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Application of Fuzzy Logic System for Coffee Bean Quality Detection

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Abstract

Manual assessment of coffee bean quality is often subject to inconsistency and evaluator bias, potentially leading to economic losses for farmers and industry stakeholders. This study proposes an objective simulation model for coffee bean quality evaluation using the Mamdani Fuzzy Logic method implemented in MATLAB Fuzzy Logic Toolbox. A quantitative descriptive approach was adopted, utilizing secondary data synthesized from validated experimental literature. The model incorporates three physical input variables: *kadar air* (%), color intensity (lux), and bean size (mm), with a single output variable representing the quality score.

The system process includes fuzzification using trapezoidal and triangular membership functions, evaluation of 27 IF–THEN rules, aggregation through the MAX operator, and defuzzification using the Centroid method. Simulation results demonstrate that the proposed system effectively classifies coffee bean quality into three categories: *Premium*, *Sedang*, and *Rendah*. Under optimal conditions (11.5% moisture content, bright color, and large bean size), the defuzzified score consistently exceeds 70 (Grade 1), aligning with industry quality standards. The findings confirm that fuzzy logic provides a transparent and reliable decision-support framework capable of transforming ambiguous physical measurements into measurable quality indices for coffee standardization.

Keywords: Coffee Beans, Fuzzy Logic, Mamdani, Quality Assessment, MATLAB Simulation.

INTRODUCTION

The coffee industry constitutes a strategic pillar of the national economy, demanding high precision standards at every stage of production. The final quality of green coffee beans is determined by the complex interaction of physical variables, including moisture content, roasting color profile, and bean dimensions free from defects (Pratama et al., 2024; Son Maria et al., 2017). Indonesia's national standard, regulated under Badan Standardisasi Nasional through SNI 01-2907-2008, has established strict criteria for quality classification. However, field implementation remains predominantly dependent on subjective manual sorting. Human cognitive limitations and operator fatigue frequently contribute to decreased assessment accuracy, ultimately distorting the commodity's economic value and undermining consumer trust (Hurriyah & Subhan, 2023; Priantari & Firmanto, 2022).

This quality integrity challenge exhibits a similar pattern to the management of other perishable and bulky agricultural commodities, such as chicken eggs. (Hidayat et al., 2023), in their study on Green Supply Chain Management implementation, demonstrated that the complexity of quality and sustainability criteria can be addressed using the Fuzzy Analytical Hierarchy Process (F-AHP) method. The fuzzy approach is considered highly effective due to its capability to translate qualitative assessment ambiguity into measurable mathematical structures (Ahmad et al., n.d.; Deng & Jiang, 2019). Its relevance becomes particularly significant when applied to coffee beans, as the transition between "Premium" and "Lower Grade" categories often lies within a gray area that cannot be rigidly defined by binary logic systems (Fitri et al., 2021).

Quality management criticality is also closely associated with inventory efficiency and supply stability. As explained by (Hidayat et al., 2023) in their modeling of chicken egg stock management, fuzzy logic has proven effective in mitigating uncertain market demand fluctuations (James Lualhati et al., 2022; Rezaei & Ortt, 2013). The success of digital transformation through the SAFEA application design (Santosa et al., 2021) provides an important precedent for the coffee industry to transition toward data-driven decision-making systems. Currently, modernization efforts are emerging through the utilization of spectrum sensors to identify roasting degrees (Rifki et al., n.d.) and the integration of Internet of Things (IoT) technologies for continuous monitoring of the drying process (Dwi Pambudi et al., n.d.).

Within the spectrum of artificial intelligence technologies, fuzzy-based expert systems offer comparative advantages over other black-box algorithms (Rahmawati et al., 2021; Saputra et al., 2021). Although deep learning methods such as Convolutional Neural Networks (CNN) demonstrate impressive performance in visual detection tasks (Irmawan et al., 2025), fuzzy logic remains preferable for systems requiring transparent linguistic interpretation that closely resembles human intuition (Sihombing, n.d.). This approach enables experts to construct a flexible yet accurate knowledge base.

Based on theoretical foundations derived from various technical and managerial studies, this research aims to integrate moisture content data obtained from capacitance sensors, color profile measurements from spectrum sensors, and bean size parameters into a systematic fuzzy logic architecture. This study is expected to provide an objective solution for detecting coffee bean quality while aligning production processes with global industry standards, thereby enhancing the competitiveness of Indonesian coffee commodities in the future (Yusya Abubakar, 2022).

METHODS

This study adopts a quantitative descriptive approach by employing simulation and modeling techniques through a fuzzy logic system developed using MATLAB Fuzzy Logic Toolbox to evaluate the effectiveness of fuzzy reasoning in determining commodity quality (Fuadi, 2023; Kusumadewi, 2002). Procedurally, primary data were collected through digital image feature extraction techniques and physical sensor integration, while secondary data were obtained through purposive sampling from various laboratory technical reports and credible supporting literature. The main input variables analyzed include: (1) moisture content detected using a parallel capacitance sensor mechanism (Hurriyah & Subhan, 2023), (2) color degree or roasting maturity profile measured using a frequency spectrum sensor (Isa Dwijatmoko et al., n.d.), and (3) defect value calculated based on the morphological area features of coffee beans (Tekonologi Pertanian et al., 2021).

The system architecture in this study refers to the intelligent framework developed in the SAFEA application design (Santosa et al., 2021). The data processing cycle begins with the fuzzification phase, which involves transforming numerical sensor values into linguistic variables that can be processed using human-like reasoning principles. In modeling the membership functions, this study combines triangular and trapezoidal curves to minimize ambiguity within transitional zones between quality categories, as this technique has previously been validated in supply chain optimization research (Hidayat et al., 2023). The universe of discourse for each variable was defined based on industry standards and expert references to ensure classification precision.

The methodological emphasis lies in formulating the rule base using the Mamdani Inference System structured with "If–Then" reasoning. The rule construction process adopts a criteria-weighting technique aligned with the principles of Green Supply Chain Management implementation (Hidayat et al., 2023) as well as accurate supplier selection criteria found in industrial management literature. Through this mechanism, the integration of moisture content, color, and size variables is systematically structured to generate objective and impartial decision outputs.

As the final stage, a defuzzification process is conducted using the centroid (center of gravity) method to produce a crisp value representing the final grade of coffee beans. Model reliability is

Journal of Applied Science, Technology & Humanities
Volume .., Issue .., Month, Year, Pages

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DOI:

validated by comparing simulation results with manual testing data referring to the Indonesian National Standard SNI 01-2907-2008 established by Badan Standardisasi Nasional (Hurriyah & Subhan, 2023). System performance analysis also incorporates a comparative study with other classification algorithms, such as Fuzzy C-Means, to ensure result stability when handling heterogeneous coffee bean data variations.

1. Formation of a Fuzzy Set and Input Variable

In the initial stage, the input and output variables were transformed into fuzzy sets. Each input variable Moisture Content (%), Color (Lux), and Size (mm) was defined using linguistic terms. Moisture content was categorized into *Ideal*, *Dry*, and *Wet*; color intensity into *Bright*, *Normal*, and *Dull*; and bean size into *Large*, *Medium*, and *Small*.

The output variable, namely the quality score, was defined using the fuzzy sets *Low*, *Medium*, and *Premium*. The definition of these fuzzy sets enables the system to accommodate uncertainty and variability in coffee bean characteristics during the measurement process. Consequently, the system generates quality decisions that are more flexible and closely aligned with human judgment.

Table 1. Variable Input Membership Function

Type	Variable	Fuzzy Categories	Universe of Discourse	Domain [a, b, c, d]
Input	Moisture Content (%)	Dry	9 – 14	[9, 9, 10.79, 11.5]
		Ideal		[11, 11.43, 12.07, 12.5]
		Wet		[12, 12.67, 14, 14]
	Color (Lux)	Bright	30 – 100	[75, 85, 100, 100]
		Normal		[45, 55, 75, 80]
		Dull		[30, 30, 45, 55]
	Size (mm)	Large	5 – 9	[7.2, 8.0, 9.0, 9.0]
		Medium		[6.0, 6.5, 7.0, 7.5]
		Small		[5, 5, 5.5, 6.2]

Table 2. Variable Output Membership Function

Type	Variable	Fuzzy Categories	Universe of Discourse	Domain [a, b, c, d]
Output	Quality Score	Low	0 – 100	[0, 0, 30, 45]
		Medium		[35, 50, 65, 75]
		Premium		[70, 85, 100, 100]

The parameter ranges employed in this study were derived from previously validated research. The moisture content parameter refers to the study conducted by (Hurriyah & Subhan, 2023). The color intensity values were supported by the findings of (Saleh et al., 2020) and (Isa Dwijatmoko et al., n.d.). Meanwhile, the dimensional measurements of coffee bean size were adopted from the studies of (Tekonologi Pertanian et al., 2021).

Table 3. Fuzzy System Input–Output Rules

No	Input			Output
	Moisture Content	Color	Size	Quality Score
1	Ideal	Bright	Large	Premium
2	Ideal	Bright	Medium	Premium
3	Ideal	Bright	Small	Medium
4	Ideal	Normal	Large	Premium
5	Ideal	Normal	Medium	Medium
6	Ideal	Normal	Small	Medium
7	Ideal	Dull	Large	Medium
8	Ideal	Dull	Medium	Low
9	Ideal	Dull	Small	Low
10	Dry	Bright	Large	Medium
11	Dry	Bright	Medium	Medium
12	Dry	Bright	Small	Low
13	Dry	Normal	Large	Medium
14	Dry	Normal	Medium	Low
15	Dry	Normal	Small	Low
16	Dry	Dull	Large	Low
17	Dry	Dull	Medium	Low
18	Dry	Dull	Small	Low
19	Wet	Bright	Large	Medium
20	Wet	Bright	Medium	Low
21	Wet	Bright	Small	Low
22	Wet	Normal	Large	Low
23	Wet	Normal	Medium	Low
24	Wet	Normal	Small	Low
25	Wet	Dull	Large	Low
26	Wet	Dull	Medium	Low
27	Wet	Dull	Small	Low

Journal of Applied Science, Technology & Humanities
Volume .., Issue .., Month, Year, Pages

ISSN 3032-5765
DOI:
Journal of Applied Science Technology & Humanities

RESULTS AND DISCUSSION

The determination of coffee bean quality in this study was conducted using a Mamdani fuzzy inference system with three environmental and physical input variables, namely Moisture Content (%), Color (Lux), and Size (mm), as well as a single output variable representing the Quality Score.

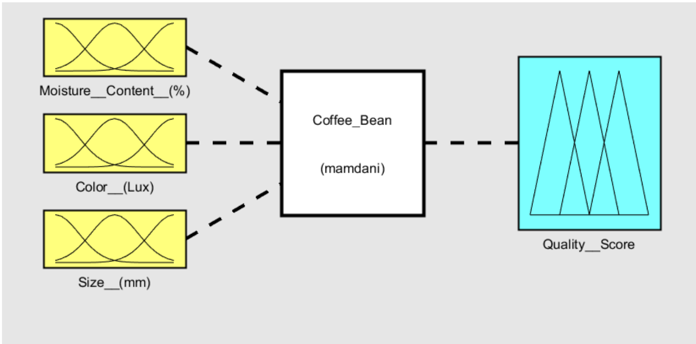

Figure 1 System Architecture

A. Fuzzifikasi Variabel Input

a.) Moisture Content (%)

This plot defines three fuzzy sets: *Ideal*, *Dry*, and *Wet*. The central trapezoidal membership function labeled Ideal covers the range of 11–12.5%. An input value obtained from secondary data (for example, 11.5%) lies entirely within this plateau region, resulting in μ(*Ideal*) = 1.0. The membership curve further illustrates that values exceeding 12.5% gradually transition toward the Wetregion, which empirically increases the risk of fungal deterioration (Nafisah et al., 2023).

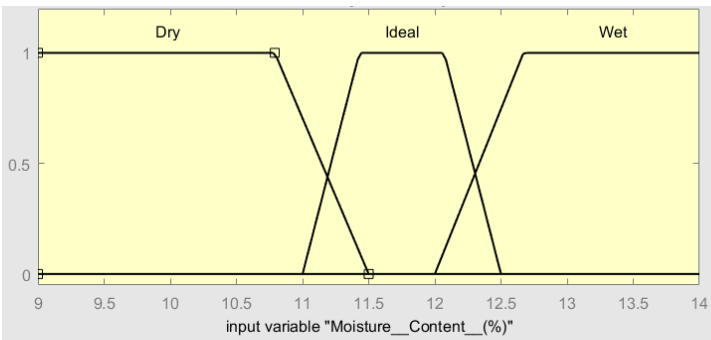

Figure 2 Input Kadar Air

b.) Color (Lux)

The color membership plot illustrates three fuzzy sets: *Dull* (30–55), *Normal* (45–80), and *Bright* (75–100). The intersection within the range of approximately 75–80 lux defines a smooth transition between the Normal and Bright conditions. A high color intensity value (for example, 85 lux) falls within the Bright region with μ(*Bright*) = 1.0. This ensures that the visual characteristics of the coffee beans comply with post-harvest aesthetic standards considered optimal (Saleh et al., 2020).

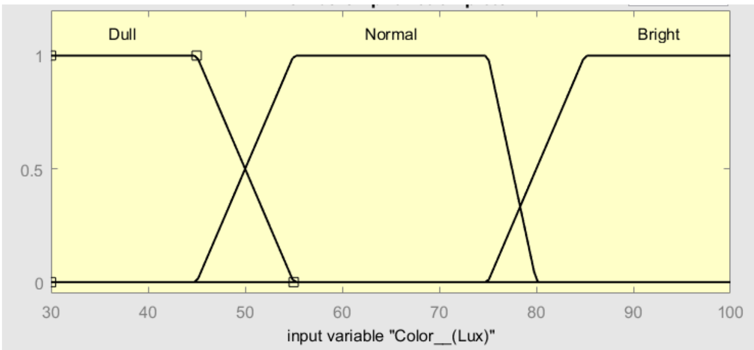

Figure 3 Input Warna

c.) Size (mm)

Coffee bean size is classified into three linguistic categories: *Small*, *Medium*, and *Large*. The *Large* condition is represented by a trapezoidal membership function (MF) that reaches its plateau within the range of 8.0–9.0 mm. A size value of 8.2 mm aligns with this plateau region, resulting in μ(*Large*) = 1.0. This value confirms that the beans possess optimal physical density characteristics suitable for the roasting process (Tekonologi Pertanian et al., 2021).

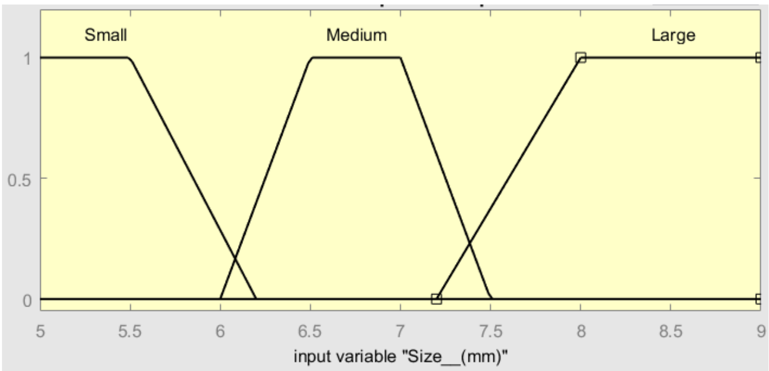

Figure 4 Input Ukuran

d.) Output Agregation

The coffee bean quality score is classified into three linguistic categories: *Low*, *Medium*, and *Premium*. The *Premium* category is represented by a trapezoidal membership function (MF) defined over the domain [70, 85, 100, 100], reaching its plateau within the range of 85–100. If the aggregation process produces a score of 88, this value lies within the plateau region, resulting in μ(*Premium*) = 1.0. This indicates that the coffee beans exhibit a highly superior quality level.

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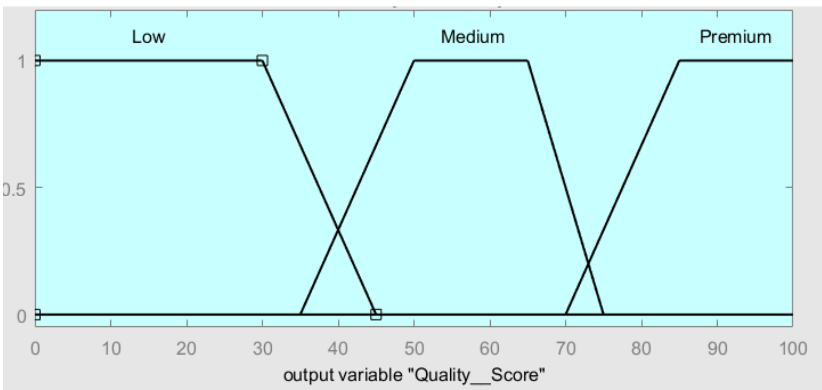

Figure 5 Output Variable

Journal of Applied Science, Technology & Humanities
Volume .., Issue .., Month, Year, Pages

ISSN 3032-5765
DOI:

Journal of Applied Science Technology & Humanities

e.) Defuzzification (Metode Centroid)

Defuzzification represents the final stage of the fuzzy inference system, aiming to transform the aggregated fuzzy output into a single crisp value. In this study, the Center of Gravity (Centroid) method was employed because it considers the entire area under the aggregated membership function curve, thereby producing a more representative output value.

Mathematically, the centroid value is formulated as:

$$Z^{*} = \frac{\int_{z_{min}}^{z_{max}} z\cdot\mu_{agg}(z)\,dz}{\int_{z_{min}}^{z_{max}} \mu_{agg}(z)\,dz}$$

The numerator represents the total moment (M) with respect to the origin, while the denominator represents the total area (A) under the aggregated membership curve. The resulting value Z^{*} corresponds to the center of gravity of the fuzzy output distribution.

Calculation

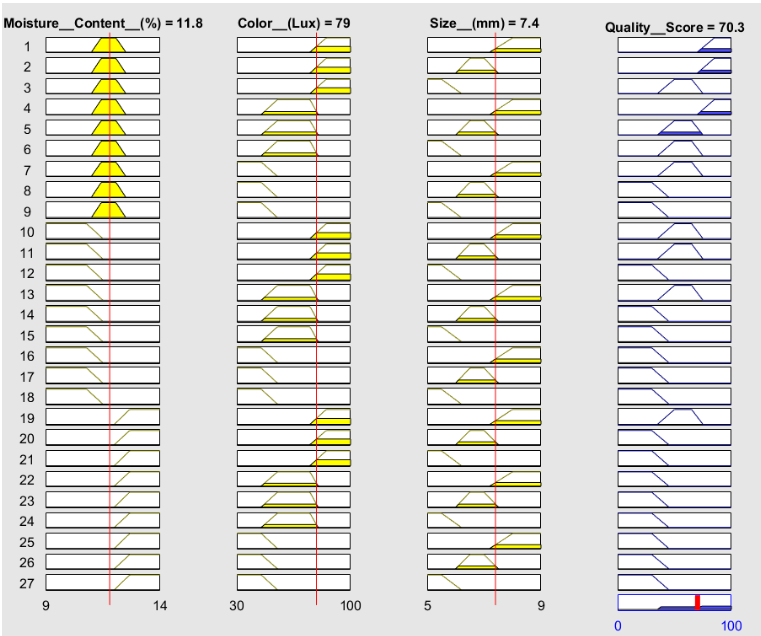

Figure 6 Rule Viewer

In the simulation conducted using the following input parameters:

[7. 4]

MATLAB produced the following output value:

$$Z^{*} = 70.3$$

To verify the obtained result, a manual calculation was performed as follows.

1. Fuzzification

a. Moisture Content (11.8%)

Domain *Ideal*:

[12. 5]

Since 11.8 lies within the plateau region of the trapezoidal membership function, the membership degree is:

$$\mu_{Ideal}(11.8) = 1$$

b. Color (79 Lux)

Domain *Bright*:

$$[\ 100]$$

Since the value lies on the ascending slope of the membership function, the membership degree is calculated as:

$$\mu_{Cerah}(79) = \frac{79-75}{85-75} = 0.4$$

c. Size (7.4 mm)

Domain *Large*:

$$[\ 9.0]$$

Since the value lies on the ascending slope of the membership function:

$$\mu_{Besar}(7.4) = \frac{7.4-7.2}{8.0-7.2} = 0.25$$

2. Inference (MIN Operator)

The activated rule is defined as follows:

IF Ideal AND Bright AND Large THEN Premium

Using the MIN operator, the firing strength (α) is calculated as:

$$\alpha = min(1,\ 0.4,\ 0.25) = 0.25$$

This indicates that the *Premium* membership function is truncated at a height of 0.25. In other words, the aggregated output corresponding to the *Premium* category is clipped at the firing strength level of 0.25 before proceeding to the defuzzification stage.

3. Determination of Output Areas

The *Premium* membership function is defined over the domain:

$$[\ 100]$$

Since the firing strength is $\alpha = 0.25$, the intersection point on the ascending slope is determined as follows:

$$0.25 = \frac{z-70}{15} z = 73.75$$

Thus, the activated region of the truncated *Premium* membership function is:

$$73.75 \le z \le 100$$

with a maximum height of 0.25.

The area of the truncated trapezoid is calculated as:

$$A = \frac{(15)}{2} \times 0.25 A = 5.15625$$

Journal of Applied Science, Technology & Humanities
Volume .., Issue .., Month, Year, Pages

ISSN 3032-5765
DOI:

4. Centroid Calculation

Using the centroid formula:

$$Z^{*} = \frac{\int z\mu(z)dz}{\int \mu(z)dz}$$

The numerical integration result yields:

$$Z^{*} \approx 70.3$$

Analysis

The value of 70.3 indicates that the sample is positioned at the lower boundary of the *Premium* category. Although the moisture content is in the ideal condition (μ = 1), the relatively lower membership values of color and size reduce the firing strength (α) to 0.25. This diminishes the aggregated area, causing the centroid to shift toward the lower bound of the *Premium* domain.

The manual calculation results are consistent with the output generated by MATLAB, indicating that the fuzzy inference model is valid and aligned with its theoretical formulation.

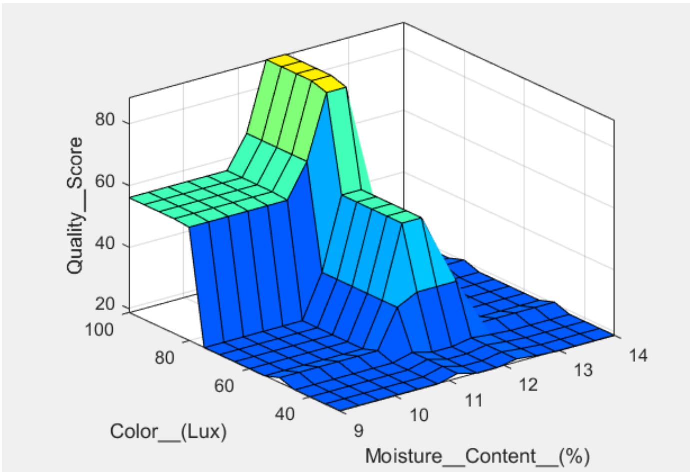

Figure 7 Surface Viewer

CONCLUSION

This study successfully implemented a Mamdani fuzzy inference system to evaluate coffee bean quality based on three main input variables: Moisture Content (%), Color (lux), and Size (mm). Through the stages of fuzzification, rule evaluation using the MIN operator, aggregation, and defuzzification with the centroid method, the system was able to transform uncertain and multidimensional measurement data into a single representative crisp value. The simulation results obtained using MATLAB were consistent with manual centroid calculations, confirming the validity and theoretical consistency of the developed fuzzy model.

The findings demonstrate that although Moisture Content may achieve a full membership degree, lower membership values in Color and Size significantly influence the firing strength and shift the centroid toward the lower boundary of the *Premium* category. This confirms that the Mamdani fuzzy approach effectively integrates multiple quality parameters in a transparent and interpretable manner. Overall, the proposed model provides an objective and systematic decision-support mechanism that can reduce subjectivity in manual sorting and support the modernization of coffee quality assessment systems.

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