelow = \frac{x-a}{b-a}$$

$$\frac{3-3}{4-3} = \frac{0{,}75}{1}$$

$$= 0{,}75$$

$$\mu\_notenough = 0$$

The actual temperature is 43°C in the range of 42.5°C to 44°C, the membership degree (µT_normal) obtained is 0.33, indicating that the temperature is close to the "normal" category. The slightly low incubation time is calculated using a similar method, resulting in a membership value of 0.75 for the actual time of 3 hours in the range of 3–4 hours, indicating that the time is close to the "slightly low" category. For other categories such as high temperature (µT_high) and insufficient time (µT_notenough), the membership value is 0, indicating that these conditions are not relevant. Through this calculation, the fuzzy system is able to determine how close the current condition is to the optimal category, helping in regulating fermentation so that the quality of yogurt is maintained.

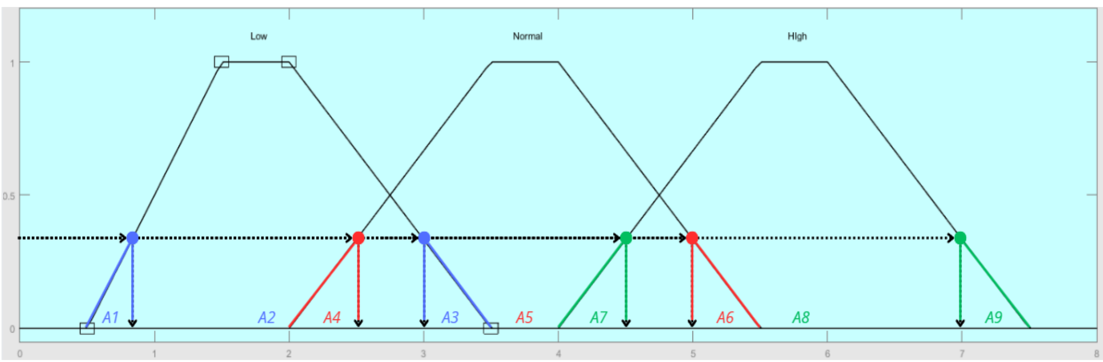
$$
\mu SF[Z]\begin{cases}
Low\begin{cases}
0, x \le 0,5\\
\dfrac{x-0,5}{1,5-0,5}, 0,5 \le x \le 1,5\\
1, 1,5 \le x \le 2\\
\dfrac{3,5-x}{3,5-2}, 2 \le x \le 3,5\\
0, 3,5 \le x
\end{cases}\\
Normal\begin{cases}
0, x \le 2\\
\dfrac{x-2}{3,5-2}, 2 \le x \le 3,5\\
1, 3,5 \le x \le 4\\
\dfrac{5,5-x}{5,5-4}, 4 \le x \le 5,5\\
0, 5,5 \le x
\end{cases}\\
High\begin{cases}
0, x \le 4\\
\dfrac{x-4}{5,5-4}, 4 \le x \le 5,5\\
1, 5,5 \le x \le 6\\
\dfrac{7,5-x}{7,5-6}, 6 \le x \le 7,5\\
0, 7,5 \le x
\end{cases}
\end{cases}
$$

$$
\mu SF[Z]\begin{cases}
Low\begin{cases}
0, x \le 0,5\\
x-0,5 \quad, 0,5 \le x \le 1,5\\
1, 1,5 \le x \le 2\\
2,33-0,67x \quad, 2 \le x \le 3,5\\
0, 3,5 \le x
\end{cases}\\
Normal\begin{cases}
0, x \le 2\\
0,67x-1,33, 2 \le x \le 3,5\\
1, 3,5 \le x \le 4\\
3,67-0,67x \quad, 4 \le x \le 5,5\\
0, 5,5 \le x
\end{cases}\\
High\begin{cases}
0, x \le 4\\
0,67x-2,67 \quad, 4 \le x \le 5,5\\
1, \; 5,5 \le x \le 6\\
5-0,67x \quad, 6 \le x \le 7,5\\
0, 7,5 \le x
\end{cases}
\end{cases}
$$

This figure shows fuzzy membership functions to group variables into three main categories: Low, Normal, and High. Each category has a different range of values and equations that determine the degree of membership at each range of values. For example, for the category "Low," the membership range varies between 0 and 3.5, with the function decreasing or increasing linearly with the value x. In the category "Normal," the membership range is from 2 to 5.5, where the membership values are mapped based on linear equations at the range. The category "High" has a membership range from 4 to 7.5, also with linear equations that determine the degree of membership.

6. **Defuzzification**

Moment Calculation



$$A1 = \frac{0{,}29\ x\ 0{,}33}{2} = 0{,}0462$$

$$A2 = 2{,}22 \text{ x } 0{,}33 = 0{,}7326$$

$$A3 = \frac{0{,}5\ x\ 0{,}33}{2} = 0{,}0825$$

$$A4 = \frac{0{,}5\ x\ 0{,}33}{2} = 0{,}0825$$

$$A5 = 2{,}5 \text{ x } 0{,}33 = 0{,}825$$

$$A6 = \frac{0{,}5\ x\ 0{,}33}{2} = 0{,}0825$$

$$A7 = \frac{0{,}5\ x\ 0{,}33}{2} = 0{,}0825$$

$$A8 = 2{,}5 \text{ x } 0{,}33 = 0{,}825$$

$$A9 = \frac{0{,}5\ x\ 0{,}33}{2} = 0{,}0825$$

$$M1 = 0$$

$$M2 = \int_{0,5}^{1,5} (x - 0{,}5)x\ dx = 0{,}5833$$

$$M3 = \int_{1,5}^{2} (1)x\ dx = 0{,}875$$

$$M4 = \int_{2}^{3,5} (2{,}33 - 0{,}67x)x\ dx = 1{,}82515$$

$$M5 = 0$$

$$M6 = 0$$

$$M7 = \int_{2}^{3,5} (0{,}67x - 1{,}33)x\ dx = 2{,}2611$$

$$M8 = \int_{3,5}^{4} (1)x\ dx = 1{,}875$$

$$M9 = \int_{4}^{5,5} (3{,}67 - 0{,}67x)x\ dx = 3{,}34845$$

$$M10 = 0$$

$$M11 = 0$$

$$M12 = \int_{4}^{5,5} (0{,}67x - 2{,}67)x\ dx = -6{,}15595$$

$$M13 = \int_{5,5}^{6} (1)x\ dx = 2{,}875$$

$$M14 = \int_{6}^{7,5} (5 - 0{,}67x)x\ dx = 3{,}2948$$

$$M15 = 0$$

Final Calculation

$$Z* = \frac{(M1+M2+M3+M4+M5+M6+\text{............}+M15)}{(A1+A2+A3+A4+A5+A6+A7+A8+A9)}$$

$$= \frac{10{,}78185}{2{,}8413}$$

$$= 3{,}7946$$

The figure illustrates the defuzzification process in yoghurt production to determine acidity based on temperature, time, and pH variables. Using the center of gravity method, a final crisp value of 3.7946 is calculated as the weighted average of fuzzy membership degrees. Temperature (43°C), time (3.75 hours), and pH (3.75) are represented by triangle or trapezoid graphs, showing their membership degrees. This crisp value indicates the yoghurt's acidity level, classified as low, medium, or high, based on fuzzy logic to derive a precise value from uncertain variables.

Interpretation of Defuzzification

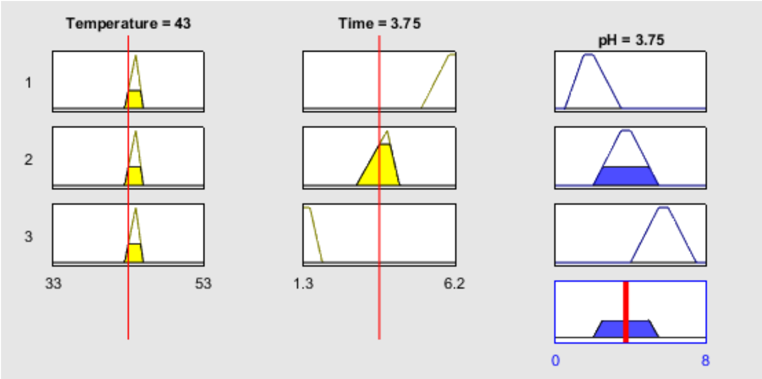


Figure 6 Matlab result calculation

Based on the figure 6, the calculation results using the Matlab method produce an incubation temperature value of 43 (temperature = normal), incubation time 3.5 H (time = Little low). So the results of the temperature and incubation time have an output value of pH 3.75 (pH = normal) in accordance with the rules.

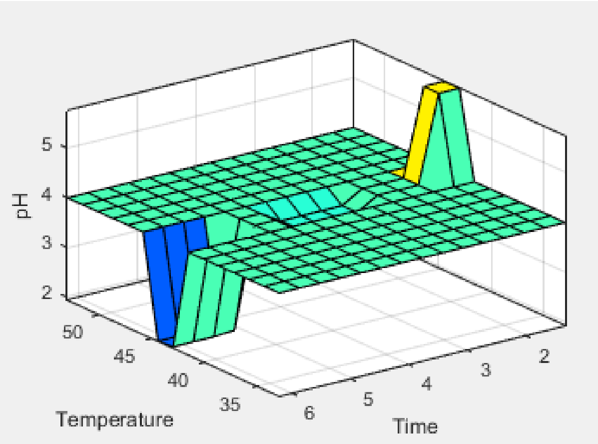


Figure 7 Matlab surface data result

CONCLUSION

This study succeeded in applying a fuzzy logic control model to maintain the pH quality of yogurt using temperature and incubation time parameters as the main variables. This model process begins with the selection of fuzzy rules and membership functions, which are developed based on a range of values for incubation temperature (33-53°C) and incubation time (0-7 hours). Each parameter was converted into a linguistic category, such as “Normal” or “High”, to facilitate data interpretation. The inference system uses the Mamdani method, with the Centroid method for defuzzification, producing consistent and stable pH values, which correspond to the desired quality parameters. The test results show that when the temperature is set at 43°C (the “Normal” category) and the incubation time is 3.5 hours (the “Little Low” category), the system produces a yoghurt pH of 3.75, which is in the “Normal” category according to the regulations set. This model not only helps in resolving input data uncertainty, but also improves the accuracy and efficiency of yogurt production control. This fuzzy model is effective to apply to automated yogurt production processes, because it is able to adapt in real-time to varying input conditions, making it an ideal solution for the food industry to achieve consistent quality standards.

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