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Fuzzy Logic Approach to Determine Apple Maturity for Harvesting Decision

Muhammad Rafi Andika Wijaya[1]
[1]Food Quality Assurance Supervisor, College of Vocational Studies, IPB University
rafiandikawijaya@apps.ipb.ac.id

Anindya Salsabila Hamdani Putri[2], **Ayu Nur Fadhila**[3], **Fional Alvina Nirmala Putri**[4], **Nisrina Fatin Nadra**[5], **Putri Nurbaiti**[6], **Senja Surya Gama**[7], **Syadza Afifah Nuri**[8], **Mrr Lukie Trianawati**[9], **Annisa Raihanah Maimun**[10], **Wuliddah Tamsil Barokah**[11], **Roma Juliana Arios**[12]
[23456789] Food Quality Assurance Supervisor, College of Vocational Studies, IPB University
[101112] Computer Engineering Technology, College of Vocational Studies, IPB University
[2]shpanindya@apps.ipb.ac.id, [3]ayfadhilanur@apps.ipb.ac.id[4]fionalalvina@apps.ipb.ac.id,
[5]nisrinafnadra@apps.ipb.ac.id, [6]putrinurbaiti@apps.ipb.ac.id, [7] senjasuryagama@apps.ipb.ac.id,
[8]sy_dzaanuri@apps.ipb.ac.id, [9]mrrlukietrianawati@apps.ipb.ac.id, [10]annisaraihanah@apps.ipb.ac.id,
[11]19tamsilwuliddah@apps.ipb.ac.id, [12]romajarios@apps.ipb.ac.id

ABSTRACT

This study aims to develop a fuzzy logic–based system for determining the maturity level of Anna apples as a basis for harvest decision-making. Five key parameters were used as input variables: Flesh Firmness (FF), Soluble Solid Content (SSC), Starch Pattern Index (SPI), Total Acidity (TA), and Hue°, with one output variable representing the maturity level (unripe, ripe, and overripe). The research employed a literature review method with a qualitative descriptive approach by collecting data from scientific journals and relevant documents discussing apple maturity and the application of fuzzy logic in agriculture. Data analysis was conducted using MATLAB through processes including fuzzification, formulation of If–Then rules, Mamdani inference, and defuzzification to produce a crisp output value representing apple maturity. The results indicate that the fuzzy logic system effectively models apple maturity parameters and provides accurate, objective, and efficient decisions compared to conventional subjective methods. The application of fuzzy logic offers a non-destructive classification method that assists farmers in determining the optimal harvest time, improving post-harvest quality, and maintaining product consistency.

Keywords: Apple maturity, Fuzzy logic, MATLAB, Fruit quality, Decision-making.

INTRODUCTION

Apples (Malus domestica) are one of Indonesia's valuable biological resources and leading horticultural commodities that grow well in highland areas such as Batu City, Malang, and their surroundings. The cultivation of apples in Indonesia began during the Dutch colonial period, but commercial production only started in the 1960s following the discovery of an artificial defoliation technique. The development of the apple industry advanced further with the introduction of leaf-pruning and branch-bending technologies, which allowed farmers to control fruiting periods according to planting schedules. Leaf pruning serves as an artificial substitute for low-temperature exposure, a key requirement for breaking dormancy in plants originating from temperate climates (Anggara, D.S.T., et al., 2017). In general, apple trees can bear fruit twice a year, and their cultivation is both technically feasible and economically profitable (Fadilah, R., et al., 2024).

Despite its potential, apple cultivation in Indonesia faces several significant challenges, including price fluctuations, low fruit quality, and weak competitiveness compared to imported apples. Although Malang City has approximately 292,500 apple trees producing a total annual yield of 11,375 tons, productivity remains relatively low at around 38 kg per tree. Apple quality is highly dependent on proper harvesting and post-harvest handling. Apples harvested 113–120 days after flowering typically have a shelf life of 3–4 weeks, whereas those picked at 127–141 days only last 1–2 weeks, as indicated by wrinkled skin. This demonstrates that harvest timing significantly influences the storage duration and overall quality of the fruit (Maya Cholidah, 2017).

During storage, apples undergo several degradative changes that can be detected through physical property testing at different storage stages. However, such tests are often destructive in nature, highlighting the need for non-destructive methods for quality evaluation. In addition, apple productivity has declined due to land degradation, caused by excessive use of chemical fertilizers and pesticides that damage soil quality (Bawindaputri, T.A., et al., 2017). The aging of trees and pest infestations also contribute to declining yields (Balitjestro, 2014). Climate change factors such as rising temperatures, drought, and extreme rainfall further exacerbate these problems, reducing apple production both in quantity and quality.

These challenges emphasize the need for a more objective, accurate, standardized, and efficient classification system to help farmers ensure that the harvested fruits meet consumer specifications. To address these issues, the integration of Near Infrared Reflectance (NIR) spectroscopy and fuzzy logic has been proposed as an innovative solution for determining fruit quality. NIR technology works by analyzing the absorption of near-infrared light to evaluate the internal characteristics of fruit. The NIR spectroscopy method enables rapid, non-destructive determination of both physical and chemical attributes of apples, thereby maintaining the integrity of the fruit while improving efficiency in quality assessment (Rizky, 2022).

Furthermore, fuzzy logic has proven effective in handling uncertainty and variability in fruit characteristics by providing a more adaptive representation of quality classes. Previous studies have shown that fuzzy logic-based systems can enhance classification accuracy. Arinal et al. (2025) identified the ripeness levels of apples using Mamdani fuzzy logic with an accuracy rate of 96%. Similarly, Alfajri (2025) developed an Internet of Things (IoT)-based apple sorting system employing Sugeno fuzzy logic, capable of automatically classifying fruit quality using color and gas sensors with an error rate of only 6.67%. These findings indicate that the combination of fuzzy logic and sensor technology can significantly improve the precision and efficiency of fruit quality determination.

Based on these considerations, this study aims to develop a quality determination system for apple fruits using the fuzzy logic method based on the parameters of Flesh Firmness, Soluble Solid Contents, Starch Pattern Index, Total Acidity, and Hue as the main quality indicators. The proposed system is expected to assist farmers in accurately determining apple quality according to consumer specifications. Moreover, the application of fuzzy logic in the classification process is anticipated to enhance the accuracy of selection and reduce the potential for human error during manual evaluation. Ultimately, the outcomes of this research are expected to contribute to increasing the economic value and market competitiveness of red apples, particularly the Anna variety, both domestically and internationally.

METHODS

Data Collection

This research was conducted using a literature review method through a process of data collection and analysis employing a qualitative descriptive approach. The literature review was obtained from scientific journals, articles, and relevant documents discussing apple maturity parameters such as flesh firmness, soluble solid contents, starch pattern index, total acidity, and hue°, as well as the application of fuzzy logic in agricultural decision-making.

Data sources were selected based on their relevance, validity, and credibility to support both theoretical and empirical analyses in this study (Gusti et al., 2025). Through this literature review, the author was able to gain secondary data and further develop a comprehensive theoretical foundation to understand the relationship between apple maturity characteristics and the application of fuzzy logic in determining the apple's maturity level more accurately.

Data Analysis

Fuzzy logic is a decision-making method that operates based on degrees of membership within a range of 0–1, allowing it to handle uncertainty and vagueness in data more flexibly than binary logic, which recognizes only true or false values. Data analysis was carried out using

MATLAB (Matrix Laboratory) as the platform for developing the fuzzy logic system, due to its capability to process data with no clear boundaries, such as apple maturity parameters.

The analysis process began with the determination of input and output variables, the construction of membership functions, and the design of If–Then rules using the Fuzzy Logic Toolbox and MATLAB's Graphical User Interface (GUI) (Ramdani, 2015). Each variable was defined in the FIS Editor, and the membership functions were created and adjusted using the Membership Function Editor to represent the linguistic characteristics of maturity parameters. The inference stage was conducted through the Rule Editor, where MATLAB calculated the activation degree of each rule and performed aggregation. The inference results were visualized using the Rule Viewer, which shows the influence of each input on the output, while the Surface Viewer was used to display the three-dimensional relationships between variables. The final stage, defuzzification, produced a crisp value that served as the quantitative basis for determining the apple maturity level.

RESULTS AND DISCUSSION

Data Analysis

Fuzzy Logic systems begin with defining the structure of the machine itself. The first step is establishing fuzzy rules based on data from expertise. These rules form the basis of the inference process resulting in visualized output. The Mamdani Fuzzy Logic method is commonly used for classification works based on various inputs, especially grading agricultural products (Arinal et al 2025).

In this study, the fuzzy logic systems for determining apple' quality consist of five input variables namely Flesh Firmness (FF), Soluble Solid Content (SSC), Starch Pattern Index (SPI), Total Acidity (%TA), and Hue° with one output variable that is Level of Maturity which corresponds to the fruit's grade. The general apple color this study uses is green with reddish hue color derived from Granny Smith and general red apple.

Fuzzification

The first step in fuzzy logic application is defining the membership functions of each input variable based on expert knowledge. The overlapping value among the input variables with a range of full membership degrees makes the trapezoidal membership function (*trapmf*) most appropriate for this case (Khairuddin *et al.* 2021).

Table 1. Input Variables

Variables	Fuzzy Set	Universe Set	Domain
Flesh Firmness	Low	5. 89 - 8.09	[5,89 - 7,67]
	Medium		[6,33 - 7,97]
	High		[6,51 - 8,09]
Soluble Solid Contents	Low	9,78 - 11,48	[9, 78 - 11,28]
	Medium		[9,98 - 11,18]
	High		[10,36 - 11,48]
Starch Pattern	Low	3,8 - 8,69	[3,8 - 6,78]

Index	Medium		[4,43 - 7,91]
	High		[6,07 - 8,69]
	Low Medium		[0,41 - 0,55]
Total Acidity		0,41 - 0,66	[0,44 - 0,62]
	High		[0,46 - 0,66]
Hue°	Light	0 - 60	[30 - 60]
	Deep		[0 - 30]

Source : Sredojevic (2025)

Table 2. Output Variables

Variable	Fuzzy Set	Domain
Unripe	Grade B	0-40
Ripe	Grade A	40-70
Overripe	Grade C	70-100
Maturity		

Fuzzy Operator

Based on the defined input and output, a rule base is constructed in the form of IF THEN statements. These rules would be describing the relationship between input and output. The greater number of well-defined rules would enhance the system's precision, as it enables more specific and nuanced output values.

Table 3. Rules

No	Input					Output
	FF	SSC	SPI	TA	Hue°	
1*	High	Low	Low	High	Light	Unripe
2.	High	Medium	Low	Medium	Light	Unripe
3.	High	High	Low	Low	Deep	Ripe
4*	Medium	Medium	Medium	Medium	Deep	Ripe

5.	Medium	High	-	Low	Deep	Ripe
6.	Low	High	-	Low	Deep	Overripe
7*	Low	Medium	High	Low	Deep	Overripe
8.	Low	High	High	Low	Light	Overripe
9.	-	Low	-	High	-	Unripe
10.	Medium	Low	Low	High	-	Unripe
11.	-	High	-	Low	Deep	Ripe
12.	Low	-	High	-	Deep	Overripe

this symbol (*) represent the real-case expert evaluation in determining apple's quality (original rules)

Fuzzy Mamdani Method

Membership functions for each variable are defined using trapezoidal formulas as the foundation of developing a fuzzy logic system. These steps help predict and accommodate demand and fluctuation of products particularly nature-based like fruits. Fuzzy logic itself allowed the input to be a fuzzy value and then processed using interference and defuzzified to predict accurate values (Gusti *et al,* 2025).

For example, the membership function for "Flesh Firmness" in the "Medium" fuzzy set can be represented using MATLAB as shown in Figure 2. All other input categories or fuzzy sets are similarly modeled using this function type.

$$\mu p\_[Fuzzy\ Set]\ [Variable] = \begin{cases} 0,\ x \le a \\ \frac{x-a}{b-a},\ a \le x \le b \\ 1,\ b \le x \le c \\ \frac{d-x}{d-c},\ c \le x \le d \\ 0,\ d \le x. \end{cases}$$

$$\mu p\_Low\ [FF] = \begin{cases} 0,\ x \le 0 \\ \frac{x-0}{0-0},\ 0 \le x \le 0 \\ 1,\ 0 \le x \le 6 \\ \frac{7-x}{7-6},\ 6 \le x \le 7 \\ 0,\ 7 \le x \end{cases}$$

$$\mu p\_Low\ [SSC] = \begin{cases} 0,\ x \le 9 \\ \frac{x-9}{9-9},\ 9 \le x \le 9 \\ 1,\ 9 \le x \le 9{,}8 \\ \frac{10{,}5-x}{10{,}5-9{,}8},\ 9{,}8 \le x \le 10{,}5 \\ 0,\ 10{,}5 \le x \end{cases}$$

$$\mu p\_Medium\ [FF] = \begin{cases} 0,\ x \le 6 \\ \frac{x-6}{6{,}3-6},\ 6 \le x \le 6{,}3 \\ 1,\ 6{,}3 \le x \le 7{,}5 \\ \frac{8-x}{8-7{,}5},\ 7{,}5 \le x \le 8 \\ 0,\ 8 \le x \end{cases}$$

$$\mu p\_Medium\ [SSC] = \begin{cases} 0,\ x \le 9{,}8 \\ \frac{x-9{,}8}{10-9{,}8},\ 9{,}8 \le x \le 10 \\ 1,\ 10 \le x \le 11 \\ \frac{11{,}3-x}{11{,}3-11},\ 11 \le x \le 11{,}3 \\ 0,\ 11{,}3 \le x \end{cases}$$

$$\mu p\_High\ [FF] = \begin{cases} 0,\ x \le 7 \\ \frac{x-7}{7{,}5-7},\ 7 \le x \le 7{,}5 \\ 1,\ 7{,}5 \le x \le 7{,}5 \\ \frac{8{,}5-x}{8{,}5-7{,}5},\ 7{,}5 \le x \le 8{,}5 \\ 0,\ 8{,}5 \le x \end{cases}$$

$$\mu p\_High\ [SSC] = \begin{cases} 0,\ x \le 10{,}8 \\ \frac{x-10{,}8}{11{,}2-10{,}8},\ 10{,}8 \le x \le 11{,}2 \\ 1,\ 11{,}2 \le x \le 12 \\ \frac{12-x}{12-12},\ 12 \le x \le 12 \\ 0,\ 12 \le x \end{cases}$$

$$\mu p\_Low\ [TA] = \begin{cases} 0,\ x \le 0{,}4 \\ \frac{x-0{,}4}{0{,}4-0{,}4},\ 0{,}4 \le x \le 0{,}4 \\ 1,\ 0{,}4 \le x \le 0{,}45 \\ \frac{0{,}55-x}{0{,}55-0{,}45},\ 0{,}45 \le x \le 0{,}55 \\ 0,\ 0{,}55 \le x \end{cases}$$

$$\mu p\_Low\,[SPI] = \begin{cases} 0, \; x \le 3 \\ \frac{x-3}{3-3}, \; 3 \le x \le 3 \\ 1, \; 3 \le x \le 4,5 \\ \frac{6-x}{6-4,5}, \; 4,5 \le x \le 6 \\ 0, \; 6 \le x \end{cases}$$

$$\mu p\_Medium\,[SPI] = \begin{cases} 0, \; x \le 4,5 \\ \frac{x-4,5}{5-4,5}, \; 4,5 \le x \le 5 \\ 1, \; 5 \le x \le 6,5 \\ \frac{7,5-x}{7,5-6,5}, \; 6,5 \le x \le 7,5 \\ 0, \; 7,5 \le x \end{cases}$$

$$\mu p\_Medium\,[TA] = \begin{cases} 0, \; x \le 0,45 \\ \frac{x-0,45}{0,5-0,45}, \; 0,45 \le x \le 0,5 \\ 1, \; 0,5 \le x \le 0,6 \\ \frac{0,65-x}{0,65-0,6}, \; 0,6 \le x \le 0,65 \\ 0, \; 0,65 \le x \end{cases}$$

$$\mu p\_High\,[SPI] = \begin{cases} 0, \; x \le 6,5 \\ \frac{x-6,5}{7,5-6,5}, \; 6,5 \le x \le 7,5 \\ 1, \; 7,5 \le x \le 9 \\ \frac{9-x}{9-9}, \; 9 \le x \le 9 \\ 0, \; 9 \le x \end{cases}$$

$$\mu p\_High\,[TA] = \begin{cases} 0, \; x \le 0,55 \\ \frac{x-0,55}{0,6-0,55}, \; 0,55 \le x \le 0,6 \\ 1, \; 0,6 \le x \le 0,7 \\ \frac{0,7-x}{0,7-0,7}, \; 0,7 \le x \le 0,7 \\ 0, \; 0,7 \le x \end{cases}$$

$$\mu p\_Light[Hue^{\circ}] = \begin{cases} 0, \; x \le 25 \\ \frac{x-25}{35-25}, \; 25 \le x \le 35 \\ 1, \; 35 \le x \le 60 \\ \frac{60-x}{60-60}, \; 60 \le x \le 60 \\ 0, \; 60 \le x \end{cases}$$

$$\mu p\_Deep\,[Hue^{\circ}] = \begin{cases} 0, \; x \le 0 \\ \frac{x-0}{0-0}, \; 0 \le x \le 0 \\ 1, \; 0 \le x \le 25 \\ \frac{35-x}{35-25}, \; 25 \le x \le 35 \\ 0, \; 35 \le x \end{cases}$$

Figure 1. Membership Functions of Input Variables

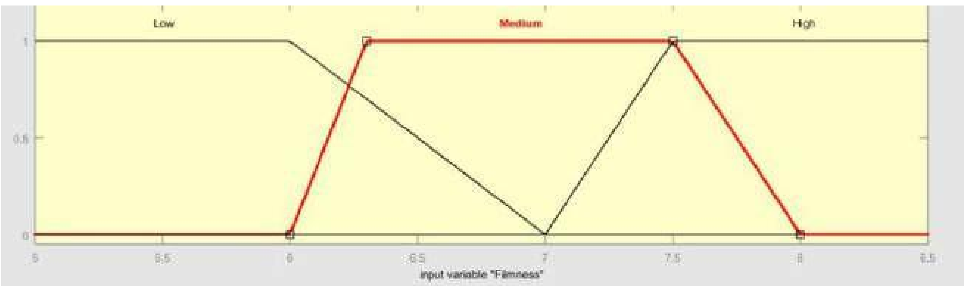

Figure 2. Membership Function of The “Flesh Firmness” Input Variable

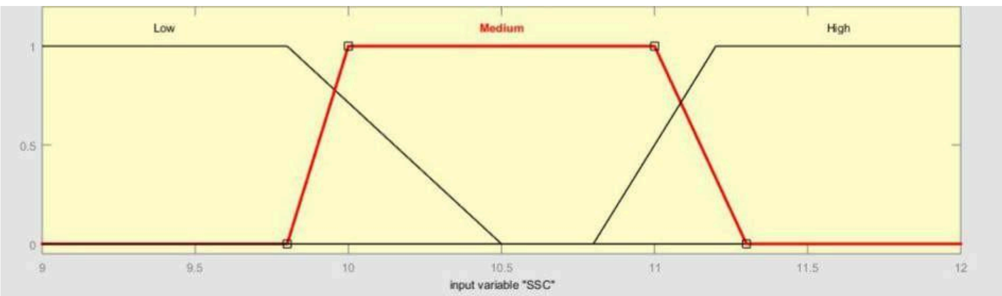

Figure 3. Membership Function of The “Soluble Solid Content” Input Variable

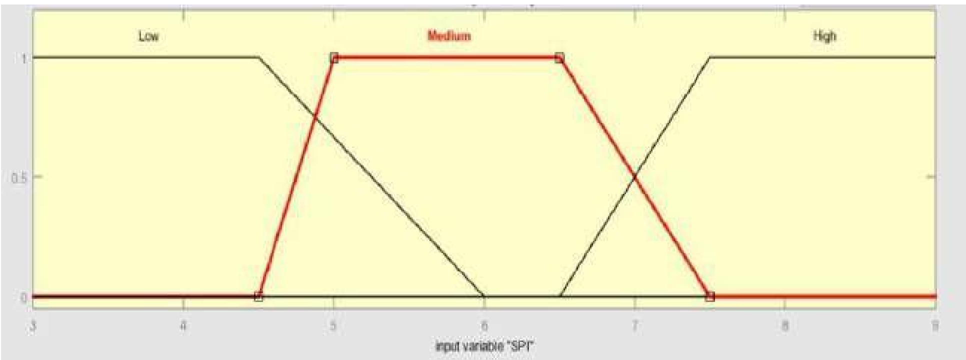

Figure 4. Membership Function of The “Starch Pattern Index” Input Variable

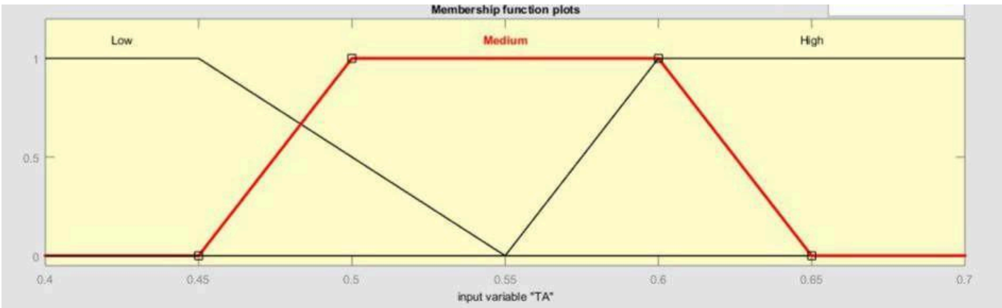

Figure 5. Membership Function of The “Total Acidity” Input Variable

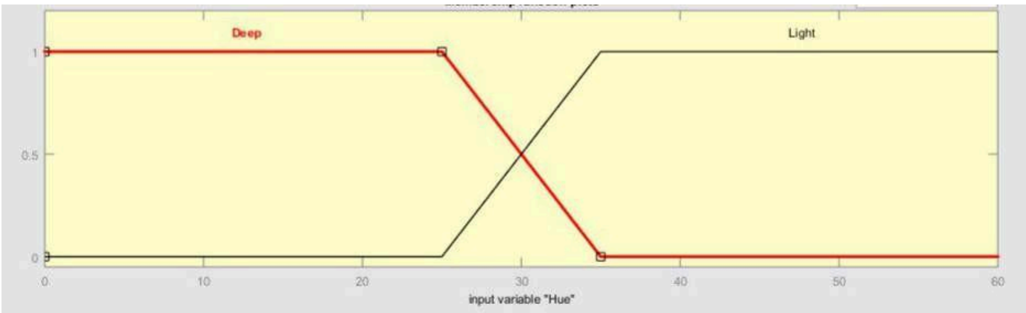

Figure 6. Membership Function of The “Hue” Input Variable

$$\mu p\_Unripe\,[Maturity] = \begin{cases} 0, & x \leq 0 \\ \frac{x-0}{0-0}, & 0 \leq x \leq 0 \\ 1, & 0 \leq x \leq 40 \\ \frac{50-x}{50-40}, & 40 \leq x \leq 50 \\ 0, & 50 \leq x \end{cases}$$

$$\mu p\_Ripe\,[Maturity] = \begin{cases} 0, & x \leq 40 \\ \frac{x-40}{50-40}, & 40 \leq x \leq 50 \\ 1, & 50 \leq x \leq 65 \\ \frac{75-x}{75-65}, & 65 \leq x \leq 75 \\ 0, & 75 \leq x \end{cases}$$

$$\mu p\_Overripe\,[Maturity] = \begin{cases} 0, & x \leq 70 \\ \frac{x-70}{80-70}, & 70 \leq x \leq 80 \\ 1, & 80 \leq x \leq 100 \\ \frac{100-x}{100-100}, & 100 \leq x \leq 100 \\ 0, & 100 \leq x \end{cases}$$

Figure 7. Membership Function of The “Hue” Input Variable

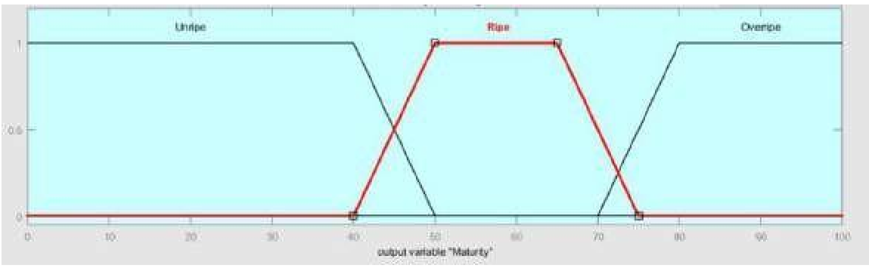

Figure 8. Membership Function of The "Maturity Level" Output Variable

Defuzzification

Defuzzification is the process of converting the fuzzy inference output into a real, crisp value. The defuzzification method is important for its effect on fuzzy system ability to give real value. This value represents the maturity level that farmers can use to make harvesting decisions. The Mamdani FIS has five defuzzification method which are Centroid, Bisector, Mean of Maximum (MoM), Smallest of Maximum (SoM), and Largest of Maximum (LoM) (Gaddafi, 2016 in Neonbeni *et al.,* 2022).

The defuzzification method this study uses is the centroid method, also known as the Center of Area (COA) or Center of Gravity (COG). This method is used as is suitability because it produces a precise numerical output based on the weighted center of the aggregated fuzzy inference curve. The fuzzy inference curve itself is the combined area of the resulting membership functions as shown in Figure 9.

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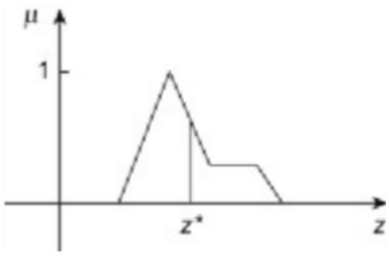

Figure 9. Centroid Method Defuzzification

In this case, it provides a practical tool for farmers to determine apple maturity at harvest. This practice would help farmers to meet customer preferences and market quality standards and trends. Satisfying these demands can improve consumer loyalty and increase the economic value of agricultural products.

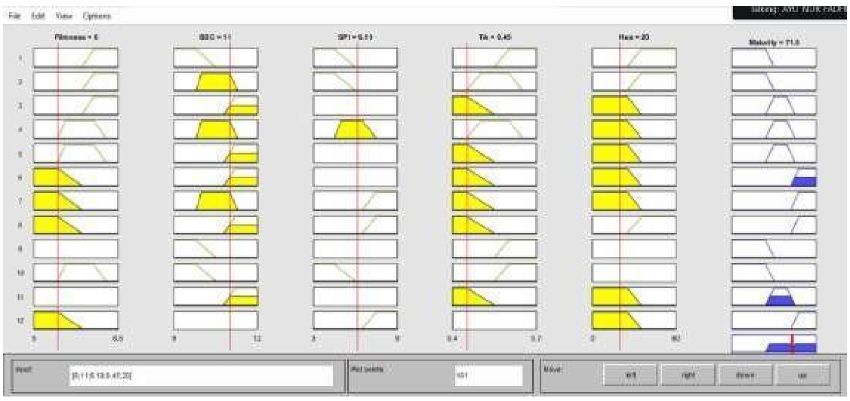
Figure 10. Defuzzification

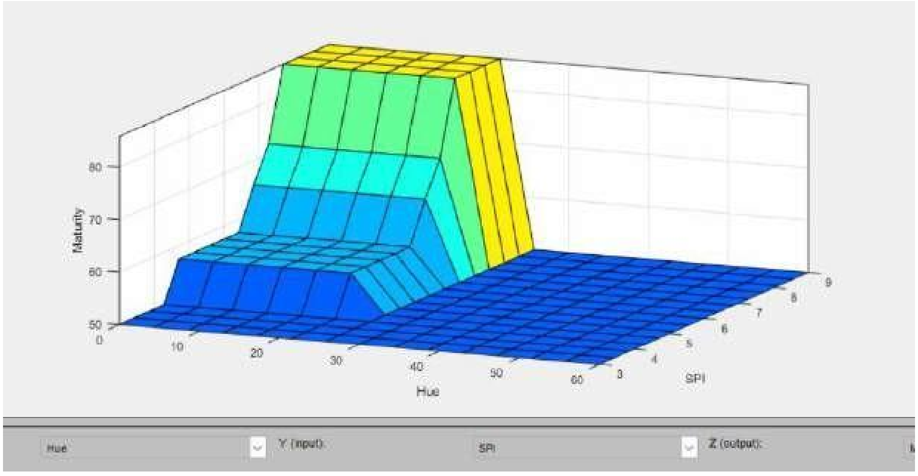

Figure 11. Surface Analysis of Defuzzification

As shown in Figure 11, the surface view produced in MATLAB illustrates the relationship among input variables and the resulting maturity level. Such visualizations can provide insights into consumer preferences and market trends, supporting data-driven marketing strategies and product innovation (Gusti *et al,* 2025).

Manual Example

Table 4. Manual Example of Fuzzy Logic

Aspect	Value	Membership function
Firmness (N)	6	$\mu p\_low\ [6] = \frac{7-6}{7-6} = 1$ $\mu p\_high\ [6] = 6 \leq 6{,}5 = 0$
SSC (°Brix)	11	$\mu p\_low\ [11] = 11 \leq 11{,}5 = 0$ $\mu p\_high\ [11] = \frac{11-10{,}5}{11{,}5-10{,}5} = 0{,}5$
SPI	7,5	$\mu p\_low\ [7{,}5] = 7{,}5 \geq 6 = 0$ $\mu p\_high\ [7{,}5] = \frac{7{,}5-6}{8-6} = 0{,}75$
TA (%)	0,5	$\mu p\_low\ [0{,}45] = x = 1$
Hue°	20	$\mu p\_deep\ [20] = x = 1$

Table 5. Fuzzy Operator of Manual Example

No	FF	SSC	SPI	TA	Hue	IF THEN	α	OUTPUT

1	H	L	L	H	L	Min (0 ; 0 ; 0 ; 0 ; 0)	0	
2	H	M	L	M	L	Min (0 ; 0 ; 0 ; 0 ; 0)	0	
3	H	H	L	L	D	Min (0 ; 0,5 ; 0 ; 1 ; 1)	0	
4	M	M	M	M	D	Min (0 ; 0 ; 0 ; 0 ; 1)	0	
5	M	H		L	D	Min (0 ; 0,5 ; 1 ; 1)	0	
6	L	H		L	D	Min (1 ; 0,5 ; 1 ; 1)	0,5	Overripe
7	L	M	H	L	D	Min (1 ; 0 ; 0,75 ; 1 ; 1)	0	
8	L	H	H	L	L	Min (1 ; 0,5 ; 0,75 ; 1 ; 0)	0	
9		L		H		Min (0 ; 0)	0	
10	M	L	L	H		Min (0 ; 0 ; 0 ; 1)	0	
11		H		L	D	Min (0,5 ; 1 ; 1)	0,5	Ripe
12	L		H		D	Min (1 ; 0,75 ; 1)	0,75	Overripe

Following the fuzzy operator stage (as summarized in Table 5), the next step is the implication process, where the firing strength (α) is applied to clip the output membership function at the intersection level. The resulting compositions are then simplified before defuzzification

$$\mu SF(z) = \begin{cases} 0, & x \leq 40 \\ \frac{x-40}{10}, & 40 \leq x \leq 70 \\ 0,5; & 45 \leq x \leq 70 \\ \frac{75-x}{10}, & 70 \leq x \leq 72,5 \\ \frac{x-70}{10}, & 72,5 \leq x \leq 77,5 \\ 0,75; & 77,5 \leq x \leq 100 \\ 0, & 100 \leq x \end{cases}$$

The simplified membership function facilitates the calculation of the first moment and area using basic integral and geometric formulas. For example, the area segment between 40–45 (representing a triangular area) has a height of 0,5 also the moment with μ = 0,5 with a lower bound of 45, and an upper bound of 75.

$$A1 = \frac{(45-40)\, x\, 0.5}{2} = \frac{2.5}{2} = 1,25$$

$$M2 = \int_{45}^{70} (0,5)z\, dz = 0,25z^2|^{70}{}_{45} = 0,25(70^2) - 0,25(45^2) = 718,75$$

The total area and moment of all segments are then used to compute the centroid, which represents the final output corresponding to the given inputs. The value of 74,17 below means that the apple's maturity is at an overripe stage which is between 70 - 100.

$$z^* = \frac{\int \mu x(z).z\, dz}{\int \mu x(z)\, dz} = \frac{moment}{area} =$$

$$\frac{1,25 + 12,5 + 0,9375 + 2,5 + 16,875}{54,1667 + 718,75 + 66,6667 + 188,5417 + 1497,6563} = \frac{34,0626}{2525,7813} = \mathbf{74,17}$$

Case Study

In general, the ripeness testing of apples is traditionally carried out through human visual observation. However, this method has a low level of accuracy due to the varying visual conditions and perceptions among individuals (Ramadhan *et al,* 2024). Besides observing the physical appearance of the apples, another common method used to determine ripeness is the tapping method, known as the acoustic impulse response technique. Nevertheless, this method is also subjective and relatively time-consuming (Agusta, 2016). As a result of the inaccuracy of these traditional methods and observations, apples are often harvested either overripe or underripe, leading to potential economic losses for farmers. Therefore, the fuzzy logic method is applied so that fruit ripeness can be evaluated objectively and rapidly. Moreover, farmers can utilize the results of this testing to determine ripeness parameters accurately, efficiently, and appropriately according to the desired apple quality, thereby preventing financial losses when distributing the produce to markets or industries (Simanjuntak *et al*, 2020).

Example Dataset

In this study, five variables were used to determine the ripeness of apples. First, Flesh Firmness (FF), which refers to the textural property crucial for assessing harvest quality, as fresh and intact apples generally exhibit higher firmness levels. This firmness is closely related to the moisture content and freshness preferred by consumers (Fathizadeh, 2021). Second, Soluble Solid Contents (SSC), which increase due to the hydrolysis of starch into sugars during the apple ripening process. However, SSC levels may continue to rise after ripening, resulting in a watery texture in apples (Iwanami et al., 2024). Third, the Starch Pattern Index (SPI), which is influenced by pre-harvest factors. Trees with lower apple yields tend to produce fruits with darker coloration due to higher starch concentrations. Starch concentration can also be affected by variety, climate, and tree conditions (Doerflinger *et al,* 2015). Next, Total Acidity (TA) also plays a significant role in apple ripeness. In apples, the predominant acid is malic acid, accounting for up to 90% of total organic acids. Apple varieties with lower malic acid content tend to taste sweeter, as the acid content decreases during storage, particularly under high-oxygen conditions (Ján & Davide, 2018). Finally, Hue°, representing the true color values such as red, yellow, and violet, is used to determine and differentiate color variations like red, green, and others (Pah *et al,* 2021). These five variables are then modeled using fuzzy logic, either manually or through MATLAB software.

Fuzzy logic is an appropriate approach to mapping an input space into an output space. This decision-making method mimics human reasoning under uncertain or ambiguous conditions, where each input variable has a degree of membership in several fuzzy sets, such as *low*, *medium*, and *high*. These categorical divisions represent the characteristics of the fruit at different ripening stages.Referring to Table 3, a higher (*high*) value of Flesh Firmness (FF) indicates that the apple is still firm or unripe; at a *medium* level, the texture begins to soften, signaling that the ripening process is underway; while at a *low* level, the apple becomes very soft, indicating an overripe condition. This pattern also applies to other parameters such as Soluble Solid Content (SSC), Starch Pattern Index (SPI), Titratable Acidity (TA), and Hue°, each reflecting specific changes in fruit characteristics throughout the ripening process. In addition, the fuzzy logic system includes a set of rules that connect the input variables to the apple's ripeness level. These rules serve as the foundation for decision-making in determining the output based on the given inputs. In the case of apples, the rules are used to classify ripeness levels according to the parameters FF, SSC, SPI, TA, and Hue°. Hence, this rule-based system can emulate expert reasoning in evaluating apple ripeness, determining whether the fruit falls into the categories of *ripe*, *unripe*, or *overripe* (Hartano, 2017).

a. Unripe

   Unripe apples can be caused by moderate to high levels of acidity. This occurs because acidic substances or salts can inhibit the browning process in apples by reducing absorption capacity. Such browning affects the taste, increases the alkalinity, and can damage the fruit's nutritional quality (Wahyuni *et al,* 2024). In addition to taste, high acidity levels are directly proportional to moderate to high firmness levels, as observed in rules 1, 2, and 10 of Table 3. This condition occurs because apples contain pectin, a water-soluble polysaccharide compound capable of forming a gel, which contributes to the fruit's chewy texture (Nurani, 2020). However, the Soluble Solid Contents (SSC) and Starch Pattern Index (SPI) values are inversely related to acidity; the lower these values, the lower the amount of starch hydrolyzed into sugar. As a result, apples exhibit a sour taste, and the ripening process tends to proceed more slowly. Furthermore, unripe apples generally have a brighter color, which is often perceived as an indicator of good external quality (Ikhsan, 2024). With the inverse relationship between acidity and firmness levels compared to SSC and SPI values, fuzzy logic technology facilitates accurate classification of apple ripeness levels, ensuring consistent output results (Ciputra *et al,* 2018).

b. Ripe

The ripeness of apples is an essential aspect to consider, as it significantly influences quality, taste, and harvest timing. However, manual ripeness determination is often inaccurate; therefore, the fuzzy logic method is required to produce more objective and consistent decisions, ensuring that no party suffers losses due to mismatched ripeness levels. Referring to Table 3, apples categorized as *ripe* correspond to rules 3, 4, 5, and 11. These four rules differ in parameter categories, yet their combinations still meet the criteria for apple ripeness, resulting in a *ripe* output. Based on the data, when the Flesh Firmness (FF) value reaches *high* to *medium*, it indicates that the fruit's texture begins to soften but remains firm. This condition signifies that the ripening process has begun, while the cell wall structure remains sufficiently strong to maintain firmness. The reduction in firmness is influenced by enzymatic activity that breaks down cell wall components such as pectin and hemicellulose (Su *et al,* 2022). For the Soluble Solid Contents (SSC) parameter, a similar pattern is observed—*medium* to *high* SSC values indicate that the apple has reached its optimal ripening stage. The increase in SSC results from the hydrolysis of starch into simple sugars such as glucose, fructose, and sucrose during fruit ripening (Biegert *et al,* 2021). The Starch Pattern Index (SPI) parameter corresponds closely with Hue°, as both assess color changes in apples but focus on different aspects. The SPI value indicates the extent of surface color change toward redness, while Hue° describes the intensity of that color. Thus, even when SPI shows a *low* value, Hue° may display a *deep* or intense color, suggesting that a smaller portion of the apple's skin has already undergone significant color transformation. The final parameter, Total Acidity (TA), also plays a role in assessing ripeness. Ripe apples generally have *low* to *medium* acidity levels compared to unripe ones, as the ripening process reduces organic acid content—particularly malic acid—which is converted into sugars and volatile compounds that contribute to the fruit's aroma (Rosidah, 2020). Therefore, the implementation of fuzzy logic for apple ripeness detection assists farmers and industry stakeholders in determining the optimal harvest time and maintaining the overall quality of the fruit.

c. Overripe

Apples in the overripe stage exhibit physiological conditions that have surpassed the optimal ripeness phase. In this case, apples categorized as *overripe* at harvest indicate that the ripening process has progressed beyond the ideal point for picking. Based on observations in Table 3, samples with the "Overripe" output — specifically rules 6, 7, 8, and 12 — show a general pattern characterized by low Flesh Firmness (FF), high Starch Pattern Index (SPI), low Total Acidity (TA), and Hue° values that tend to be *deep* or *light*. These conditions indicate that the fruit has reached the final stage of physiological ripening on the tree. According to Sredojevic et al. (2025), the decrease in firmness and total acidity in the late growth stages of apples results from the degradation of pectin and the utilization of organic acids as an energy source for respiration — a common occurrence when harvesting is delayed. Additionally, the Soluble Solids Content (SSC) values in overripe apples tend to fall within the *medium-high* range, indicating that most starch has been converted into simple sugars such as sucrose and fructose. This finding aligns with Sabzi (2022), who stated that SSC and SPI are strong indicators that apples have reached or surpassed their ideal ripeness level. A high SPI value signifies nearly complete starch hydrolysis in the fruit tissue. Furthermore, studies have shown that lower acidity levels correspond to more advanced ripening stages (Arnal *et al,* 2024). From a color perspective (Hue°), a deeper hue reflects the loss of green pigment (chlorophyll) and the emergence of new pigments such as anthocyanins (red and purple), marking the fruit's maturation process. The deeper the Hue° value, the further the ripening process progresses, often accompanied by lower pH values that reflect changes in acidic compounds during ripening. Altogether, these combinations signify fruit that has passed its peak ripeness, resulting in an *overripe* output. Fuzzy logic rules allow the system to determine ripeness levels gradually, without rigid boundaries between categories. As noted by Grabska *et al.* (2023), integrating multiple physical, chemical, and visual quality parameters in multivariate models such as fuzzy logic enables more accurate assessment of harvest maturity. Therefore, applying fuzzy logic to detect overripe apples can help determine the latest optimal harvest time and ensure the fruit maintains the best quality for consumption.

In applying the fuzzy logic system for determining apple ripeness levels, each quality parameter — Flesh Firmness (FF), Soluble Solids Content (SSC), Starch Pattern Index (SPI), Total Acidity (TA), and Hue° (color) — possesses a *membership degree* that represents its contribution to one of the ripeness categories (*Unripe*, *Ripe*, or *Overripe*). The values of these parameters are then combined using a set of fuzzy rules that simulate human reasoning under uncertain or ambiguous conditions — in this case, evaluating ripeness based on the interaction of parameters without rigid categorical boundaries. For example, consider an apple with measured values of FF (*low*), SSC (*high*), SPI (*high*), TA (*low*), and Hue° (*light*). Through the fuzzy logic process, each parameter has a degree of membership within its respective category. This combination activates a specific fuzzy rule that classifies the fruit as *Overripe*. The system then calculates the degree of membership for each ripeness level and determines that the highest membership degree corresponds to the *Overripe* category. This condition indicates that the fruit has passed its optimal ripeness — with sugar levels (SPI and SSC) peaking, acidity decreasing, and flesh texture becoming very soft. The *light* Hue° value may occur when color transformation is incomplete, suggesting the apple has just surpassed the *ripe* stage but not yet shown full visual signs of overripeness. Although color is often a sensitive ripeness indicator, some apples may still appear light even when physiologically overripe. This combination aligns with findings by Kistechok *et al.* (2024), who reported that during storage, SPI and SSC increase while TA gradually decreases as a result of ongoing ripening and organic acid metabolism. These combined indicators are used to classify advanced ripeness stages leading to the *overripe* category. The integration of multiple parameters provides a more realistic and accurate ripeness assessment than conventional methods (Grabska *et al,* 2023). Thus, this apple example illustrates that the fuzzy logic system does not rely on a single variable to determine ripeness; rather, it evaluates the interaction between parameters, producing logical and human-like decisions that closely reflect real-world ripeness assessment practices.

CONCLUSION

The application of the Mamdani Fuzzy Logic system in determining apple maturity provides an effective, objective, and flexible approach for classifying fruit ripeness levels based on multiple quality parameters—Flesh Firmness (FF), Soluble Solids Content (SSC), Starch Pattern Index (SPI), Total Acidity (TA), and Hue°. Through fuzzification, rule-based inference, and defuzzification, the system can translate uncertain and overlapping input data into clear and practical ripeness outputs: unripe, ripe, and overripe. The results demonstrate that fuzzy logic successfully simulates human reasoning, producing accurate classifications that align with physical, chemical, and visual changes during fruit maturation. Compared to conventional visual or manual methods, this approach minimizes subjectivity, reduces errors in harvest timing, and enhances decision-making efficiency for farmers and the food industry. Therefore, the integration of fuzzy logic technology supports data-driven agricultural practices, helping maintain fruit quality, meet market standards, and increase the economic value of apple production.

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