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Environmental Characterization of Vanilla Processing Facilities Using IoT Monitoring for Material Design Considerations

Shabrina Choirunnisa[1], Wendy Triadji Nugroho[2], Mas'ud Hermansyah[3], , Bagus Putu Yudhia Kurniawan[4], Andarula Galushasti[5], Khafidurrohman Agustianto[1]

[1] Department of Information Technology, Politeknik Negeri Jember, Indonesia
[2] Department of Engineering, Politeknik Negeri Jember, Indonesia
[3] Department of Digital Business, Politeknik Negeri Jember, Indonesia
[4] Department of Agribusiness Management, Politeknik Negeri Jember, Indonesia
[5] Department of Agricultural Production, Politeknik Negeri Jember, Indonesia
* Correspondence: shabrinacnisa@polije.ac.id

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Abstract: This study aims to characterize the environmental conditions (temperature and relative humidity) in vanilla processing facilities using an Internet of Things (IoT)-based monitoring system. Monitoring was conducted in three main rooms: Boiling Room, Fermentation Room, and Drying Room. Temperature and humidity data were collected continuously and analyzed using descriptive and inferential statistics (One-Way ANOVA and Kruskal-Wallis) along with data visualization (boxplots). The results showed that the Boiling Room had the highest average temperature (43.75°C) with the largest fluctuation (CV = 46.42%). Meanwhile, the Fermentation Room recorded the highest average relative humidity (71.05%). Statistical tests indicated significant differences in temperature between rooms ($p < 0.001$). Based on these environmental characteristics, this study developed Material Design Considerations that recommend appropriate materials for each operational condition: high thermal stability and thermal fatigue resistance for the Boiling Room, and moisture resistance and corrosion resistance for the Fermentation Room. This approach bridges IoT data with engineering material selection to improve the reliability of vanilla processing facilities. The study provides practical contributions to integrating IoT technology with material design considerations in the vanilla agroindustry.

Keywords: Environmental characterization, Internet of Things, Material design considerations, Vanilla

1. Introduction

Vanilla (Vanilla planifolia) is a high-value plantation commodity widely used as a raw material in the food, cosmetic, and pharmaceutical industries, as well as in natural fragrance products. Vanilla quality is heavily influenced by post-harvest stagesspecifically scalding, fermentation, and drying which aim to generate the primary aroma compound, vanillin. Environmental conditions during these processes, particularly temperature and humidity, play a crucial role in determining the successful development of the flavor, aroma, and final quality of the vanilla product (Kurniasari et al., 2025). Temperature and humidity control in vanilla processing facilities is generally still performed manually, meaning changes in environmental conditions often go unmonitored continuously. Yet, uncontrolled fluctuations in temperature or humidity can lead to a decline in product quality, prolong processing times, and increase the risk of failure during fermentation or drying (Hidayat et al., 2023). Therefore, a real-time environmental monitoring system has become a crucial requirement for supporting a more consistent and efficient vanilla processing operation.

Advancements in Internet of Things (IoT) technology enable the automated monitoring of temperature and humidity through sensor networks capable of continuously transmitting data (Morchid et al., 2024). IoT has been widely adopted in agriculture and agro-industry, as it enhances monitoring efficiency, accelerates decision-making, and provides historical data for further analysis (Ula et al., 2025). Although various studies have utilized IoT to monitor environmental conditions in the agricultural and food processing sectors, most research still focuses on developing monitoring devices, evaluating sensor performance, or visualizing environmental data (Simon et al., 2026). The information obtained is generally used solely as an indicator of operational conditions, without being further developed into a basis for supporting engineering decisions.

On the other hand, the varying temperature and humidity characteristics at each stage of vanilla processing have direct implications for the durability of materials used in buildings, equipment, and production facility components. High-temperature environments require materials with high thermal stability, whereas high-humidity environments necessitate materials resistant to water absorption and corrosion (Arshad et al., 2024; Klenam et al., 2024). However, research linking IoT-based environmental monitoring data with material selection considerations for vanilla processing facilities remains very limited. Given this context, this study proposes a "Material Design Considerations" approach, utilizing temperature and humidity data from IoT monitoring to identify environmental characteristics in each vanilla processing room and provide preliminary recommendations regarding the material properties required to suit the specific operational conditions of each room (Kusumah & Islam, 2023). This approach not only yields information on environmental characteristics but also translates monitoring results into technical recommendations that can serve as a reference for material selection to enhance the reliability of the vanilla processing facility.

Although previous studies have successfully implemented IoT systems for environmental monitoring in agricultural processing facilities, most of them primarily focused on sensing performance, data visualization, or process monitoring. Very limited studies have translated environmental monitoring data into engineering-based decision support, particularly for selecting materials capable of withstanding specific operational conditions in agro-industrial facilities. Therefore, a framework connecting IoT environmental characterization with material design considerations remains largely unexplored.

Based on this background, this study aims to characterize temperature and humidity conditions in vanilla processing rooms using an IoT-based monitoring system, analyze environmental characteristic differences between rooms through a statistical approach, and formulate material design considerations to guide the selection of materials suited to the operational conditions of vanilla processing facilities. The findings are expected to provide a comprehensive overview of environmental characteristics across each stage of the vanilla processing workflow and identify environmental conditions that could potentially impact material performance and service life. Furthermore, this study is intended to serve as a preliminary reference for developing more reliable vanilla processing facilities by selecting materials that align with the thermal and humidity characteristics of each room. Thus, this research not only contributes to the development of IoT-based environmental monitoring systems but also expands the use of environmental data as a basis for material engineering decisions, thereby supporting the sustainability and efficiency of agro-industrial facilities.

2. Materials and Methods

Research Design

This study employs a quantitative approach using an observational method to characterize environmental conditions at a vanilla processing facility based on data from an Internet of Things (IoT)-based monitoring system. The environmental parameters monitored include temperature and relative humidity across three key vanilla processing areas: the Boiling Room, Fermentation Room, and Drying Room. The collected data were analyzed using descriptive and inferential statistical methods to identify environmental characteristics and determine differences in conditions between the rooms. Subsequently, the analysis results served as the basis for formulating material design considerations that link environmental characteristics to the required material properties for each processing area.

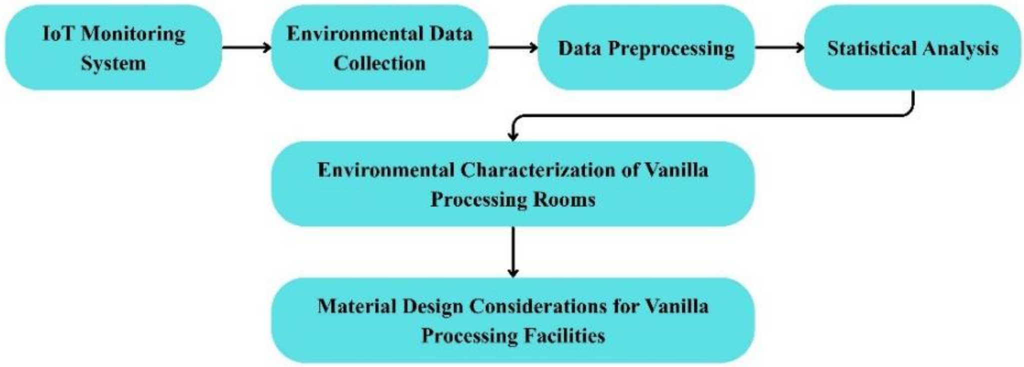

Figure 1. Research Workflow

Figure 1 illustrates the research workflow, beginning with an IoT monitoring process to acquire environmental data from the vanilla processing facility. The collected data encompasses parameters such as temperature, relative humidity, RSSI, and SNR. Subsequently, a data preprocessing stage is conducted, involving data cleaning, checking for missing values, removing duplicates, grouping data by room (Boiling Room, Fermentation Room, and Drying Room), and segregating data based on sensor type. This stage aims to ensure data quality and consistency prior to further analysis.

In the statistical analysis phase, descriptive statistics including mean, median, standard deviation, minimum and maximum values, and the coefficient of variation are employed to identify the environmental characteristics of each room. Inferential analysis follows, utilizing One-Way ANOVA and Kruskal–Wallis tests to determine whether significant differences in environmental conditions exist between the rooms. Additionally, data visualization techniques such as boxplots, violin plots, histograms, and correlation heatmaps are used to illustrate data distributions and the relationships between parameters.

The statistical analysis results are then used to characterize the environmental conditions of each vanilla processing room. This characterization informs material design considerations, leading to recommendations for material properties suited to the specific operational conditions of each room—such as requirements for thermal stability, thermal fatigue resistance, humidity resistance, dimensional stability, and corrosion resistance.

Study Site and IoT Monitoring System

The study was conducted at a vanilla processing facility comprising three main stages: scalding, fermentation, and drying. IoT sensors were installed in each room to continuously measure temperature and humidity throughout the observation period. The sensors transmitted data to a monitoring system via wireless communication, ensuring that every measurement was automatically stored in a database. In addition to temperature and humidity data, the system recorded communication parameters—specifically the Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR)—to evaluate the quality of sensor data transmission. The parameters used in the study are presented in Table 1.

Table 1. Environmental Parameters Measured by the IoT Monitoring System

Parameter	Unit	Information
Temperature	°C	Ambient temperature
Relative Humidity	%	Relative humidity
RSSI	dBm	Communication signal strength
SNR	dB	Signal-to-noise ratio
Room	-	Sensor location (Boiling, Fermentation, Drying)

Material Design Considerations Framework

The final stage of the research involves formulating material design considerations based on environmental characteristics derived from IoT monitoring results. This approach is carried out by correlating the statistical analysis findings with the material property requirements for each vanilla processing room. These relationships are outlined in Table 2.

Tabel 2. Environmental Characteristics and Corresponding Material Requirements

Environmental Characteristics	Material Considerations
High temperature	High thermal stability
High temperature fluctuations	Thermal fatigue resistance
High humidity	Moisture resistance
High humidity fluctuations	Dimensional stability
Humid environment	Corrosion resistance

3. Results and Discussion

Data Collection

The IoT monitoring system continuously recorded environmental measurements together with wireless communication quality indicators. Each record consists of the measured sensor value, communication parameters (RSSI and SNR), sensor identification, and the corresponding processing room. A sample of the raw dataset is presented in Table 3 to illustrate the structure of the collected data prior to preprocessing and statistical analysis.

Table 3. Sample of Raw Data Collected by the IoT Monitoring System

Sensor Value	RSSI (dBm)	SNR (dB)	Sensor Flag	Processing Room
72.40	-98	9.25	humidity_1	drying room
34.20	-82	9.50	temperature_1	drying room
34.30	-93	9.25	temperature_1	drying room
65.40	-81	9.25	humidity_1	drying room
…	…	…	…	…
25.49	0	0	temperature_1	boiling room
24.27	0	0	temperature_1	boiling room
25.12	0	0	temperature_1	boiling room
24.19	0	0	temperature_2	boiling room
24.98	0	0	temperature_2	boiling room
…	…	…	…	…

Sensor Value	RSSI (dBm)	SNR (dB)	Sensor Flag	Processing Room
22.66	0	0	temperature_1	fermentation room
21.89	0	0	temperature_1	fermentation room
22.76	0	0	temperature_2	fermentation room
20.81	0	0	temperature_2	fermentation room

As shown in Table 3, each observation contains both environmental information and communication quality parameters. The sensor value represents either temperature or relative humidity depending on the sensor type indicated by the Sensor Flag. Meanwhile, the RSSI and SNR values were recorded to evaluate the reliability of wireless data transmission. The collected data were subsequently cleaned, validated, and grouped according to processing room and sensor type before being used for descriptive and inferential statistical analyses.

Temperature Characteristics of the Processing Room

Temperature characterization was conducted to identify thermal conditions at each stage of the vanilla processing operation: the Boiling Room, Drying Room, and Fermentation Room. Information regarding temperature characteristics is crucial, as the thermal conditions in each room influence the processing itself and serve as a basis for determining the appropriate materials for the processing facility. Descriptive statistics for the temperature data are presented in Table 4.

Table 4. Descriptive Statistics of Temperature in the Vanilla Processing Room

Room	Mean	Median	Std	Min	Max	CV (%)
Boiling Room	43,75	33,91	20,31	22,93	100,40	46,42
Drying Room	28,20	28,26	4,47	1,00	41,61	15,85
Fermentation Room	28,06	28,05	4,39	19,82	40,99	15,63

Based on Table 4, the Scalding Room exhibited the highest average temperature at 43.75°C, whereas the Drying Room and Fermentation Room showed nearly identical average temperatures of 28.20°C and 28.06°C, respectively. This disparity indicates that the scalding process generates the highest thermal load within the overall vanilla processing workflow.

In addition to having the highest average temperature, the Scalding Room recorded a standard deviation of 20.31°C and a coefficient of variation (CV) of 46.42%. These figures are significantly higher than those of the Drying Room (15.85%) and the Fermentation Room (15.63%), indicating much greater temperature fluctuation in the Scalding Room. Conversely, the other two rooms exhibited relatively low CV values, reflecting more stable thermal conditions throughout the monitoring period.

Operationally, these results demonstrate that each stage of vanilla processing possesses distinct thermal characteristics aligned with its specific function. The Scalding Room requires high temperatures to facilitate the heating process, while the Drying and Fermentation Rooms maintain relatively constant temperatures to preserve product quality during processing.

Humidity Characteristics in the Processing Room

In addition to temperature, humidity is an environmental parameter that plays a crucial role in maintaining the quality of the vanilla processing operation. Therefore, a descriptive statistical analysis was conducted on the humidity data obtained from the IoT monitoring system.

Table 5. Descriptive Statistics of Humidity in the Vanilla Processing Room

Room	Mean	Median	Std	Min	Max	CV (%)
Drying Room	69,95	68,35	16,71	1,00	100,00	23,88
Fermentation Room	71,05	71,10	16,81	30,00	100,00	23,66

Analysis results indicate that the Fermentation Room had the highest average humidity at 71.05%, slightly higher than the Drying Room, which had an average humidity of 69.95%. This difference is relatively small, and the coefficients of variation for both rooms were nearly identical at approximately 23% indicating a relatively similar level of humidity stability.

The high humidity in the Fermentation Room aligns with the characteristics of the fermentation process, which requires an environment with sufficient moisture to support biological activity and the development of vanilla's distinctive aroma. Conversely, the Drying Room maintains slightly lower humidity as part of the process of reducing the product's moisture content before it proceeds to the next stage.

Temperature Frequency Distribution

The temperature distribution in each vanilla processing room is visualized using boxplots, as shown in Figure 2. This visualization provides information regarding the median value, interquartile range, data dispersion, and the presence of outliers in each room.

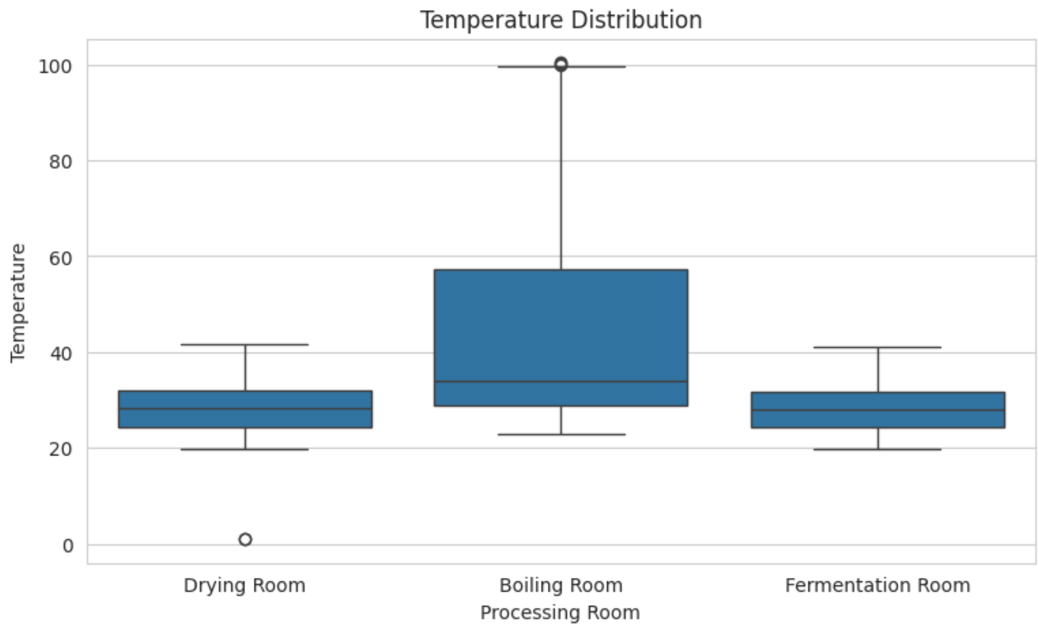

Figure 2. Boxplot of Temperature Distribution Across Vanilla Processing Rooms

Based on Figure 2, the Drying Room and Fermentation Room exhibit nearly identical temperature medians falling within the 28–30°C range—along with relatively narrow interquartile ranges. These conditions indicate that the majority of temperature data points are concentrated within a fairly uniform range, signifying relatively stable thermal conditions in both rooms throughout the monitoring period.

In contrast, the Scalding Room displays a significantly wider temperature distribution range than the other two rooms. The median temperature in this room is higher, accompanied by a larger interquartile range and longer whiskers. This indicates greater temperature variability in the Scalding Room, resulting from the periodic heating processes involved in vanilla processing.

Additionally, the boxplot reveals an outlier in the Scalding Room with a temperature reaching approximately 100°C, representing conditions where the scalding process was operating at maximum intensity. Meanwhile, a single outlier at a very low temperature is observed in the Drying Room; this was likely caused by initial measurement conditions, sensor interference, or specific operational circumstances that occurred briefly during the monitoring process.

Overall, the boxplot results reinforce the descriptive statistical findings presented in Table 4, indicating that the Boiling Room exhibits the highest level of temperature variation compared to the Drying Room and the Fermentation Room. These findings align with the higher standard deviation and coefficient of variation values observed for the Boiling Room, demonstrating that the boiling process generates the most dynamic thermal conditions among all stages of vanilla processing.

Humidity Frequency Distribution

The moisture distribution in each vanilla processing room is visualized using boxplots, as shown in Figure 3. This visualization is used to compare the median values, interquartile ranges, data dispersion, and the presence of outliers in each room.

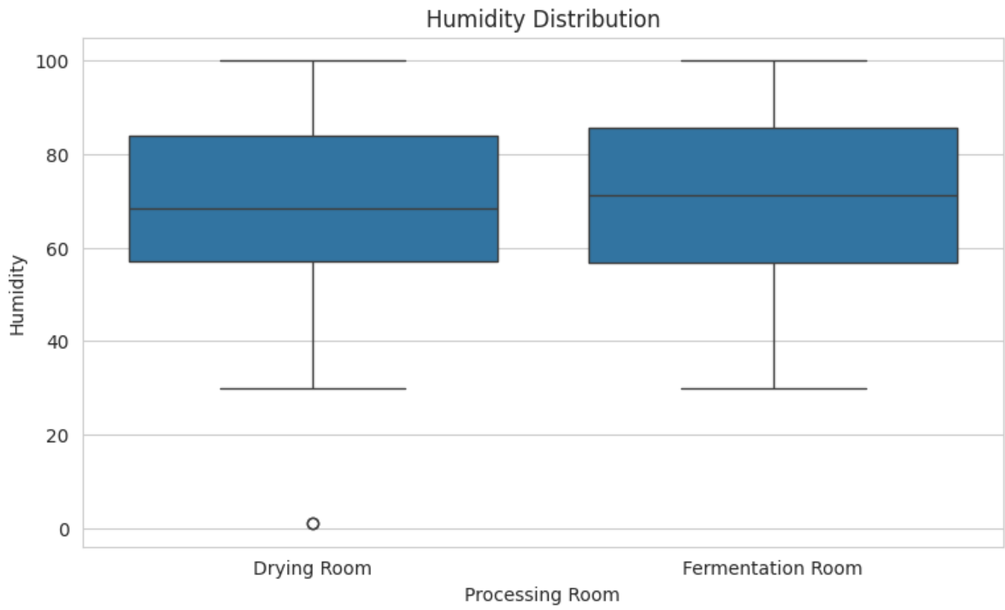

Figure 3. Boxplot of Humidity Distribution Across Vanilla Processing Rooms

Based on Figure 3, the Drying Room and the Fermentation Room exhibit relatively similar median humidity values hovering around 70% with nearly identical interquartile ranges. These results indicate that the majority of humidity data points are concentrated within a relatively consistent range, suggesting that both rooms maintained fairly stable humidity conditions throughout the observation period.

Despite having nearly identical medians, the Fermentation Room shows a slightly higher average humidity value compared to the Drying Room. This aligns with the nature of the fermentation process, which requires a high-humidity environment to preserve quality and facilitate the biochemical processes involved in vanilla processing.

Furthermore, any outliers observed in the boxplots indicate humidity levels that deviate from the typical conditions recorded during the study. Such outliers could stem from sudden environmental changes, specific operational activities, or temporary disruptions in the monitoring system. Nevertheless, the overall data distribution for both rooms displays a relatively homogeneous pattern.

These boxplot results are consistent with the descriptive statistics presented in Table 5, which show that the Drying Room and the Fermentation Room have nearly identical coefficients of variation (CV) of approximately 23%. This finding indicates that humidity variability is relatively similar in both rooms, despite their distinct operational roles within the vanilla processing workflow.

Statistical Comparison Between Rooms

To determine whether there were significant temperature differences among the vanilla processing rooms, One-Way ANOVA and Kruskal–Wallis tests were conducted. The One-Way ANOVA yielded an F-value of 1687.59 with a p-value < 0.001, while the Kruskal–Wallis test produced a statistic of 2084.98 with a p-value < 0.001. Both test results consistently indicate significant temperature differences among the vanilla processing rooms. This demonstrates that each stage of the processing workflow possesses distinct environmental characteristics corresponding to its operational function. These variations in environmental conditions show that the implementation of an IoT monitoring system can quantitatively identify thermal fluctuations, thereby serving as a basis for evaluating the processing environment and informing decision-making in vanilla processing facility management.

Correlation Analysis

To further investigate the relationship between environmental measurements and wireless communication quality, a correlation analysis was performed using the Pearson correlation coefficient. This analysis aims to determine whether variations in sensor measurements are associated with changes in communication quality, represented by the Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR). Understanding these relationships is essential to ensure that the recorded environmental data accurately reflect the actual processing conditions rather than artifacts introduced by unstable wireless communication. The correlation matrix is presented as a heatmap in Figure 4.

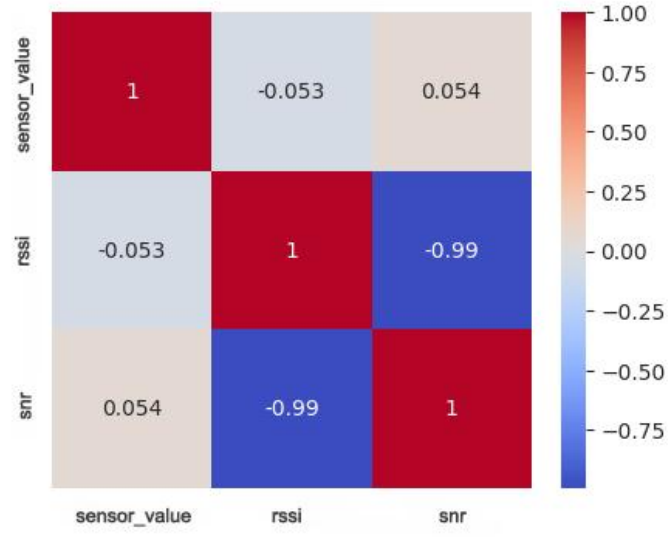

Figure 4. Correlation Heatmap of Sensor Value, RSSI, and SNR

Correlation analysis was conducted to examine the relationship between sensor readings and IoT communication quality, as represented by RSSI and Signal-to-Noise Ratio (SNR) values. As illustrated in Figure 4, the analysis reveals a very weak correlation between sensor readings and both RSSI ($r = -0.053$) and SNR ($r = 0.054$). These correlation coefficients are close to zero, indicating that variations in temperature and relative humidity recorded by the sensors are largely independent of wireless communication quality. This suggests that the environmental measurements accurately represent the actual conditions within the vanilla processing facility rather than being affected by fluctuations in signal transmission.

Conversely, RSSI and SNR exhibit a very strong negative correlation ($r = -0.99$). This inverse relationship is expected because RSSI reflects the received signal strength, whereas SNR represents the signal quality relative to background noise. As signal reception weakens, the influence of noise becomes more dominant, resulting in lower SNR values. The observed correlation therefore confirms the consistency of the wireless communication characteristics throughout the monitoring process and demonstrates that the IoT monitoring system maintained stable data transmission performance.

Overall, these findings indicate that the environmental dataset used in this study possesses a high level of reliability, making it suitable for environmental characterization and subsequent statistical analyses. More importantly, the weak relationship between sensor measurements and communication quality increases confidence that the identified environmental characteristics originate from actual operational conditions rather than communication artifacts. Consequently, the proposed Material Design Considerations are established on reliable IoT monitoring data, strengthening the validity of the engineering recommendations derived from this study.

In addition to comparing temperature variations using boxplots and violin plots, the frequency distribution of temperatures in each room was analyzed using histograms combined with Kernel Density Estimation (KDE). This visualization provides an overview of temperature data dispersion patterns, measurement ranges, and distribution trends within each vanilla processing room. Thus, the histograms and KDE curves complement the descriptive statistics in identifying the thermal characteristics of each processing stage.

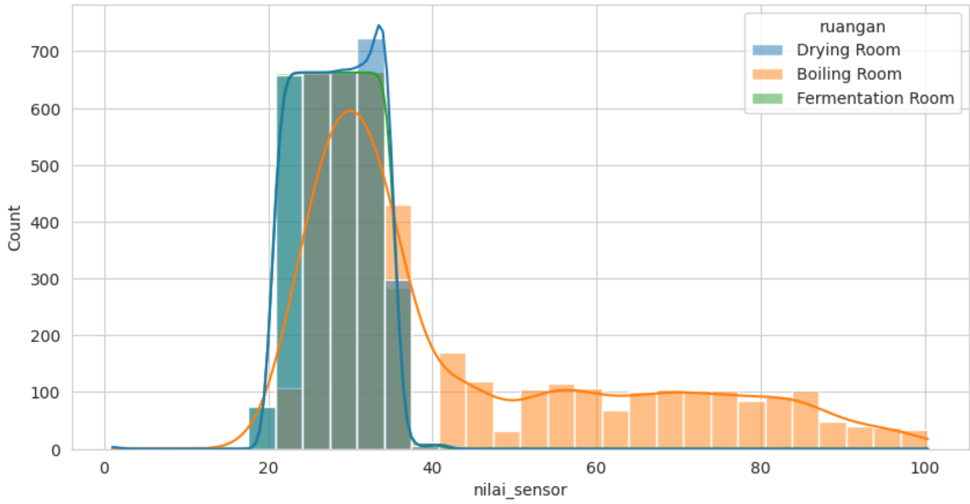

Figure 5. Temperature Distribution Across Vanilla Processing Rooms

Figure 5 illustrates the temperature distribution in each vanilla processing room, based on histograms and Kernel Density Estimation (KDE) curves. Temperature distributions in the Drying Room and Fermentation Room are concentrated within the 22–35°C range, with peaks occurring around 28–30°C. This pattern indicates that the majority of measurements fall within a relatively uniform temperature range, signifying stable thermal conditions in both rooms throughout the monitoring period.

In contrast, the Boiling Room exhibits a much broader distribution, spanning temperatures from approximately 23°C to 100°C. The KDE curve reveals that while most data points remain concentrated between 30°C and 35°C, the distribution extends to very high temperatures. This pattern suggests that high temperatures occur only during specific intervals when the boiling process is active, whereas temperatures return to lower ranges at other times. These characteristics explain why the Boiling Room displays significantly higher standard deviation and coefficient of variation values compared to the other two rooms.

Furthermore, the KDE curves for the Drying Room and Fermentation Room are relatively narrow and symmetrical, whereas the curve for the Boiling Room tends to be broader with a longer distribution tail. This difference indicates that the boiling process creates more dynamic thermal conditions than the fermentation or drying processes.

These findings align with the results of descriptive statistics, boxplots, violin plots, and ANOVA and Kruskal–Wallis tests, all of which demonstrate significant differences in temperature characteristics among the vanilla processing rooms.

Material Design Considerations

This study not only focuses on characterizing temperature and humidity within vanilla processing rooms but also develops an approach based on "Material Design Considerations" utilizing environmental monitoring data to inform the selection of materials suited to the specific operational conditions of each room. The results indicate that the Boiling Room exhibits the highest average temperature (43.75°C) with a coefficient of variation reaching 46.42%, signaling significant temperature fluctuations caused by periodic heating processes. Such conditions can induce repeated material expansion and contraction, thereby increasing the risk of micro-cracking, deformation, and the degradation of mechanical properties (Cama et al., 2025; Huang et al., 2025).

Given these characteristics, materials used in the Boiling Room should possess high thermal stability and resistance to thermal fatigue. Potential material alternatives for this area include technical ceramics, heat-resistant steels, and high-thermal-stability composites. Meanwhile, the Fermentation Room records the highest average humidity (71.05%) alongside relatively stable temperatures. This humid environment poses risks such as increased water absorption, accelerated corrosion of metallic materials, and the promotion of microbial growth, all of which can reduce the facility's service life (Lv et al., 2024). Therefore, the materials used in this room should offer moisture resistance and corrosion resistance, as well as an easy-to-clean surface. Suitable alternatives include water-resistant polymers, hydrophobic coatings, and composites with low water absorption (Rungruangkitkrai et al., 2024).

Meanwhile, the drying room maintains relatively stable temperature and humidity levels, so it does not require materials with the same high level of thermal resistance as the boiling room. Nevertheless, the temperature and humidity fluctuations that do occur during the drying process necessitate materials with good dimensional stability regarding moisture content changes, in order to minimize deformation caused by moisture absorption and desorption cycles. A summary of the relationship between environmental monitoring results and material selection considerations is presented in Table 6.

Table 6. Material Design Considerations Based on IoT Monitoring Results in the Vanilla Processing Room

Environmental Analysis Results	Research Findings	Material Considerations	Material Sample
High temperature	The Boiling Room has the highest average temperature (43.75°C).	High thermal stability	Technical ceramics, heat-resistant steel, heat-resistant composites
High temperature fluctuations	The Coefficient of Variation (CV) for the boiling room temperature was 46.42%.	Thermal fatigue resistance	Technical ceramics, superalloys, thermally stable composites
High humidity	The fermentation room has the highest average humidity (71.05%).	Resistance to moisture	Water-resistant polymers, hydrophobic coatings, composites with low water absorption
Humidity fluctuations	Humidity level of approximately 23% in the drying and fermentation room.	Dimensional stability with respect to changes in moisture content	Dimensionally stable composites, engineering polymers, low-thermal-expansion materials

Overall, this study demonstrates that environmental data obtained via IoT monitoring systems is not only useful for monitoring vanilla processing conditions but can also serve as a basis for determining material property requirements for each processing room. The "Material Design Considerations" approach offers added value compared to conventional environmental monitoring studies by linking environmental characterization with recommendations for material properties suited to operational conditions (Sun et al., 2023; Willskytt et al., 2020). Thus, this research serves as an initial step toward integrating IoT technology and materials engineering to support the development of more reliable, efficient, and sustainable vanilla processing facilities.

4. Conclusions

This study successfully characterized temperature and relative humidity conditions within a vanilla processing facility using an IoT monitoring system. Analysis revealed distinct environmental characteristics across the different rooms: the Boiling Room exhibited the highest thermal load and greatest temperature fluctuations, while the Fermentation Room showed the highest humidity levels. The developed "Material Design Considerations" approach successfully translated monitoring data into technical recommendations for material selection tailored to the specific operational conditions of each room—prioritizing attributes such as high thermal stability, thermal fatigue resistance, moisture resistance, and corrosion resistance.

This study has several limitations: (1) monitoring was conducted at only one vanilla processing facility, meaning the results cannot yet be generalized to facilities of different scales or designs; (2) the observation period was limited; and (3) the material analysis consisted of preliminary recommendations based on environmental characteristics and did not involve direct field testing of materials. Future research is recommended to: (1) expand monitoring to multiple vanilla facilities varying in location and production scale; (2) experimentally test material durability based on the generated "Material Design Considerations"; (3) integrate the IoT system with a machine-learning-based prediction platform for early warning of environmental conditions; and (4) evaluate the economic and sustainability aspects of the proposed material recommendations.

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