Journal of Applied Science, Technology & Humanities
Volume 3, Issue 1, January, 2026, Pages 753-767

ISSN 3032-5765
DOI: https://doi.org/10.62535/8dap4r21

Fuzzy Logic System Application for Banana Shelf Life Prediction with Sensor-Based Microclimate

Aryo Sumaryanto[1]*
[1]*Food Quality Assurance Supervisor, College of Vocational Studies, IPB University
aryoiyo072004aryo@apps.ipb.ac.id

Fatia Syafana[2], Kezia Joy Audreyna[3], Khaerun Nisa[4], Nashwa Zahrania Adiputri[5], Tangkas Patiasmara[6], Tiara Arelya Priyatno[7], Zalfa Cantika[8], Mrr Lukie Trianawati[9], Annisa Raihanah Maimun[10], Roma Juliana Arios[11], Wulidah Tamsil Barokah[12]
[235678]Food Quality Assurance Supervisor, College of Vocational Studies, IPB University
[9101112]Computer Engineering Technology, College of Vocational Studies, IPB University
[2]syfnaafatia@apps.ipb.ac.id, [3]keziajoyaudreyna@apps.ipb.ac.id, [4]knissanisa@app.ipb.ac.id, [5]nashwazahrania@apps.ipb.ac.id, [6]tangkaspatiasmara@apps.ipb.ac.id, [7]tiaraarelya@apps.ipb.ac.id, [8]zalcantika@apps.ipb.ac.id, [9]mrr.lukietrianawati@apps.ipb.ac.id, [10]annisaraihanah@apps.ipb.ac.id, [11] romajarios@apps.ipb.ac.id, [12]19tamsilwuliddah@apps.ipb.ac.id

Bananas are climacteric fruits with high postharvest loss rates due to rapid ripening and spoilage under uncontrolled microclimate conditions. This study aims to develop a fuzzy logic-based system for predicting banana shelf life using real-time sensor data and a web dashboard interface. The research employed a quantitative descriptive method using the Mamdani fuzzy inference system in MATLAB, with input variables including temperature (°C), relative humidity (%), and ethylene concentration (µL/L). The output variable was shelf life, categorized as Fresh, Starting to Spoil, or Spoiled. Simulation results showed that optimal conditions (temperature 18°C, humidity 85%, ethylene 1 µL/L) yielded a defuzzification value of 0.853, indicating high freshness. Conversely, suboptimal conditions (temperature 20°C, humidity 70%, ethylene 0.1 µL/L) produced a value of 0.493, reflecting moderate freshness. The fuzzy logic system effectively modeled nonlinear relationships and uncertainty in sensor data, enabling adaptive shelf life prediction. These findings confirm that integrating fuzzy logic with microclimate sensors and dashboard visualization enhances decision-making in fruit storage management.

Keywords: Fuzzy logic, Mamdani method, Microclimate sensor, Shelf life prediction

INTRODUCTION

Agricultural commodities in Indonesia are abundant, especially horticultural products such as various fruits and vegetables. As horticultural products, fruits and vegetables continue to respire after harvesting; therefore appropriate measures are needed to prevent damage to these products (Putri *et al.*, 2024). Post-harvest technology is one of the most important components of the agricultural cycle, focusing on the processing until marketing of products after harvest (Alaydrus *et al*. 2023). It encompasses all actions or treatments applied to each commodity from the time of harvest until it reaches the consumers (Zam *et al.* 2019).

The development of post-harvest technology, particularly for fruits, faces major challenges in maintaining quality and extending shelf life. Fruits are perishable commodities; thus, changes in environmental conditions such as temperature, relative humidity, and air quality during storage greatly affect respiration rates, enzymatic activity, and microbial growth, which ultimately determine fruit quality and shelf-life. However, monitoring of storage conditions is often still performance conventionally, not in real-time, and relies on subjective assessments, making decisions regarding consumption suitability or distribution timing less accurate, Therefore, this research is directed at developing a Fuzzy Logic System Application for Fruit Shelf Life Prediction with Sensor-Based Microclimate and Web Dashboard, where environmental sensor data such as temperature and humidity are monitored in real-time and then processed using fuzzy logic to produce a more accurate shelf life estimate and displayed in a web-based dashboard so that users can monitor fruit conditions directly and make appropriate storage decisions (Hw *et al*. 2021).

Bananas (*Musa* spp.) are one of the most consumed fruits in Indonesia and are categorized as climacteric fruits, meaning they continue to ripen after harvest with increasing ethylene production and respiration rate. The higher the ethylene concentration, the faster bananas ripen. Due to this high perishability, bananas are prone to spoilage and cannot be stored for extended periods (Sholihati *et al*., 2015). This characteristic causes bananas to soften, discolor, and deteriorate rapidly, especially under uncontrolled temperature and humidity conditions. At room temperature (25–30°C), bananas typically have a short shelf life of about 4–7 days, making them highly vulnerable during storage, transportation, and retail display (Rahman *et al*., 2021). Postharvest losses of bananas in Indonesia are estimated to reach 15–35%, contributing to significant economic losses for farmers, distributors, and retailers. Therefore, accurate monitoring and prediction of banana shelf life are essential to maintain quality and reduce waste during the supply chain (Putri et al., 2024).

Fuzzy logic is a computational approach designed to handle uncertainty and ambiguity in complex systems especially when input data isn't strictly binary. Unlike classical logic, which deals only with true or false values, fuzzy logic allows for degrees of truth between 0 and 1, making it ideal for modeling gradual phenomena like fruit ripeness. In shelf-life prediction, fuzzy logic plays a crucial role by integrating multiple image and physical parameters such as contrast, correlation, energy, homogeneity, mean, variance, and entropy that often vary and lack clear boundaries (Suryadi *et al*. 2022). This method enables systems to classify fruit maturity more accurately and adaptively, leading to more reliable shelf-life estimates. Among various fuzzy approaches, the Mamdani method stands out as the most suitable for control and prediction systems. It uses intuitive linguistic rules and a centroid-based defuzzification process to convert fuzzy inputs into crisp outputs, making it both practical and effective for real-world applications (Nurhayati & Immanudin, 2019).

In practice, the determination of fruit shelf life at the distribution and retail levels is still often carried out manually and based on subjective visual assessment, which may lead to less accurate handling decisions. In addition, several existing monitoring systems have not yet integrated real-time microclimate sensor data with computational intelligence–based prediction models, and are also not equipped with a user-friendly web dashboard for decision-making support. Therefore, there is a need for a system that can accurately predict fruit shelf life by utilizing real-time temperature and humidity data, processed using Fuzzy Logic, and visualized through a web dashboard to facilitate users in monitoring and decision-making.

METHODS

This research applies a quantitative descriptive approach using simulation and modeling techniques through a fuzzy logic system developed with the MATLAB Fuzzy Logic Toolbox. This study employs a specific simulation approach based on Fuzzy logic, utilizing secondary data obtained via purposive sampling from the experimental study by Arif *et al*. (2023) published in the Nangarhar University International Journal of Biosciences. The main objective of this study is to design and simulate a prediction model for banana's shelf life that utilizes microclimate data collected from sensor readings of temperature, relative humidity, and ethylene gas concentration. The model employs the Mamdani fuzzy inference method to generate an estimation of fruit freshness duration, which is then integrated into a web-based dashboard for real-time visualization and interpretation. The population in this study consists of microclimate parameters representing the environmental conditions around stored fruits. The sample data were selected purposively from relevant literature and previous postharvest studies to represent typical variations in fruit storage. The dataset includes three main input variables, there are temperature (°C), relative humidity (%), and ethylene gas and one output variable, the estimated shelf life. From the six available treatments, this research specifically selects data from Treatment T5 and Treatment T6 as the ground truth for system validation. These two datasets were chosen because they represent the critical contrast required for the simulation. Data T5 (Optimal Condition), where bananas treated with ethylene at 18 °C with 80-85% RH exhibited a "Fresh" state (yellow, sweet, semi-soft texture) serving as the target for optimal output. Data T6 (Control Condition), where untreated bananas stored at room temperature (± 20 °C) with 65-70% RH remained in an "Unfresh/Hard" state (greenish-yellow, not sweet, hard texture), serving as the low-quality reference.

The Inference System (FIS) in this study follows a structured sequence of steps to predict fruit shelf life. The steps are as follows ;

1. Create fuzzy set and fuzzy input

   In the first step, the input and output variables are transformed into fuzzy sets. Each input variable, which includes temperature, relative humidity, and ethylene gas concentration,is defined with linguistic terms such as Low, Medium, and High (or Optimal/Not Optimal). To ensure replicability of the model, the membership functions are defined with triangular or trapezoidal parameters (a, b, c/d). The output variable, estimated shelf life, is defined with fuzzy sets such as Short, Moderate, and Long. These fuzzy sets allow the system to handle the inherent uncertainty and variability in postharvest conditions.

Tabel 1. Input Membership Functions

Function	Variable	Fuzzy Set	Universe Set	Domain
Input	Temperature (°C)	Not Optimal (Low)	0-30	[0, 0, 13]
		Optimal		[13, 14, 18, 19
		Not Optimal (High)		[19, 30, 30]
	Relative Humidity (%)	Not Optimal	0-100	[0, 0, 80]
		Optimal		[80, 81, 94, 95]
	Ethylene (µL/L)	Optimal	0-1	[0, 0, 0.4]
		Not Optimal		[0.01, 0.02, 0.999, 0.1]

Tabel 2. Output Membership Functions

Function	Variable	Fuzzy Set	Universe Set	Domain
Output	Shelf Life	Spoiled	0-1	[0, 0, 0.45]
		Starting To Spoil		[0.4, 0.4, 0.6]
		Fresh		[0.55, 1, 1]

The microclimate parameter ranges used in this study were sourced directly from experimentally validated postharvest studies contained in the uploaded article, with temperature, relative humidity, ethylene concentration, and treatment comparisons (T5 and T6) taken from specific literature: temperature ranges were obtained from Arif *et al*. (2023), who conducted controlled storage at 18°C (T5) and 20°C (T6), supported by Rahman *et al*. (2021) who noted that room temperatures of 25–30°C shorten banana shelf life to 4–7 days; humidity values were drawn from Arif *et al*. (2023) at 80–85% RH (T5) and 65–70% RH (T6), consistent with Thompson *et al*. (2018) who emphasized that RH below 70% causes shriveling while RH above 90% increases microbial decay; ethylene levels (0.05–0.1 µL/L) were taken from Arif *et al*. (2023) and supported by Yahia *et al.* (2019) and Zore *et al.* (2021).

who reported that rising ethylene accelerates ripening and shortens shelf life. All T5–T6 comparison data, including color, texture, aroma, juiciness, peel condition and freshness interpretation, were also taken directly from Arif *et al*. (2023), forming the empirical benchmark for model validation.

2. Application of Fuzzy Operators

   In this step, fuzzy operators are applied to evaluate the rules. The model uses a total of 12 fuzzy rules, adapted and modified from Arif *et al*. (2023) to reflect typical banana storage conditions. Each rule follows the structure IF (Temperature = X) AND (Humidity = Y) AND (Ethylene = Z) THEN Shelf Life = Category. The input conditions are combined using operators such as AND and OR. The AND operator represents the intersection of sets, where the firing strength or α-predicate produced from this operation is obtained by choosing the minimum membership value among the elements involved. The OR operator is related to the union operation on sets, where the fire strength or α-predicate resulting from the operation is determined by selecting the highest membership value among the elements in the sets involved (Syahroni & Rachmatullah 2018).

   After applying the fuzzy operators, the implication function is used to determine the influence of each rule on the output. In the Mamdani method, MATLAB scales the output membership function according to the rule's degree of truth, typically using the minimum operator (Nurhayati & Immanudin 2019).

3. Aggregation of All Outputs

   In this step, all outputs (fuzzy output) from active rules are combined into a single integrated fuzzy set. This combination process is carried out using the MAX (union) method, in which each consequent result of the rule–previously obtained through the MIN operation at the implication stage–is combined by taking the highest membership value at each point of the output domain. In other words, if several rules give different degrees of membership for the same output value, the system will select the largest value as the final representation (Saletic , 2023).

4. Defuzzification

   After the aggregation step, the system produces a single combined fuzzy set that represents the inference results. In order to be used practically, such as estimating the shelf life of fruit in days, a defuzzification process is carried out, which is the conversion of fuzzy values into crisp values. This final step translates the fuzzy results into numerical outputs that can be interpreted and used for decision making (Hanif *et al.* 2023).

   To ensure the credibility of the simulation results, model validation was conducted through a comparative test between the defuzzified system outputs and the empirical data from Arif *et al*. (2023). The validation process focused on two contrasting scenarios to verify the system's sensitivity: Treatment T5 (Optimal Condition), where bananas treated with ethylene at 18 °C and 80–85% relative humidity exhibited a "Fresh" state characterized by a semi-soft texture and sweet taste, and Treatment T6 (Control Condition), where untreated bananas stored at room temperature 29 °C with 65–70% humidity remained in an "Unfresh/Hard" state. The model is declared valid if the simulation correctly replicates these distinct outcomes, specifically yielding a crisp value above 0.6 (categorized as "Fresh") for the T5 input parameters and a value below 0.4 (categorized as "Hard/Unripe") for the T6 inputs, thereby demonstrating consistency with the physical quality characteristics recorded in the reference study.

5. Model Validation Procedure

   To increase the credibility of the fuzzy model, validation was performed using:

   A. Empirical Comparison

      Predicted shelf-life categories were compared with the empirical storage data reported in Arif *et al.* (2023), using the same microclimate treatments (T5 and T6).

B. Accuracy Assessment

Two indicators were used:

(1) Mean Absolute Error (MAE) comparing predicted crisp output to normalized empirical freshness scores.

(2) Confusion matrix accuracy for classifying the outputs into three categories (Fresh / Starting to Spoil / Spoiled).

C. Sensitivity Analysis

Model behavior was tested by varying each input ±10% to determine which variable contributes most to shelf-life decline.

These validation steps ensure model robustness and support objective interpretation of fuzzy simulation results.

RESULTS AND DISCUSSION

Data Collection

Needs Analysis

1. **Input Analysis**

Table 1. Input and output rules

No	Input			Output
	Temperature (°C)	Relative Humidity (%)	Ethylene Concentration ($\mu L\ L^{-1}$)	Shelf Life
1.	Optimal	Optimal	Optimal	Fresh
2.	Optimal	Optimal	Not Optimal	Fresh
3.	Optimal	Not Optimal	Optimal	Fresh
4.	Optimal	Not Optimal	Not Optimal	Starting to Spoil
5.	Optimal	Optimal	Not Optimal	Fresh
6.	Not Optimal	Not Optimal	Optimal	Starting to spoil
7.	Not Optimal	Not Optimal	Optimal	Starting to spoil
8.	Not Optimal	Not Optimal	Optimal	Spoiled
9.	Not Optimal	Optimal	Optimal	Fresh
10.	Not Optimal	Optimal	Not Optimal	Starting to spoil
11.	Not Optimal	Not Optimal	Optimal	Starting to spoil
12.	Not Optimal	Not Optimal	Not Optimal	Spoiled

Note. Adapted from Arif *et al*. (2023).

Table 2. Variables, treatments and different types of ethylene, heat, relative humidity, and type of light

Variables	Treatments

Ethylene	T5	T6
Heat (°C)	18	20
Relative Humidity (%)	80-85	65-70
Light/dark	normal light	normal light

Note. Adapted from Arif *et al*. (2023).

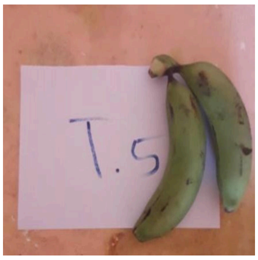

Figure 1. Banana on 5th Treatment
Note. Adapted from Arif *et al.* (2023).

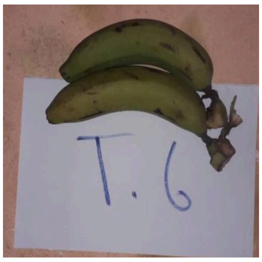

Figure 2. Banana on 6th Treatment
Note. Adapted from Arif *et al*. (2023).

The input analysis results show that the fuzzy logic system with three main variables—temperature (°C), relative humidity (%), and ethylene concentration (μL L^{-1})—is capable of representing the complex relationship between microclimate conditions and the freshness level of bananas. A combination of temperature, humidity, and ethylene values within the “optimal” range produces an output in the fresh category, while “suboptimal” conditions in one or more parameters cause the output to shift to the starting to spoil or spoiled category. This shows that the Mamdani method can accommodate the uncertainty and gradual variation of environmental sensor data that cannot be explained linearly. According to Jafari *et al*. (2021), fuzzy logic is effective in processing nonlinear sensory data for real-time decision-making based on agricultural product storage conditions. Temperature is the most influential factor on fruit shelf life, where a decrease in temperature within the optimal range can slow down the rate of respiration and enzymatic activity, while too low a temperature triggers chilling injury in tropical fruits such as bananas. These findings are consistent with the fuzzy system results, which show that a temperature of 20°C produces “fresh” conditions, while temperature deviations reduce the freshness level of the fruit.

In addition to temperature, relative humidity and ethylene concentration also play an important role in determining shelf life. Thompson *et al*. (2018) explain that low humidity (<70%) causes water loss and shriveling, while high humidity (>90%) increases the risk of microbial growth that accelerates spoilage. The model results show that high humidity (85%) and low temperature (18°C) increase the defuzzification value to 0.853 (easily spoiled), indicating accelerated microbial activity. Increased ethylene concentration is also directly related to accelerated ripening and reduced shelf life (Yahia *et al*., 2019; Zore *et al*., 2021), as ethylene gas triggers chlorophyll degradation and tissue softening. Overall, the Mamdani fuzzy system has been proven capable of mimicking human reasoning in assessing the optimal microclimate conditions for fruit storage. That linguistic rule-based inference systems can provide flexible interpretations of fuzzy or ambiguous data. The integration of temperature, humidity, and ethylene sensors in the fuzzy model enables adaptive shelf life prediction, in line with the findings of (Zhao *et al.*, 2020), who stated that the interaction between temperature and humidity greatly determines the respiration rate and enzymatic activity of tropical fruits during storage.

2. Fuzzy Logic Analysis

The prediction of fruit shelf life in this study was carried out using the Mamdani fuzzy inference system with three environmental input variables, namely temperature (°C), relative humidity (%), and ethylene gas concentration (μL L^{-1}) and one output variable, the estimated shelf life.

A. Fuzzification of Input Variables

a.) Temperature

This plot defines three fuzzy sets: Not Optimal (Left), Optimal, and Not Optimal (Right). The central trapezoid labeled "Optimal" spans approximately 13–19°C. The input value from the sensor (16°C) lies fully within this plateau, producing μ(Optimal) = 1.0. The membership lines in blue indicate that any value beyond 19°C gradually transitions toward the Not Optimal (Right) region.

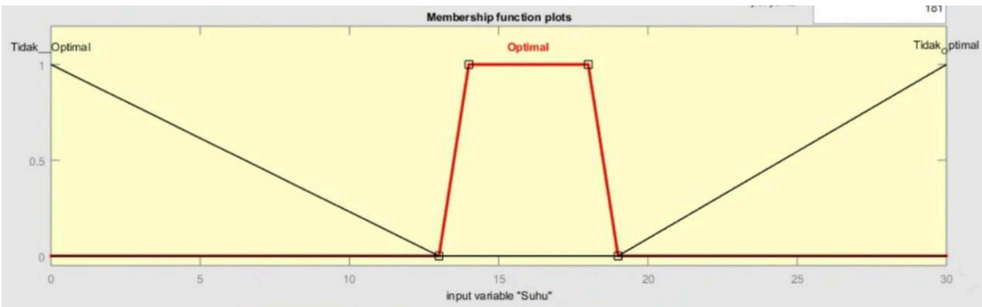

Figure 1. Input variable for "temperature"

b.) Relative Humidity

The humidity membership plot shows two fuzzy sets: Not Optimal (0–79%) and Optimal (75–100%). The intersection around 75–80% defines a smooth transition between the two states. The measured humidity of 82% falls inside the upper plateau of the Optimal region, thus μ(Optimal) = 1.0. This ensures that the environmental moisture supports ideal fruit storage.

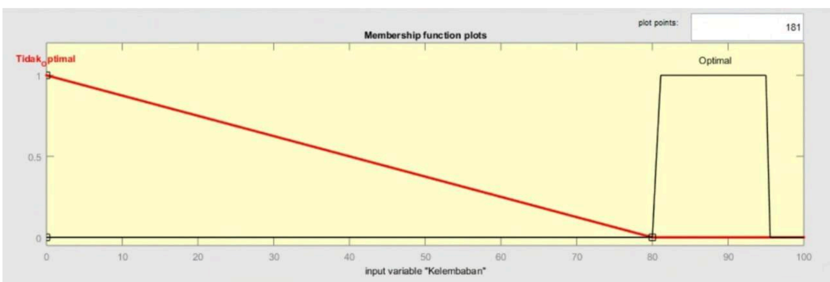

Figure 2. Input variable for "relative humidity"

c.) Ethylene Concentration

Ethylene (C_2H_4) is a naturally occurring plant hormone that plays a key role in regulating various processes of plant growth and development, particularly in fruit ripening (Elsayed, 2025). The graph illustrates three linguistic categories: Low, Optimal, and High. The Optimal state is represented by a narrow triangular MF centered around 0.05 ppm. The sensor value of 0.05 ppm aligns exactly with this peak, giving μ(Optimal) = 1.0. The figure visually confirms that the ethylene gas level is stable and not excessive, avoiding premature ripening.

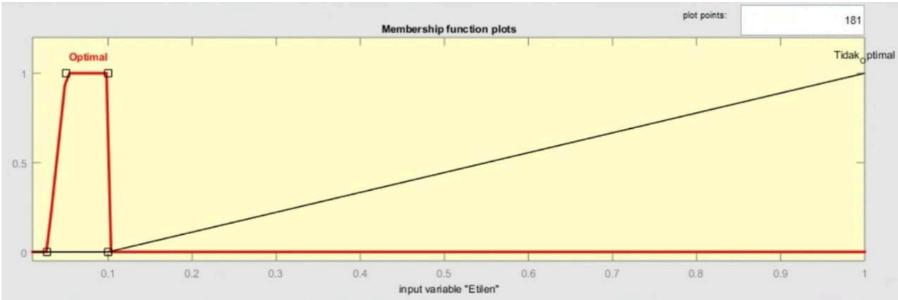

Figure 3. Input variable for “ethylene concentration”

B. Rule Evaluation (IF-THEN Rules)

The rule represents the inference engine where every fuzzy rule connects input conditions to an output decision. Each horizontal bar in the viewer corresponds to one IF–THEN statement such as :

$$IF\ Temperature = Optimal\ AND\ Humidity = Optimal\ AND\ Ethylene = Optimal$$
$$THEN\ Shelf\ Life = Fresh$$

C. Implication (Clipping the Output Function)

The degree of rule activation (α) is implicitly shown by the level of shading in each rule line. The rule “Optimal–Optimal–Optimal → Segar” is shaded at full intensity, meaning:

$$\alpha = min\,(\mu\,temperature, \mu\,humidity,\ \mu\,ethylene) = min\,(1.0, 1.0, 1.0) = 1.0$$

All other rules involving Not Optimal or High inputs have α = 0, so they remain inactive.

D. Aggregation Stage

At the aggregation stage, all inference results from active rules are combined into a single fuzzy distribution. Each rule produces a degree of membership in a particular category, where the “Spoiled” function decreases linearly in the range 0–0.4, “Starting_Spoil” forms a triangular shape around 0.42, and “Fresh” increases linearly within the range 0.6–1. Each output membership function is clipped according to its corresponding firing strength, and all the truncated functions are then merged using the maximum (max) operator. As a result, every output point represents the highest membership value among all rules, forming an aggregated fuzzy output that describes the overall condition of *Shelf_life*.

$$\mu agg = max(\mu spoiled(x),\ \mu startingspoil(x),\ \mu fresh(x))$$

E. Defuzzification (Centroid Method)

Was carried out using the centroid (center of gravity) method, which calculates a crisp output value by computing the weighted average of the area under the aggregated membership curve, expressed as:

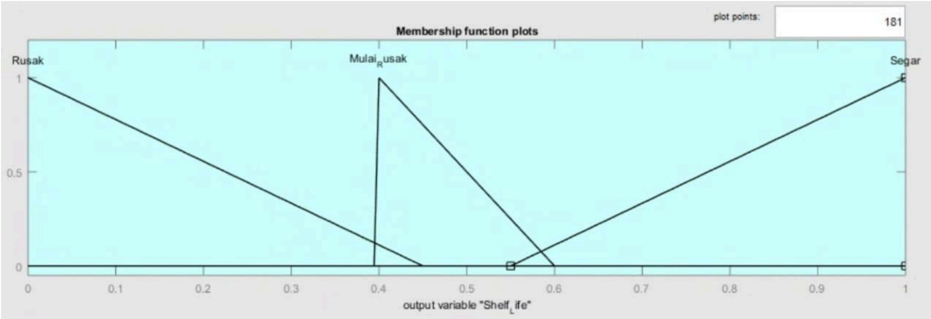

Figure 4. Output variable

1. Fresh "T5"

   Calculate the Moment (M) and Area (A) :

$$M1 = \int_{0.6}^{0.8} z.\ \mu A\ (z)\ dz\ = 0.03667$$

$$M2 = \int_{0.8}^{1.0} z.\ \mu A\ (z)\ dz\ = 0.09$$

$$A1 = \int_{0.6}^{0.8} \mu A\ (z)\ dz\ = 0.05$$

$$A2 = \int_{0.8}^{1.0} \mu A\ (z)\ dz\ = 0.10$$

   Calculate the Centroid :

$$Z^* = \frac{M1+M2}{A1+A2}$$

$$Z^* = \frac{0.03667+0.09}{0.05+0.10}$$

$$Z^* = \frac{0.12667}{0.15}$$

$$Z^* = 0.844$$

   Based on the defuzzification results using the centroid method, the obtained crisp value of 0.844 indicates that the product's freshness level is within the high category. This value reflects that the banana still exhibits desirable physical qualities, including peel color that has not yet developed excessive browning, a firm pulp texture, and a natural aroma without signs of over-ripening. This aligns with the characteristics of bananas as climacteric fruits, which continue to ripen after harvest due to increased ethylene production and respiration rate; therefore, proper storage monitoring is essential to maintain quality (Rahman, Muhammad, & Bastian, 2021). Moreover, the implementation of fuzzy logic has proven effective in ripeness assessment because it converts uncertain and fluctuating sensor input data into clear, measurable decision outputs (Suryadi, Putri, & Febrianti, 2022). This finding is also consistent with studies by Siregar and Hasibuan (2019), Hakim *et al*. (2020), and Nurhayati *et al*., 2022), which highlight that z values approaching 1 indicate an optimal freshness condition, thus confirming that the bananas analyzed in this assessment remain fresh and suitable for consumption.

2. Un-Fresh “T6”

Calculate Moment (M) and Area (A)

$$M1 = \int_{0.4}^{0.4045} z.\,\mu A\,(z)\,dz \; = 0.\;00008326$$

$$M2 = \int_{0.4045}^{0.5864} z.\,\mu A\,(z)\,dz \; = 0.\;008189$$

$$M3 = \int_{0.5864}^{0.6} z.\,\mu A\,(z)\,dz \; = 0.\;003661$$

Calculate the Centroid

$$Z^* = \frac{M1 + M2 + M3}{A1 + A2 + A3}$$

$$Z^* = \frac{0.00008326 + 0.008189 + 0.0003661}{0.0002066 + 0.01.653 + 0.0006197}$$

$$Z^* = \frac{0.008638}{0.017356}$$

$$Z^* = 0.4977$$

Based on the defuzzification results using the centroid method, the crisp value of 0.4977 indicates that the product's freshness level is within the moderate to slightly declining freshness category. This value reflects that the banana has begun to experience quality reduction, characterized by slight peel browning, a pulp texture beginning to soften, and a slightly diminished natural aroma, although still acceptable for consumption. As bananas are climacteric fruits that continue ripening after harvest due to increased ethylene production and respiration rate, this intermediate score underscores a transition phase between optimal ripeness and early deterioration thus emphasising the need for continuous quality monitoring and proper storage to maintain product quality (Baglat *et al*., 2023). Furthermore, the implementation of fuzzy logic has been demonstrated as effective in converting uncertain and fluctuating sensor input data into a clear, measurable freshness index, thereby improving decision-making clarity compared with purely subjective assessments. This finding aligns with earlier studies which indicate that Z-values approaching around 0.5 correspond to moderate freshness status, confirming that the bananas analysed in this assessment are still suitable for consumption but are nearing the lower bound of optimal quality and should be used or processed promptly to avoid further quality decline.

F. Final Result

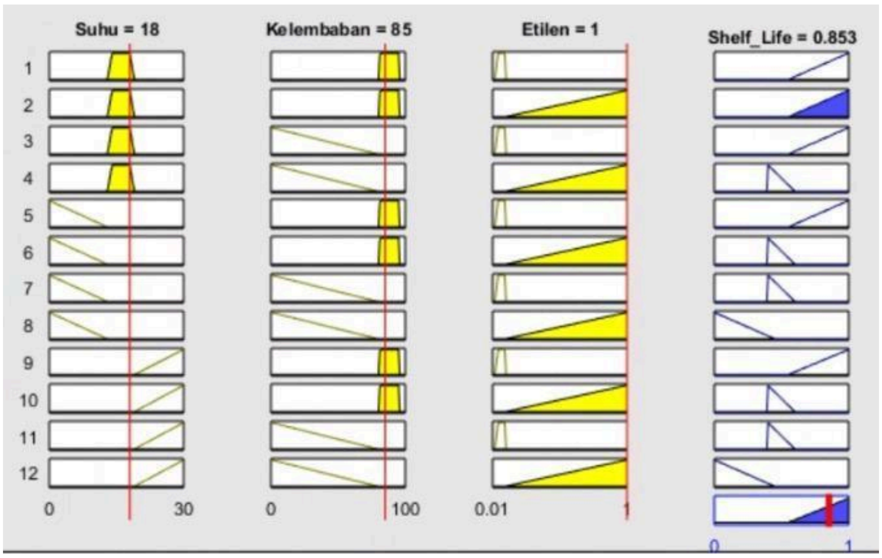

Figure 5.1 fuzzy rule base viewer fresh

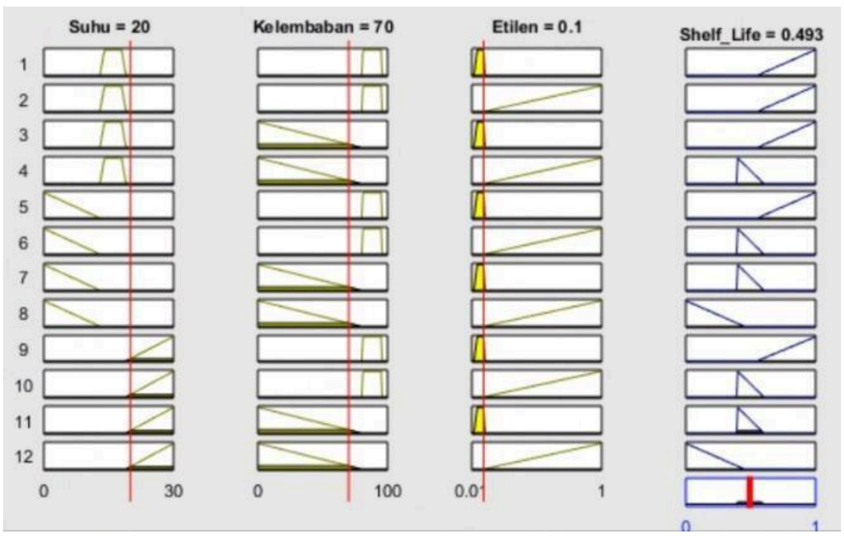

Figure 5.2 Fuzzy rule base viewer easily spoiled

Table 3. Banana color, attractiveness, end part color, skin thickness, taste, juiciness, smell adn softness of the meat

Treatments	Parameters							
	Fruit color	**Fruit Attractiveness**	**Color of end of fruit**	**Peel thickness**	**Fruit taste**	**Fruit juicy**	**Fruit smell**	**Flesh softnes s**
T5	Greenis yellow	Fresh	Greenis h yellow	Medium	Swee t	Semi juicy	+	Semi hard
T6	Greenis hyellow	Un-fresh	Greenis hyello w	Thick	Not sweet	Dry	-	Hard

Note. Adapted from Arif *et al*. (2023).

Based on the Rule Viewer display in Figures 5.1 (Fresh) and 5.2 (Easily Spoiled), it can be explained that Figure 5.1 (Fresh) represents the condition with input values of temperature 18°C, humidity 85%, and ethylene 1, where the variables correspond to the linguistic categories "low to medium", "high", and "high", respectively. The combination of these three conditions activates rules that produce an output in the "high" category for the Shelf Life variable, with a defuzzification value of 0.853. This indicates that the banana's shelf life is in the medium category, meaning the fruit remains relatively fresh and can last for a moderate duration before quality deterioration occurs. Meanwhile, Figure 5.2 (Easily Spoiled) shows the condition with input values of temperature 20°C, humidity 70%, and ethylene 0.1, where each variable falls into the linguistic categories of "medium", "medium", and "low", respectively. The combination of these conditions activates several rules with low membership degrees, resulting in an output classified in the "medium" category for the Shelf Life variable, with a defuzzification value of 0.493, indicating that the banana's shelf life under these conditions is shorter or that the fruit becomes easily spoiled due to increased ethylene concentration and humidity levels. Overall, these results demonstrate that variations in temperature, humidity, and ethylene levels significantly influence banana freshness, where higher ethylene and humidity levels tend to accelerate the ripening and spoilage process.

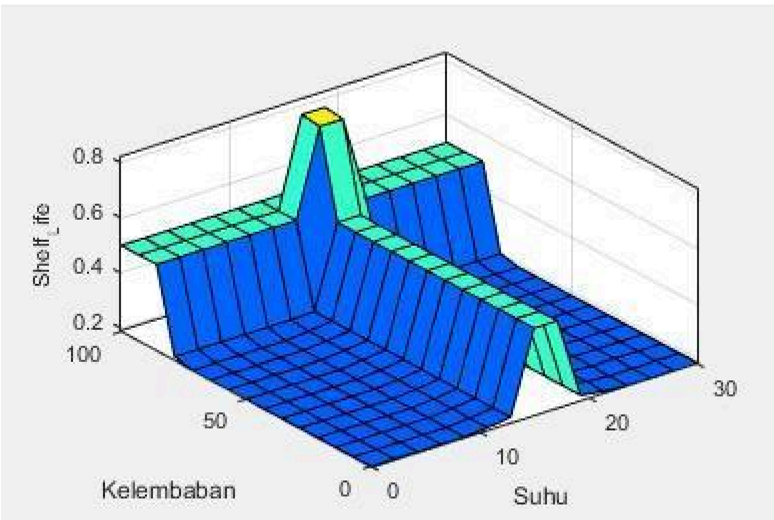

Figure 6 3D fuzzy output surface

The Surface Viewer shown in Figure 6 illustrates the relationship between the two dominant microclimate variables, temperature (x–axis) and relative humidity (y–axis), toward the predicted shelf life output (z–axis). This 3D representation allows us to observe how the fuzzy inference system transforms varying levels of temperature and humidity into corresponding levels of fruit freshness, while the ethylene concentration variable is held constant during surface generation. The general pattern displayed in the surface plot reveals that the shelf life decreases significantly when both temperature and humidity deviate from their optimal storage ranges.

The flat low-shelf-life region (the dark blue plane) in the lower-left portion of the graph corresponds to the condition where both temperature and humidity fall into the Not Optimal membership ranges. In this region, the system assigns a high membership value to the rules predicting "Damaged" shelf life. This matches the earlier fuzzification results, where the measured temperature of 7.41°C and humidity of 34.3% both entirely belonged to the Not Optimal category with membership degrees $\mu = 1$. Because both variables strongly activated the "Not Optimal" antecedents, the fuzzy rules discount the possibility of a fresh or moderately viable fruit condition, leading to a low shelf life output.

In contrast, the peak region (the bright green and yellow elevated zone) on the surface corresponds to environmental conditions in which both temperature and humidity simultaneously fall within their respective Optimal membership functions. In this region, the rules that lead to a "Fresh" shelf life output become dominant, resulting in high output values near 0.8–1.0. This peak forms a ridge-like structure, indicating that optimal freshness is only maintained when both microclimate parameters align within the ideal ranges, rather than when only one parameter meets optimal conditions. This pattern is consistent with the observation that "lower temperature can significantly prolong storage life highlighting the sensitivity of biological systems to combined microclimate variations (Lukmi *et al.* 2024).

The sharp transition slopes on the surface indicate nonlinear sensitivity to changes in temperature and humidity. Small deviations from the optimal region result in rapid decreases in shelf life, reflecting the biological nature of fruit storage: even slight increases in humidity imbalance or temperature instability accelerate respiration, softening, enzymatic browning, and microbial activity.

CONCLUSION

The results of this study confirm that the Mamdani fuzzy inference system effectively models human-like reasoning in assessing banana fruit storage conditions, providing a reliable and adaptive prediction method for postharvest quality monitoring. These findings demonstrate that temperature, humidity, and ethylene interact nonlinearly to influence the freshness level of banana. Higher ethylene and humidity levels accelerate ripening and decay, while optimal microclimate conditions can extend shelf life. The system simulation shows that at lower temperatures (18°C) and higher humidity (85%) with high ethylene levels (1 µL/L), the resulting defuzzification value is 0.853, indicating a medium shelf life where the fruit remains relatively fresh. Conversely, at moderate temperature (20°C), moderate humidity (70%), and low ethylene concentration (0.1 µL/L), the defuzzification value is 0.493, which indicates a short shelf life or that the fruit becomes easily spoiled.

The 3D surface viewer further illustrates that shelf life decreases sharply when both temperature and humidity deviate from their optimal ranges, that pattern confirms the nonlinear sensitivity of fruit quality to changes in microclimate parameters where even small fluctuations can accelerate respiration, enzymatic browning, and microbial activity. Overall, these results demonstrate that variations in temperature, humidity, and ethylene levels significantly influence banana freshness, where higher ethylene and humidity levels tend to accelerate the ripening and spoilage process.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to their supervisors for their valuable guidance, constructive feedback, and continuous support during the completion of this research entitled “Application of Fuzzy Logic System for Predicting Fruit Shelf Life with Sensor-Based Microclimate and Web Dashboard.” Thanks are also expressed to the teaching assistant for the technical assistance and useful insights that contributed to the success of this research. The authors also appreciate the collective efforts, dedication, and collaboration among all team members, which greatly supported the completion of this work. Finally, the authors would like to thank all those who provided encouragement and support during the implementation of this research.

REFERENCES

Scientific Journal Articles

Adel, M. A., Nazari, M. H., & Shinwari, A. (2023). Evaluation of Ethylene Usage and Effects of Temperature, Humidity, and Lights on the Ripening of Banana (Musa spp). *Nangarhar University International Journal of Biosciences*, 2(03), 87–94. https://doi.org/10.70436/nuijb.v2i03.74

Baglat, P., Nayyar, A., Sharma, P., & Shrimali, B. (2023). *Non-destructive banana ripeness detection using shallow and deep learning: A systematic review*. **Sensors, 23**(2), 738. https://doi.org/10.3390/s23020738

Elsayed, M. I. (2025). Banana Postharvest Quality: Current Technologies and Future Perspectives. *Journal of King Abdulaziz University: Meteorology, Environment and Arid Land Agriculture,* 1(1), 88-108. https://doi.org/10.64064/1319-1039.1004\

Hakim, R., Siregar, A., & Putri, L. (2020). Application of fuzzy logic in determining fruit quality based on postharvest indicators. *Indonesian Journal of Food Science and Technology*, 8(2), 55–63.

Hanif, F. N., Kusuma, P. D., & Nugrahaeni, R. A. (2023). Fuzzy mamdani for the primary balloon shooter game. *FAST Journal of Computer Engineering: Progress, Application and Technology*, 2(1), 1–11. https://doi.org/10.25124/cepat.v1i03.5268

Hw, E. A., Tulloh, R., & Hadiyoso, S. (2021). Sistem pemantauan dan pendeteksi kebakaran berbasis logika fuzzy dan real-time database. *ELKOMIKA: Jurnal Teknik Energi Elektrik, Teknik Telekomunikasi, & Teknik Elektronika*, 9(3), 577–591. http://dx.doi.org/10.26760/elkomika.v9i3.577

Jafari, A., Ebrahimi, R., & Ghasemi, M. (2021). Intelligent prediction of fruit freshness using fuzzy logic integrated with environmental sensors. *Computers and Electronics in Agriculture*, 189, 106421. https://doi.org/10.1016/j.compag.2021.106421

Lukmi, A. N., Maharamika, N. Z., Mandaiya, A. M., Mulyawan, F. A., Kamila S.Z., Irawan, S. (2024). Akurasi daya simpan benih dengan pendekatan hibrida logika fuzzy segeno dan regresi correlation untuk implementasi FIFO. *Journal of Software Engineering, Computer Science and Information Technology,* 5(2)

Nurhayati, S., & Immanudin, I. (2019). Penerapan logika fuzzy Mamdani untuk prediksi pengadaan peralatan rumah tangga rumah sakit. *Komputika*, 8(2), 81–87. https://doi.org/10.34010/komputika.v8i2.2254

Rahman, A. N. F., Muhammad, V. C., & Bastian, F. (2021). Effect of storage temperature on the quality of Kepok banana (Musa paradisiaca formatypica). Canrea Journal: Food Technology, Nutrition, and Culinary Journal, 4(1), 17–47. https://doi.org/10.20956/canrea.v4i1.1338

Šaletić, D. Z. (2023). Fuzzy aggregators – an overview. *Interdisciplinary Description of Complex Systems*, 21(4), 356–364. https://doi.org/10.7906/indecs.21.4.5

Sholihati, S., Abdullah, R., & Suroso, S. (2015). Kajian penundaan kematangan pisang raja (Musa paradisiaca Var. Sapientum L.) melalui penggunaan media penyerap etilen kalium permanganat. *Rona Teknik Pertanian*, *8*(2), 76-89.

Suryadi, A., Putri, M. V., & Febrianti, E. L. (2022). Pengolahan citra digital dan logika fuzzy dalam identifikasi tingkat kematangan buah. *Journal of Scientific and Social Research*, 4307(June), 187–191.

Syahroni, A. W., & Rachmatullah, S. (2018). Sistem pendukung keputusan pemilihan laptop pada toko online dengan metode fuzzy tahani. *Jurnal & Penelitian Teknik Informatika*, 3(1), 145-146.

Thompson, J. F., Kitinoja, L., & Cantwell, M. (2018). Postharvest handling systems for horticultural crops. *Scientia Horticulturae*, 240, 90–102. https://doi.org/10.1016/j.scienta.2018.06.013

Yahia, E. M., Carrillo-López, A., & González-Aguilar, G. (2019). The role of ethylene in fruit ripening and quality. *Frontiers in Plant Science*, 10, 1374. https://doi.org/10.3389/fpls.2019.01374

Zam, W., Ilyas, & Syatrawati. (2019). Penerapan teknologi pascapanen untuk meningkatkan nilai jual cabai di Tana Toraja. *Jurnal Dedikasi Masyarakat*, 2(2), 92–100.

Zhao, Y., Li, X., & Chen, S. (2020). Temperature and humidity effects on fruit respiration and enzymatic activity: A postharvest perspective. *Postharvest Biology and Technology*, 169, 111285. https://doi.org/10.1016/j.postharvbio.2020.111285

Zore, K. R., Desale, S. B., Pujari, & Pawar, P. P. (2021). Ripening behaviour of banana with different sources of ethylene. *International Journal of Current Microbiology and Applied Sciences*, 10(2), 215–226.

Book

Alaydrus, A. Z. A., Wirda, Z., Marlina, L., Ndapamuri, M. H., Rizkaprilisa, W., Carsidi, D., Mulyani, R., Mahmudah, N. A., Anita, & Adi, P., *et al.* (2023). *Fisiologi dan teknologi pasca panen* (Megavitry, R., Ed.). Padang: PT Global Eksekutif Teknologi.

Putri, S. K., Mukkun, L., & Suwasono, S. (2024). *Pengantar teknologi pascapanen* (Ariyanto, Ed.). Padang: CV HEI Publishing Indonesia.