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Application of Multi-Parameter Fuzzy Logic as a Decision Support System for Monitoring the Safety and Quality Stability of Postharvest Coffee Beans in the Agro-Industrial Storage Chain

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Abstract

Coffee is a key agricultural commodity that plays a strategic role in Indonesia's economy, yet maintaining the safety and quality of post-harvest coffee beans remains a major challenge due to environmental fluctuations during storage. This study aims to apply a multi-parameter fuzzy logic system as a decision support tool for monitoring the temperature, humidity, and CO_2/VOC gas concentration in the agro-industrial coffee storage chain. A qualitative descriptive approach was employed using literature analysis and fuzzy logic simulation with the Mamdani inference method. The simulation results demonstrated that the fuzzy system can effectively classify storage risk levels into safe, moderate, and high-risk categories based on environmental variations. At optimal conditions of 20–25°C temperature and 60–70% relative humidity, the system maintained coffee bean quality in accordance with SNI 01-2907-2008 standards. Conversely, conditions exceeding 30°C and 75% humidity resulted in a high-risk index due to increased moisture, microbial growth, and oxidation. The fuzzy-based monitoring system offers a more adaptive and precise assessment compared to conventional threshold methods, enabling early detection of quality degradation. This research provides a practical reference for developing intelligent control systems to ensure sustainable post-harvest coffee quality management.

Keywords: fuzzy logic, coffee beans, post-harvest quality, storage monitoring, decision sup

INTRODUCTION

Coffee is one of the strategic plantation commodities that contributes to Indonesia's economy (Fithriyyah et al., 2020), namely as a foreign exchange earner, a source of farmers' income, a supplier of industrial raw materials, a creator of employment opportunities, and a driver of regional development (Dirjenbun 2018). One of Indonesia's agricultural products that has become a world favorite is coffee, as Indonesian coffee is renowned for its strong flavor. This is evidenced by a survey conducted in 2016–2017, which showed that Indonesia ranked fourth in international coffee exports after Brazil, Vietnam, and Thailand (Indonesia Investment 2017). This significant contribution needs to be supported by appropriate post-harvest technology and facilities for farmers to produce high-quality coffee. Proper handling will result in good coffee quality (Soolany and Aji 2022; Yokawati and Wachjar 2019).

The quality of coffee beans is largely determined by proper harvesting and post-harvest processing (Dirjen Perkebunan 2018; Molenaar 2020), so how coffee is processed after being harvested will affect, and even give an effect on, the final result of brewed coffee.

In other words, processing during post-harvest handling is an important factor that must not be overlooked to produce high-quality coffee beans (green beans). The common coffee harvesting and post-harvest processes in coffee processing to obtain coffee beans (green beans) include red cherry picking, sorting, drying, parchment peeling, and packaging.

Based on the standard SNI 01-2907-2008, after the coffee beans are harvested, post-harvest processing must be carried out. The post-harvest processing method affects the quality of coffee beans (Hall et al., 2022; Alixandre et al., 2023). Coffee bean storage plays a crucial role in maintaining the quality, freshness, and flavor of coffee. Factors such as temperature, humidity, air exposure, and light can affect the shelf life of coffee beans. Several aspects that need to be considered for proper coffee bean storage include the green bean storage warehouse, as good storage affects the quality or grade of the coffee beans obtained and also requires capacity and storage regulations in the warehouse. One indicator of good coffee bean quality is coffee beans with a moisture content of less than or equal to 12.5% and a good coffee aroma, meaning they do not smell musty (BSN 2008). To produce coffee with the best flavor and quality, the ideal coffee bean drying conditions range from 40–55℃ with 40% humidity. Mulato (2012) explained that drying coffee beans at high temperatures would cause green coffee beans to turn yellowish-brown, thus being categorized as defective hidey beans and affecting coffee flavor. Ideally, coffee beans should be stored in airtight containers at a stable temperature (15–25°C) and relative humidity of 60–70% to prevent mold growth or oxidation. Previous research by Deva Bella Amanda (2021) showed that storing coffee beans in rooms with good temperature and humidity control can reduce quality degradation by up to 30%.

Coffee quality is assessed from the aftertaste, all of which are influenced by storage and processing factors. High-quality coffee generally has a strong aroma, balanced flavor, and long aftertaste. Previous research by Deva Bella Amanda (2021) showed that storing coffee beans in humid conditions can reduce aroma intensity and cause rancid flavors. According to Pane *et al.* (2022), storing coffee beans with humidity that is too low can also reduce moisture content, thereby affecting the appearance and taste of the beans. The longer the coffee beans are stored, the more likely color changes occur from green to blue, yellowish, and brown indicating that the beans are damaged. During storage, coffee beans may experience quality degradation due to pest damage, one of which is caused by the Araecerus fasciculatus beetle. The damage caused by pests includes perforated coffee beans, feeding grooves, and mold growth around the holes on the bean surface (Rahayu et al., 2022).

Based on the above background, the problem that becomes the focus of this research relates to how to maintain the quality and stability of coffee bean quality during post-harvest storage. The quality of coffee that easily decreases due to temperature and humidity fluctuations becomes a major challenge, especially for smallholder farmers who still rely on conventional methods. Therefore, this research seeks to apply a fuzzy logic-based system to help control the temperature and humidity of coffee bean storage warehouses more precisely and adaptively. Through this approach, it is expected that the designed system will be able to prevent quality degradation of coffee beans caused by external factors such as mold, pests, or excessive humidity, so that the quality and flavor of coffee can be maintained until the distribution stage.

METHODS

This study uses a qualitative descriptive approach, with literature review as the primary basis for data collection and analysis. This approach was selected because the goal is to describe and evaluate the application of multi-parameter fuzzy logic (Mamdani method) for monitoring coffee bean storage quality in agro-industrial settings. According to Sugiyono (2019), qualitative descriptive research depicts phenomena systematically and factually based on credible scientific sources. Data were collected through literature studies of journals, proceedings, books, and related scientific publications discussing storage conditions of coffee beans and fuzzy logic applications. Literature selection was based on relevance, credibility, and validity. Data analysis followed content analysis stages: data reduction, data presentation, and drawing interpretive conclusions, as suggested by Miles et al. (2014). Qualitative analysis was carried out interactively until consistent interpretation was achieved. A qualitative descriptive method was used with fuzzy logic simulation to evaluate post-harvest coffee storage conditions. Parameter constraints were sourced from credible scientific literature related to temperature, humidity, and CO_2/VOC environmental limits in coffee storage.

To solve problems in the Mamdani fuzzy logic algorithm, there are several stages that are carried out based on research (Aziz & Mulyanto 2023), namely:

1. Fuzzy Set Creation (fuzzyfication)
   At this stage, the author creates variables used to determine the criteria for a book to be considered readable. These variables consist of input variables and output variables.
2. Rule Creation
   In this stage, the author creates rules derived from the variables that have been created. These rules are used to determine the output that will become a decision.
3. Rule Composition
   In this stage, a calculation is performed using the MAX-MIN method, which means determining the maximum and minimum values of the rules that have been determined.
4. Defuzzification
   In this stage, a calculation is performed to determine the domain value of each variable.

Fuzzy Logic System Development

A Mamdani-type Fuzzy Inference System (FIS) was constructed with three input variables and one output variable:

1) Temperature (°C)
2) Relative Humidity (%RH)
3) CO_2/VOC gas concentration (%)
4) Output: Storage Risk Index (scale 0–100)

To standardize information, the membership function (MF) structure is compacted into a single table:

Variable	Linguistic Set	Range	MF Type
Temperature	Low / Medium / High	15–35°C	Triangular / Trapezoidal
Humidity	Low / Medium / High	30–90%	Triangular / Trapezoidal
CO_2/VOC	Low / Medium / High	0–100%	Triangular / Trapezoidal
Risk Index	Low / Moderate / High	0–100	Triangular / Trapezoidal

These ranges reflect recommended coffee bean storage guidelines from SNI 01-2907-2008 and relevant studies.

Rule base

The set of rules is formulated as follows:

1. If the temperature is low, humidity is low, and CO_2/VOC is low, then the Risk Index (R) is Low Risk.
2. If the temperature is moderate, humidity is low, and CO_2/VOC is low, then the Risk Index (R) is Low Risk.
3. If the temperature is moderate, humidity is low, and CO_2/VOC is low, then the Risk Index (R) is Moderate.
4. If the temperature is moderate, humidity is high, and CO_2/VOC is low, then the Risk Index (R) is Moderate.

5. If the temperature is high, humidity is high, and CO_2/VOC is high, then the Risk Index (R) is High Risk.
6. If CO_2/VOC is high, then the Risk Index (R) is Moderate.
7. If humidity is high and CO_2/VOC is moderate, then the Risk Index (R) is Moderate.
8. If the temperature is high, humidity is low, and CO_2/VOC is low, then the Risk Index (R) is Moderate.
9. If the temperature is low, humidity is high, and CO_2/VOC is low, then the Risk Index (R) is Moderate.

Inference and Defuzzification

- Logical Operator: MAX–MIN composition
- Output Method: Centroid Defuzzification
- Final output form: Numerical value representing overall Storage Risk Index

This integration allows simultaneous interpretation of interacting environmental parameters, ensuring a more adaptive assessment than rigid threshold-based control.

RESULTS AND DISCUSSION

The Effect of Environmental Parameters on Post-Harvest Coffee Bean Quality

The quality of coffee beans after harvesting is greatly influenced by environmental conditions during storage, particularly by temperature, humidity, and the presence of carbon dioxide (CO_2) gas, which are interrelated in determining the physical and chemical stability of coffee beans. Excessively high temperatures and humidity can increase the moisture content of coffee beans, accelerate biochemical reactions, and trigger the growth of microbes and insects that reduce product quality, while balanced CO_2 levels play a role in maintaining freshness and preventing the oxidation of volatile compounds that affect the aroma and distinctive taste of coffee. Therefore, controlling these three factors during storage is very important to maintain the quality of coffee so that it remains optimal until the next processing stage.

Air humidity is an important factor that greatly affects the stability of coffee bean quality during storage because it is directly related to the moisture content in the beans. After undergoing the drying and hulling processes, the moisture content of coffee beans is generally in the range of 11-12% and must be maintained so that it does not exceed the limit set in SNI 01-2907-2008, which is a maximum of 12.5%. The hygroscopic nature of coffee beans causes them to easily absorb or release water vapor depending on the humidity of the surrounding air. If the air humidity is too high, the moisture content of the beans can increase above 13% and trigger the growth of fungi such as Aspergillus niger, A. flavus, and A. ochraceus, which have the potential to produce ochratoxin A, thereby reducing product quality and safety. Conversely, excessively low humidity causes excessive water loss, resulting in brittle bean texture and reduced aroma and flavor. Therefore, the ideal relative humidity during storage is in the range of 60–85%, with a stable moisture content of 10–12%, so that the coffee beans remain dry, are not prone to mold, and are able to maintain their physical and sensory quality over a long storage period (Pane et al., 2022).

To maintain stable environmental factors during coffee bean storage, the use of CO_2 gas injection technology is one effective method for preserving bean quality. CO_2 injection replaces the air around the coffee beans, thereby reducing oxygen levels, which ultimately inhibits mold growth and insect activity during storage. In addition, the presence of CO_2 gas helps maintain moisture balance around the coffee beans, so that the moisture content can be maintained at around 10–12% for up to 12 months of storage. An atmosphere dominated by CO_2 also reduces the risk of oxidation of volatile compounds that affect aroma and keeps the color of coffee beans stable without noticeable changes during long-term storage (Pane et al. 2022).

According to Pane et al. (2022), a combination of temperature control at 10–21°C, relative humidity at 60–85%, and the use of hermetic packaging with approximately 60% CO_2 injection has been proven to maintain the quality of coffee beans for up to 12 months of storage. These conditions maintain the moisture content of coffee beans in the range of 10–12%, suppress mold growth and insect attacks, and keep the color and aroma stable. This method is far more effective than conventional storage in burlap sacks, which causes the moisture content to increase by up to 11.4% in six months.

Applying Fuzzyfication to Coffee Bean Storage Conditions, Quality, and Safety

The fuzzyfication process in this multi-parameter fuzzy logic system serves to translate the readings of temperature, humidity, and volatile gas (CO_2/VOC) sensors into linguistic forms that can be processed by the Fuzzy Inference System (FIS). Figure 1 shows the input data obtained from the DHT22, BME688, and Moisture Sensor sensors, then converted into degrees of membership in each fuzzy set. The temperature range used is 15–35°C, humidity 30–90%, and volatile gas levels 0–100%. Each input variable is divided into three fuzzy sets, namely low, medium, and high. Meanwhile, the output variable, the Storage Risk Index, has a universe of discourse of 0–100, which is classified into three linguistic categories: safe (0–33), alert (34–66), and high risk (67–100). Through this fuzzyfication process, the system can assess coffee bean storage conditions more adaptively based on real environmental variations in the warehouse, so that the final result reflects the level of stability of coffee bean quality during storage in the agro-industrial supply chain.

Figure 1. Input ranges (T 15–35°C, RH 30–90%, CO_2/VOC 0–100%) and Risk Index (0–100)

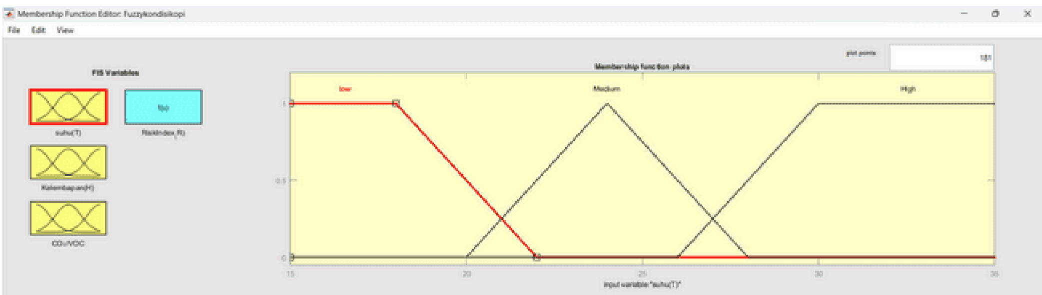

Figure 2. Temperature MFs (Low 15–25°C, Med 20–28°C, High 26–35°C)

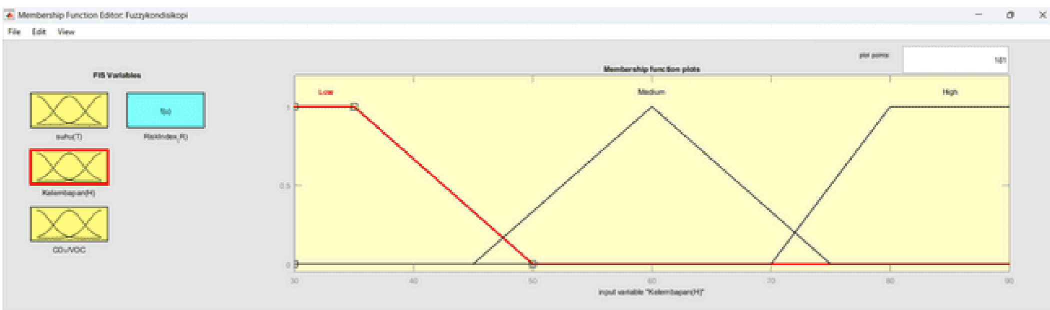

Figure 3.Humidity MFs (Low 30–55%, Med 45–75%, High 70–90%)

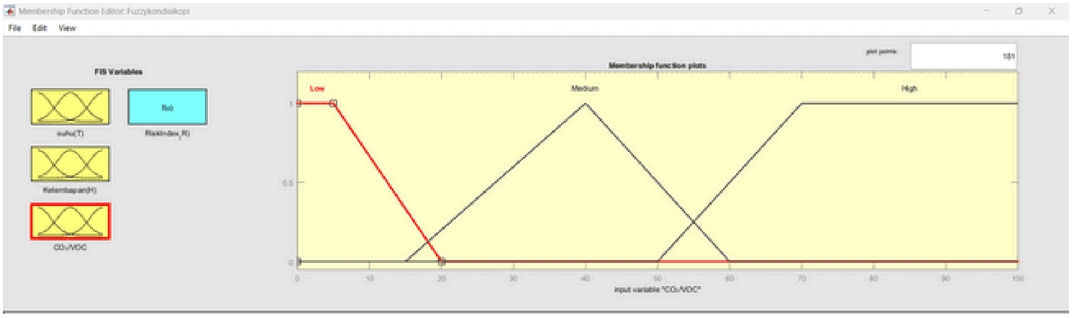

Figure 4. CO_2/VOC MFs (Low 0–20%, Med 15–60%, High 50–100%)

Temperature input membership set

$$\mu_{Low}(x)=\begin{cases}0, & x<15\\ \frac{x-15}{18-15}, & 15\le x<18\\ 1, & 18\le x\le 22\\ \frac{22-x}{22-18}, & 22<x\le 22\\ 0, & x>22\end{cases}$$

$$\mu_{Medium}(x)=\begin{cases}0, & x<20\\ \frac{x-20}{24-20}, & 20\le x<24\\ \frac{28-x}{28-24}, & 24\le x\le 28\\ 0, & x>28\end{cases}$$

$$\mu_{High}(x)=\begin{cases}0, & x<26\\ \frac{x-26}{30-26}, & 26\le x<30\\ 1, & 30\le x\le 35\\ 0, & x>35\end{cases}$$

The membership function for the Temperature variable is divided into three fuzzy sets: low, medium, and high. The temperature is categorized as low with a full membership value (1) between 18 and 22, and it decreases to zero for x < 15 or x > 25. The temperature categorized as medium is a triangular function that peaks in the range of 24–28, with zero membership outside the range of 20 and 28. Meanwhile, the high temperature is a trapezoidal function that has a full membership value (1) between 30 and 35, and decreases to zero for x < 26 or x > 35.

Humidity input membership set

$$\mu_{Low}(x)=\begin{cases}0, & x<30\\ \frac{x-30}{35-30}, & 30\le x<35\\ 1, & 35\le x\le 50\\ \frac{50-x}{50-35}, & 50<x\le 50\\ 0, & x>50\end{cases}$$

$$\mu_{Medium}(x)=\begin{cases}0, & x<45\\ \frac{x-45}{60-45}, & 45\le x<60\\ \frac{75-x}{75-60}, & 60\le x\le 75\\ 0, & x>75\end{cases}$$

$$\mu_{High}(x)=\begin{cases}0, & x<70\\ \frac{x-70}{80-70}, & 70\le x<80\\ 1, & 80\le x\le 90\\ 0, & x>90\end{cases}$$

The membership function for the humidity variable is also divided into three fuzzy sets: low, medium, and high. Humidity is categorized as low with a full membership value (1) for the range of 35 to 50, and it decreases to zero for x < 30 or x > 55. The humidity categorized as medium is a triangular function that has zero membership outside the range of 45 and 75, reaching its maximum value between 60 and 75. Finally, the high humidity is a trapezoidal function that has a full membership value (1) in the range of 80 to 90, and decreases to zero for x < 70 or x > 90.

Volatile gas input membership set

$$\mu_{Low}(x)=\begin{cases}1, & x\le 5\\ \frac{20-x}{20-5}, & 5<x<20\\ 0, & x\ge 20\end{cases}$$

$$\mu_{Medium}(x)=\begin{cases}0, & x<15\\ \frac{x-15}{40-15}, & 15\le x<40\\ \frac{60-x}{60-40}, & 40\le x\le 60\\ 0, & x>60\end{cases}$$

$$\mu_{High}(x)=\begin{cases}0, & x<50\\ \frac{x-50}{70-50}, & 50\le x<70\\ 1, & 70\le x\le 100\\ 0, & x>100\end{cases}$$

The membership function for the Volatile Gas input is defined by three fuzzy sets: low, medium, and high. The low set is a trapezoidal function that reaches its full membership (1) for $x \le 5$ and decreases to zero at $x \ge 20$. The Medium set is a triangular function that ramps up from x=15 to a peak at x=40 and then ramps down to zero at $x \ge 60$. The High set is a trapezoidal function that ramps up from x=50 to achieve full membership (1) between x=70 and x=100, becoming zero for $x \le 50$ or $x > 100$.

Risk Indeks output membership set

$$\mu_{LowRisk}(R)=\begin{cases}1, & R\le 10\\ \frac{33-R}{33-10}, & 10<R<33\\ 0, & R\ge 33\end{cases}$$

$$\mu_{Moderate}(R)=\begin{cases}0, & R<30\\ \frac{R-30}{50-30}, & 30\le R<50\\ \frac{66-R}{66-50}, & 50\le R\le 66\\ 0, & R>66\end{cases}$$

$$\mu_{HighRisk}(R)=\begin{cases}0, & R<60\\ \frac{R-60}{75-60}, & 60\le R<75\\ 1, & 75\le R\le 100\\ 0, & R>100\end{cases}$$

The membership function for the Risk Index output (R) is defined by three fuzzy sets: Low Risk, Moderate Risk, and High Risk. The Low Risk set is a trapezoidal function with full membership (1) for $R \le 10$ and decreases to zero at $R \ge 33$. The Moderate Risk set is a triangular function that ramps up from R=30 to its peak at R=50 and then ramps down to zero at $R \ge 66$. The High Risk set is a trapezoidal function that ramps up from R=60 to achieve full membership (1) between R=75 and R=100, becoming zero for $R < 60$ or $R > 100$.

Rule base

In this system model, a rule base is designed to link three key storage condition parameters: temperature (T), humidity (H), and CO_2/VOC levels (C), to a single output parameter, the Risk Index (R). Each rule represents a specific combination of environmental conditions that results in a different level of risk to the stability of post-harvest coffee bean quality. Nine fuzzy rules are used to describe the relationship between temperature, humidity, and CO_2/VOC concentrations and the risk index.

Through this rule base, the fuzzy system can adaptively analyze the combination of storage environmental conditions to generate a defuzzified risk index value that more accurately describes the potential for coffee bean quality degradation. A graphical representation of the rule base can be seen in Figure 5.

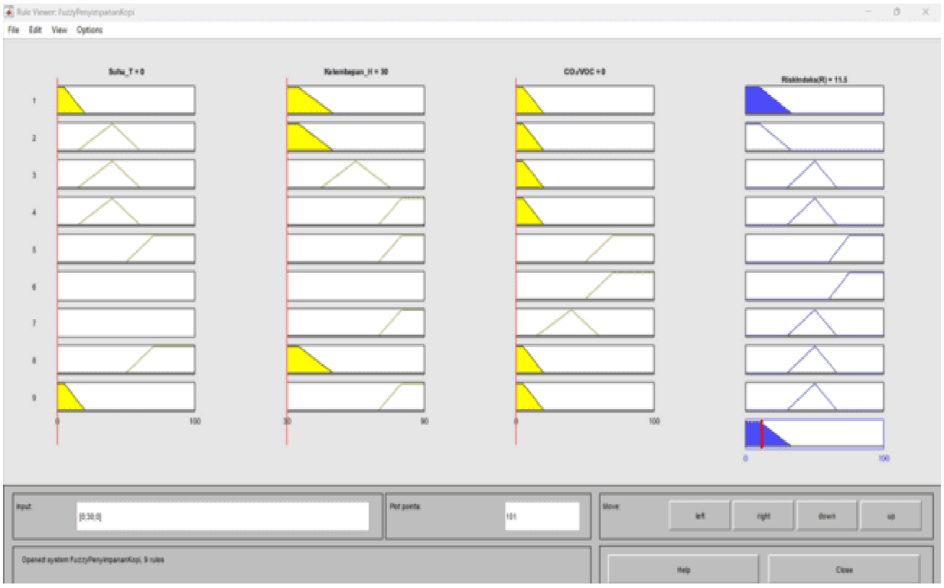

Figure 5. Fuzzy rule base for T–RH–CO_2/VOC

Fuzzy logic simulation on several coffee bean storage conditions against risk index

A fuzzy logic system is used as a tool to interpret and assess changes in storage conditions that affect post-harvest coffee bean quality. Unlike conventional systems that only assess conditions based on fixed value limits (e.g., "safe" or "unsafe"), a fuzzy system can process data that is uncertain and changes gradually. In the context of coffee bean storage, monitored parameters include storage room temperature (°C), relative humidity (%), and volatile gas levels of CO_2/VOC (%), which are indicators of biological activity within the coffee beans and their environment.

Through a fuzzy approach, each parameter has a membership function that describes the condition level, such as low, medium, and high. These values are then processed through the Mamdani inference process to produce a Risk Index (R) output, which indicates the level of risk of coffee bean quality decline. The Risk Index (R) output is grouped into three categories: safe (Low Risk), alert (Moderate), and action (High Risk). The fuzzy system assesses a combination of these parameters simultaneously to describe the actual state of the storage environment, thus being able to detect changes in conditions early before the quality of the coffee beans declines.

Table 2. Simulation data of coffee bean storage condition parameters

Condition	**Storage condition parameters**		
	Temperature (°C)	**Humidity (%)**	**Volatile gas (CO_2/VOC)**
A	20	40	10
B	25	50	30
C	30	75	65

Figure 6. Simulation A (20°C, 40%, 10%; Risk ≈15%)

The fuzzy logic system simulation results demonstrate the system's ability to evaluate changes in temperature, humidity, and volatile gas (CO_2/VOC) levels as key indicators of coffee bean quality stability during storage. Under condition A (20°C; 40%; 10%), the system generated a low Risk Index (~15%), indicating stable storage conditions. This aligns with SNI 01-2907-2008 and previous studies showing that temperatures around 20–25°C and moderate humidity support stable moisture levels and minimal biochemical activity.

Figure 7. Simulation B (25°C, 50%, 30%; Risk = 50)

Condition B (25°C; 50%; 30%) produced a moderate Risk Index (50), reflecting early signs of microclimate imbalance. This result is consistent with findings by Pane et al. (2022), who noted that increases in temperature and humidity heighten the likelihood of moisture gain and gradual quality decline, even before visible defects occur.

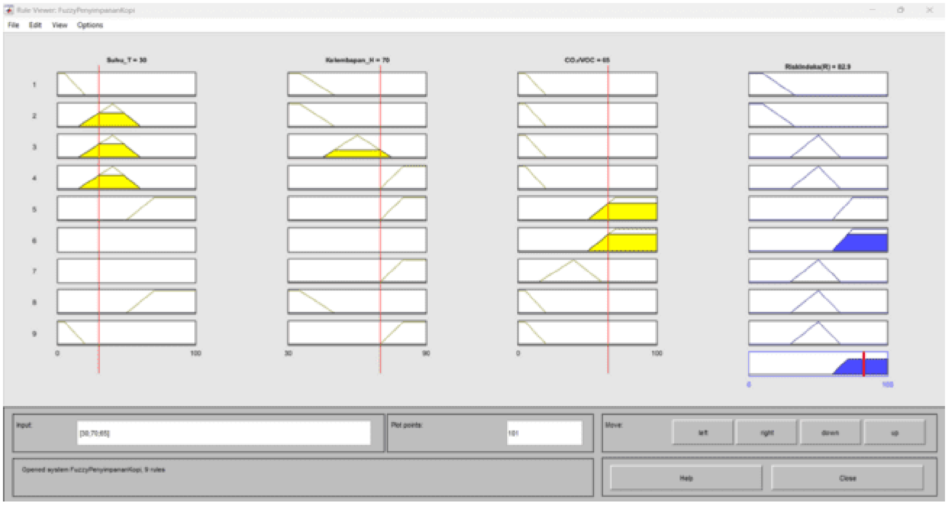

Figure 8. Simulation C (30°C, 75%, 65%; Risk ≈83)

Meanwhile, in condition C (30°C; 75%; 65%) produced a high Risk Index (~83), indicating strong potential for rapid quality degradation. This corresponds with prior literature reporting that temperatures above 30°C and relative humidity over 75% accelerate microbial activity, moisture absorption, and chemical deterioration (Pane et al., 2022). The simulation thus validates the system's ability to detect high-risk environments.

CONCLUSION

This study concludes that the application of a multi-parameter fuzzy logic system provides an effective and adaptive approach for monitoring and maintaining the safety and quality stability of post-harvest coffee beans in the agro-industrial storage chain. The simulation results demonstrated that fuzzy logic can interpret variations in temperature, humidity, and CO_2/VOC concentration to generate a comprehensive risk index reflecting real storage conditions. The system successfully identified safe, moderate, and high-risk categories based on environmental fluctuations, allowing for early detection of potential degradation.

By integrating temperature, humidity, and gas parameters into a unified decision-support model, the fuzzy logic system offers a more precise assessment compared to conventional threshold-based monitoring methods. The findings indicate that maintaining optimal environmental conditions temperatures between 20–25°C and relative humidity between 60–70% helps preserve the physical and sensory qualities of coffee beans, in accordance with SNI 01-2907-2008 standards. Overall, the use of multi-parameter fuzzy logic contributes to enhancing post-harvest management, ensuring consistent product quality, and supporting sustainable practices within the coffee agro-industry. Future development of this system can be directed toward real-time sensor integration and automation to further improve efficiency and decision accuracy in industrial-scale applications.

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