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Original Research Article

Analysis of Quality Loss in The Roasted Coffee Bean Storage and Improvement Based on Internet of Things (IoT)

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Abstract: The quality of coffee is of paramount importance, and this study focuses on analysing the moisture content, pH, and CO_2 degassing rate of roasted coffee beans to determine the effect of ambient storage on their quality. Ambient storage with fluctuating temperature conditions is commonly found in coffee shops. During the study, ambient temperature fluctuated in the range from 26.5 to 32.5°C. The study revealed that the ambient storage temperature has no significant impact on the moisture content and pH of the roasted coffee beans during the eight-day storage. However, a noticeable variation in the CO_2 degassing rate was observed during the storage across this temperature range. When the storage temperature increased, the CO_2 release was also increased from the beans during the first four days. The sensory evaluation with coffee experts further confirmed the detrimental effects of ambient temperature on coffee cup's sensory properties, which were perceived as freshness qualities for the consumers. Statistical analysis showed a high Pearson correlation coefficient of r =-0.914 between the cumulative CO_2 degassing and the overall sensory score. This negative correlation suggests that as the cumulative CO_2 degassing rapidly increases, the overall sensory score decreases. This can be attributed to the fast depletion of CO_2 inside the coffee beans, leading to faster oxidation as well as a decline in the desired sensory qualities and the overall quality of the coffee. Notably, a threshold ambient temperature of 30.7°C was identified, beyond which the rate of CO_2 degassing accelerated significantly. The implementation of an Internet of Things (IoT)-based monitoring system was proposed to detect the threshold temperature conditions that led to rapid CO_2 degassing. When such a temperature was approached, the system would promptly send alert notifications, enabling swift corrective actions to maintain the coffee's quality. This study underscores the importance of timely interventions to ensure the preservation of coffee quality throughout the storage process.

Keywords: Coffee quality; Coffee degassing; CO_2 degassing; Oxidation; Coffee staling; IoT-based monitoring system; Coffee storage; Digitalisation.

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1. Introduction

Coffee is one of the most popular beverages consumed worldwide, with a rich history and a diverse range of flavours and preparations. Over the years, there has been a significant increase in coffee consumption across various regions (Berampu *et al*., 2019). This surge can be attributed to multiple factors, including shifting cultural norms, globalisation, and the emergence of coffee as a lifestyle choice (Grinshpun, 2014; Abdul Ghani *et al*., 2019). Freshness plays a vital role in ensuring the optimal taste and aroma of coffee (Yeretzian *et al*., 2017). Consumers have become increasingly aware of the impact of freshness on their coffee-drinking experience, seeking the highest quality beans to satisfy their discerning palates. The quality of roasted beans directly affects the overall freshness of the coffee and contributes to its desirable taste and aroma (Yeretzian *et al.*, 2017). These beans undergo meticulous roasting techniques that bring out their unique flavours and characteristics. As a result, they retain their freshness for a longer period, ensuring a more satisfying coffee-drinking experience. On the other hand, lower-quality roasted beans may lack some level of freshness and can result in a less enjoyable cup of coffee.

Roasting initiates the formation of CO_2 and other volatile compounds through a combination of chemical reactions and physical changes that occur within the beans (Kreuml *et al*., 2013; Schenker & Rothgeb, 2017; Yeretzian *et al.*, 2017). The formation of CO_2 and other volatile compounds results in an increased internal pressure, causing the coffee beans to expand and eventually crack (Wang & Lim, 2015; Schenker & Rothgeb, 2017). Although much of the CO_2 produced is lost during roasting, significant portions of CO_2 remain trapped in the beans, which slowly diffuse out during subsequent storage (Wang & Lim, 2015). Such a phenomenon is called degassing and is essential for flavour development (Poltronieri & Rossi, 2016). Nevertheless, the degassing of CO_2 can also lead to a decline in freshness over time during storage (Smrke *et al*., 2017). The rate of CO_2 degassing in coffee beans during storage is greatly influenced by temperature (Yeretzian & Wyser, 2017). The loss of CO_2 becomes a contributing factor to coffee staling. Staling is a term commonly used in the context of coffee to describe the gradual deterioration of flavour and aroma over time. CO_2 acts as a natural preservative, helping to slow down the oxidation process that leads to flavour deterioration. As coffee beans age and lose their CO_2 content, they become more susceptible to the effects of oxygen and moisture, resulting in accelerated staling.

Another important freshness quality of the roasted beans is the pH of the brewed coffee. When coffee beans are freshly roasted, they tend to produce a more acidic brew, characterised by a lower pH value. This acidity contributes to the bright and vibrant flavours commonly associated with high-quality coffee. A preferable pH range for a palatable coffee experience typically ranges from 4.95 to 5.20 (Pareira & Moreira, 2021). As coffee beans age, however, their acidity gradually diminishes, leading to an increase in the pH of the brewed coffee. This change in pH can impact the perceived taste and overall enjoyment of the beverage (Kong *et al.,* 2020). In terms of sensory evaluation, a good quality coffee involves a well-balanced acidity with a fruity, aromatic note, and is rounded by a slight almond aroma (Pareira & Moreira, 2021). Yüksel *et al*. (2020) observed that brewed coffee has a decreasing value of pH during storage, transitioning from around 5.2 to approximately 4.8. This decline in pH is attributed to the formation of hydrogen ions, a phenomenon that typically occurs as coffee loses its freshness (Yüksel *et al*., 2020). Besides, carboxylic acid is known as the largest group of organic acids in coffee. It plays a significant role in coffee's acidity by generating a substantial quantity of hydrogen ions, resulting in a sour taste in the coffee beverage (Pareira & Moreira, 2021). Consequently, the presence of carboxylic acids and carbonic acid in coffee collectively contributes to heightened acidity, lowering the pH of the coffee.

The freshness of coffee beans is also closely tied to the moisture content of the beans. Coffee beans can absorb moisture from their surrounding environment. This can occur when the beans are exposed to high humidity or stored in an environment with excess moisture (Corrêa *et al*., 2016). When coffee beans absorb moisture, it can impact their freshness and overall quality. Excess moisture can lead to the growth of mould and the development of off-flavours (Basha *et al*., 2021). It can also cause the beans to lose their desirable aroma and taste.

Extreme variations or prolonged exposure to unfavourable storage conditions, especially temperature, can affect the quality of the coffee beans. Fluctuations in storage temperature for coffee shops and small roasteries are common, where coffee is usually stored on shelves or storage room at fluctuating ambient temperature, sometimes with inefficient air conditioning. The importance of having an Internet of Things (IoT)-based monitoring system for coffee bean storage is to enable remote monitoring, allowing food business operators to continuously track temperature conditions as well as receive instant alerts if there are any deviations from the desired range. An IoT-based system is reported to enable a timely corrective action and could prevent further quality deterioration for the food and beverage industries (Hasnan *et al*., 2023). Such a system is particularly beneficial for small coffee shops striving to serve or sell fresh coffee yet face challenges in automatically controlling the temperature of their premises or storage areas, which directly impacts the freshness of their coffee beans. With the above background, the study aims to: 1) determine how ambient storage conditions affect moisture content, pH, CO_2 degassing, and sensory properties of coffee, 2) identify the ambient temperature threshold that accelerate the quality deterioration during storage, and 3) develop an IoT monitoring system based on storage temperature data for delaying the deterioration of the roasted coffee beans. It is crucial to acknowledge that the findings of this study are specific to the prepared bean sample and may differ when applied to other coffee beans with varying varieties, qualities, preparation methods, roasting techniques, and storage conditions, as well as duration.

2. Materials and Methods

2.1. Procurement of Roasted Bean and Preparation

Medium roast Arabica coffee beans were obtained from a reliable supplier and packed in 200 g portions using one-way valve packaging to preserve freshness. All beans were sourced from the same roasting batch and delivered to the laboratory within 24 h of roasting. The one-way valve in each package allowed CO_2 to escape without letting external air in. Upon arrival, eight packs (Pack 1 to Pack 8) from the same batch were stored in a dark environment with fluctuating temperatures (26.5°C to 32.5°C) for daily analysis of moisture content and pH. These fluctuations in ambient temperature align with the conditions observed in our collaborative industries in Bangi and Kajang, Malaysia. An additional pack (Pack 9) from the same batch was sealed in a Ziplock bag to capture the released CO_2, which was then measured using a sensor (SCD30 Grove, Cytron, Malaysia) for CO_2 concentration, temperature, and humidity. This pack remained undisturbed and was stored alongside the other samples. Measurements were taken over an eight-day period, a duration chosen based on the practices of collaborating coffee shops that use beans within one week to maintain the freshness of brewed coffee.

2.2. Measurement of Moisture Content (MC)

The daily analysis of moisture content adopted the method from Qi *et al.* (2023). The coffee beans were ground and quickly tested using a moisture analyser (XM50, Precisa, Switzerland) as in Figure 1. The temperature of the moisture analyser was 120°C and a standard mode was selected. The amount needed to be weighed inside the moisture analyser was approximately 3 g. The moisture content was determined directly from the moisture analyser. The sample was measured in triplicate, and the average values were determined.

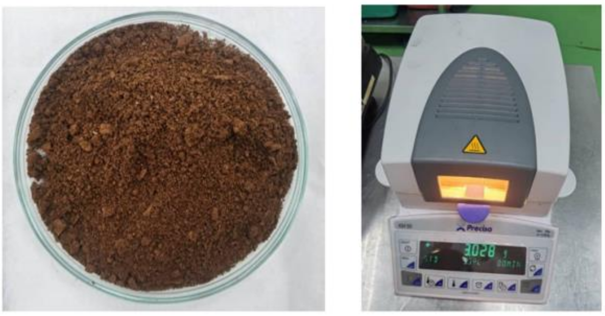

Figure 1. Moisture analyses

2.3. Measurement of pH

A coffee espresso for daily pH analysis was prepared using a coffee maker (Clear, AeroPress, USA). The AeroPress was prepared by placing a filter paper into the filter cap and twisting it securely onto the chamber. The chamber was then positioned on top of a 250 mL beaker. Next, 15 g of roasted ground coffee beans were added to the chamber, followed by the addition of 125 mL of hot water (85°C). The mixture was gently stirred for 10 s to ensure proper saturation. Subsequently, the plunger was inserted into the chamber, leaving a gap of approximately 1 cm, and left to sit for 30 s. Applying a gentle, constant pressure, the plunger was pressed down, causing the espresso to drip into the beaker. The pH value of the espresso sample was measured daily using a calibrated pH meter (PB-10, Sartorius, Germany). The sample was measured in triplicate, and the average values were determined.

2.4. Measurement of CO_2 Cumulative Released Concentration and Degassing Rate

Pack 9 of the roasted coffee beans was placed inside a Ziplock bag along with the SCD30 sensor to measure both the storage temperature and the CO_2 release rate. The sensor was also able to detect the humidity of the storage, which remained relatively constant at 61% ± 2%. The continuous measurements of storage temperature and CO_2 release were recorded daily for a duration up to 8 days. To enable continuous data transmission without disturbing the collection of CO_2 gas, a microcontroller and a Wi-Fi network were utilised to send the collected temperature data to ThingSpeak, an IoT-based platform. The purpose of the Ziplock bag was to prevent the CO_2 released from the one-way valve packaging of the beans from escaping into the surrounding environment. The SCD30 sensor inside the Ziplock bag, thus was able to measure the accumulated CO_2 levels for every 24 h in ppm as well as the storage temperature within the bag. The daily degassing rate of CO_2 (R_n), released, was determined based on the following Equation 1 as adopted from Geiger *et al.* (2005):

$$R_n = RC_n - RC_{n-1} \tag{1}$$

where,

R_n : degassing rate of CO_2 for day *n*

RC_n : cumulative degassing of CO_2 on day *n*

RC_{n-1} : cumulative degassing of CO_2 on day *n-1*

2.5. Sensory Evaluation

The cupping evaluation of Arabica coffee was conducted following a standardised and widely accepted methodology. The beans were ground to a consistent particle size suitable for cupping, ensuring uniform extraction (von Blittersdorff & Klatt, 2017). A cupping table was set up, providing an individual cup for each panellist to maintain separation and prevent cross-contamination. To ensure a controlled environment, consistent lighting and temperature were maintained throughout the evaluation. Three well-trained and certified panellists were selected for the sensory evaluation and were experienced in coffee cupping techniques, as they were readily certified and familiar with the sensory attributes of Arabica coffee. The evaluation used a 5-point Likert scale to rate the sensory attributes, including aroma, taste, body, acidity, and aftertaste. The Likert scale ratings ranged from 1 (poor) to 5 (excellent).

2.6. Determination of the Threshold Temperature Value That Increases the CO2 Degassing Rate

The setup of the experiment was the same as in Section 2.4 since the sensor SCD30 was able to measure the storage temperature as well. This investigation aimed to pinpoint the specific temperature at which the degassing initiates accelerated progression. Temperature surpassing this threshold level leads to an increased rate of degassing, ultimately resulting in the deterioration of coffee bean quality. Consequently, recording the threshold temperature becomes imperative for sustaining a stable CO_2 degassing rate below this critical threshold, thereby extending the freshness of the coffee beans.

2.7. Development of an IoT-Based Monitoring System for Roasted Coffee Beans Based on Storage Temperature

Several elements are required in an IoT-based system, such as real-time monitoring, remote accessibility, alert and notifications, data logging and storage, scalability and energy efficiency (Mohammed *et al*., 2022; Chong *et al*., 2023). Table 1 below shows the services and facilities that were required for developing the IoT-based system. Figure 2 shows the required coding that needs to be developed in Arduino IDE for temperature monitoring and in ThingSpeak for alert notification.

Table 1. Requirement of services and facilities for developing the IoT-based monitoring system for roasted coffee beans

No.	Service/facility	Requirements of the IoT-based system
1.	Sensor Network	• Capture temperature readings and wirelessly transmit data to a centralised gateway or cloud platform.
2.	Gateway/Cloud Platform	• Serve as a central hub for receiving and processing temperature data from sensors. • Conduct data aggregation, filtering, and preprocessing tasks prior to securely storing the data.
3.	Communication Protocols	• Employ standard communication protocols like Wi-Fi or cellular networks for data transfer from sensors to the gateway/cloud platform.
4.	Data Storage and Management	• Store temperature data in a database or cloud storage for long-term storage and retrieval. • Enable efficient querying and retrieval of historical data to facilitate analysis and reporting.
5.	User Interface	• Offer user-friendly web or mobile interfaces for authorised users to access real-time temperature data, view historical trends, set temperature thresholds, configure alerts, and manage system settings.
6.	Analytics and Reporting	• Incorporate data analytics capabilities to perform statistical analysis, generate reports, and visualise temperature trends. • Assist in identifying anomalies, patterns, and areas for potential improvement.
7.	Security and Authentication	• Implement robust security measures to protect data integrity and ensure secure access. • Include authentication mechanisms, encryption protocols, and access control policies to prevent unauthorised access or tampering.

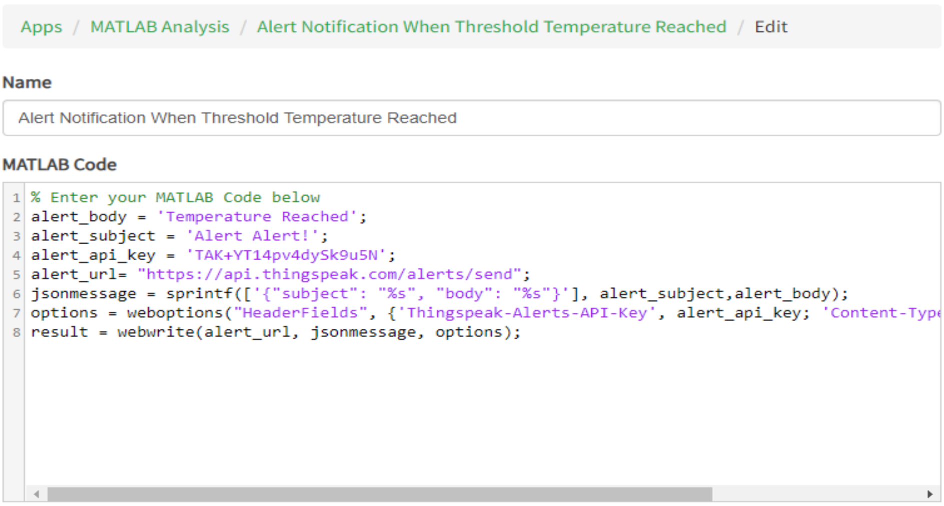

Figure 2. Coding for temperature monitoring and alert

2.8. Testing and Analysis of the Designated IoT-Based Storage Monitoring System

This step involves verifying whether the system meets and performs the defined requirements as presented in Table 2. This evaluation was adopted from Mohammed *et al.* (2022) and Chong *et al.* (2023).

Table 2: Performance testing of IoT-based storage monitoring system

	Analysis	Procedure
Functions	Real Time Monitoring	• Verify that the system provides real-time temperature monitoring and a prompt display on the user interface.
	Remote Accessibility	• Test the system's remote accessibility by accessing the user interface from various locations and devices to ensure that authorised personnel can monitor temperature data remotely.
	Alerts & Notifications	• Trigger temperature deviations intentionally to validate if the system generates and delivers alerts or notifications promptly to the designated recipients.
	Data Logging and Storage	• Verify that the system correctly logs temperature data at regular intervals and stores it securely in the designated database or cloud storage.
Performance Testing	Response Time	• Measure the system's response time by simulating temperature variations and observing how quickly the system detects and reflects these changes on the user interface.
	Energy Efficiency	• Evaluate the energy efficiency of the monitoring devices/sensors by monitoring their power consumption and battery life. Ensure that they meet the specified requirements and do not drain power excessively.
Security Testing	Authentication and Authorisation	• Verify the system's authentication mechanisms by attempting unauthorised access. Ensure that only authorised users can access the system and perform relevant actions.
	Data Encryption	• Validate that data transmitted between sensors, gateways, and the cloud platform is encrypted to maintain data integrity and prevent unauthorised access.
Data Analysis	Historical Data Analysis	• Analyse the stored temperature data to identify trends, patterns, and anomalies. Validate that the system provides accurate and reliable historical data for further analysis and reporting.
	Reporting and Visualisation	• Generate reports and visualisations based on historical data to assess the system's reporting capabilities. Ensure that the reports provide meaningful insights and assist in decision-making.

3. Results and Discussions

This section reports and discusses the analyses of the moisture content, pH of the brewed coffee, CO_2 degassing and sensory properties. The measurement was taken continuously for the first day, Day-1, after roasting until Day-8. The relative humidity of the storage was maintained at 61% ± 2%. The daily storage temperature during this period exhibited a range of 26.5°C to 32.5°C. The storage temperature variations were a result of uncontrollable factors, including customer activity such as opening doors, the presence of a crowded environment, and the heat generated during the brewing process.

3.1. Effect of Ambient Storage on the Bean's Moisture Content and pH of the Brewed Coffee

Table 3 shows the effect of ambient storage on the beans' moisture content and pH of the brewed coffee. Upon analysis of the data, it was observed that there were non-significant differences in the moisture content and pH of the brewed coffee across the storage duration. This suggests that the ambient storage did not have a substantial impact on these two factors within the first week of storage for the sampled coffee beans. Monitoring the moisture content of coffee beans is crucial in maintaining the quality and flavour of brewed coffee. Changes in moisture content can result in variations in taste, aroma, and overall beverage quality. However, in this study, the moisture content of the beans remained relatively stable during the eight-day storage, indicating that the storage conditions did not lead to significant moisture loss or gain for the tested coffee beans. The range of moisture content obtained was between 2.01 to 2.21% which was within the range of 1 to 5% as reported by Yusibani *et al.* (2023) and Bolka and Emire (2020) for roasted coffee beans of the Arabica variety. Similarly, the present study indicates that storage temperature did not have a significant impact on the pH of coffee over the eight-day storage in the range of 5.06 to 5.08. This is because, according to Muzykiewicz-Szymańska *et al.* (2021), the pH is commonly affected by other factors such as the brewing method (hot or cold), the degree of roasting, and the fineness of the bean grinding.

Table 3. Average moisture content of ground coffee bean and pH of the brewed coffee within 8 days of storage time

Storage Time (Day)	Average Moisture Content (%)	pH of the Brewed Coffee
0 (initial)	2.07 ± 0.08^a	5.06 ± 0.06^a
1	2.01 ± 0.01^a	5.06 ± 0.08^a
2	2.03 ± 0.04^a	5.08 ± 0.10^a
3	2.01 ± 0.03^a	5.06 ± 0.02^a
4	2.03 ± 0.01^a	5.06 ± 0.08^a
5	$2.05 + 0.02^a$	5.06 ± 0.03^a
6	2.06 ± 0.00^a	5.06 ± 0.15^a
7	2.13 ± 0.01^a	5.06 ± 0.21^a
8	2.21 ± 0.01^a	5.08 ± 0.13^a

*Values followed by the same letter within the same column are not significantly different from each other (p>0.05). All values are reported as mean ± standard deviation.

3.2. Effect of Ambient Storage on the Cumulative CO_2 Released Concentration

In Figure 3 below, it was observed that during the ambient storage period from Day 1 to Day 8, the concentration of CO_2 degassing (measured in parts per million, ppm) inside the collection bag exhibited an increasing trend until Day 4. However, after Day 4, the CO_2 concentration reached a plateau and remained relatively stable until Day 8. The initial rise in CO_2 levels within the collection bags corresponded with a simultaneous decrease in CO_2 content inside the coffee beans. This decrease was attributed to the degassing behaviour of the coffee beans, where CO_2 naturally escapes from the beans over time. The stagnation of CO_2 degassing after Day 4 suggests that most of the CO_2 trapped in the coffee beans has been released by this point. Since CO_2 plays a crucial role in creating crema in espresso, which adds to the sensory appeal of brewed coffee, this plateau indicates that after Day 4, the beans may begin to lose their ability to form a desirable crema and could result in a potentially flatter taste.

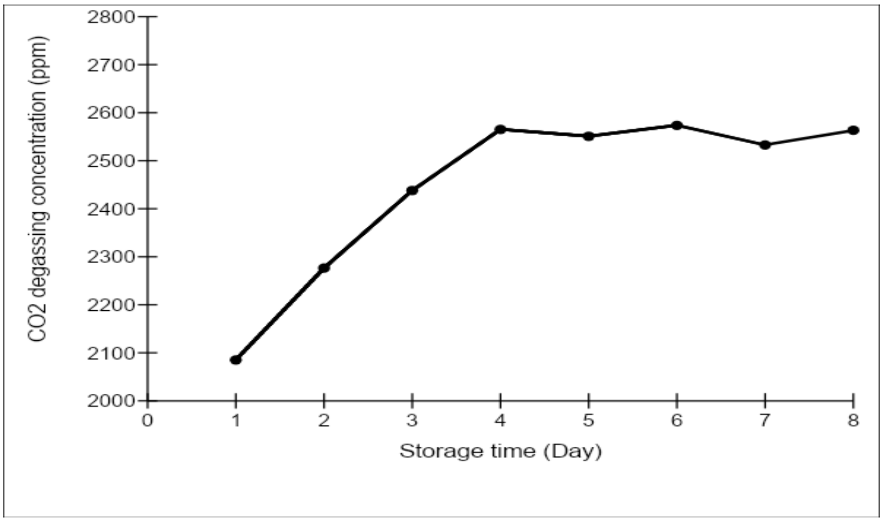

Figure 3: Concentration of CO_2 degassed during 8 days of ambient storage time

The initial increasing trend in CO_2 degassing indicates that the coffee beans were actively releasing CO_2 during the early days of storage, which is a natural process as the trapped CO_2 within the beans was gradually released over time, and this was collected in the collection bag. According to Smrke *et al.* (2022), the degassing happens mainly due to two mechanisms: 1) the diffusion flow due to a CO_2 concentration differential and 2) hydrodynamic flow due to pressure differentials, namely the pressure-driven flow of CO_2 out of the coffee particles since the pressure of CO_2 inside the beans is greater than one atmosphere.

The stabilisation of the CO_2 concentration inside the collection bag from Day 4 suggests that most of the initial degassing had occurred from the beans and the rate of CO_2 release had reached a relatively constant level. This finding was consistent with previous studies conducted by Geiger *et al.* (2005) and Smrke *et al.* (2022), who reported similar trends. Smrke *et al.* (2022) observed that the cumulative emission of CO_2 from the beans showed an increasing trend during the initial storage period, and then became stagnant within less than 10 days. Similarly, Geiger *et al*. (2005) discovered a comparable trend within a 20-day storage period. The variation in the duration for the emission to become stagnant could be attributed to differences in coffee bean varieties and roasting degrees, which influence the CO_2 generation and release dynamics. This stability could indicate a state where the beans reach a point where most of the trapped CO_2 has been released. At this stage, the rate of CO_2 release tends to stabilise as the remaining gas inside the beans reaches a state of equilibrium with the external environment, including pressure. This leads to a plateau in the CO_2 emitted concentration, indicating that a significant portion of the degassing process has occurred and deterioration in freshness has occurred due to the loss of CO_2 from the beans (Smrke *et al*., 2017; Wang & Lim, 2015; Smrke *et al*., 2022). A plateau in CO_2 emission concentration can indeed indicate that a significant portion of the degassing process has occurred.

Based on the above discussion, the study proceeded to further analyse the possible correlation between the daily CO_2 degassing rate and the recorded average daily temperature as depicted in Table 4 below. In the initial 4 days, a high degassing rate was detected and attributed to the CO_2 diffusion from the beans to the external environment. In this duration, the degassing rate was strongly dependent on the ambient temperature, with the Pearson correlation coefficient $r = 0.7$. This diffusion process was highly influenced by the storage temperature, whereby the highest rate was on Day 1 with the average temperature of 31.5℃ on that day. After the fourth day, the degassing rate decreased, as it became dependent on the remaining CO_2 concentration inside the beans, which had significantly depleted. At this point, Smrke *et al*. (2022) found that coffee has lost its freshness due to a major release of CO_2 from the beans had occurred. This allows oxygen to enter the bean and oxidise flavour compounds that are important for coffee's enticing quality. This loss of CO_2 was also undesirable because the gas plays a crucial role in forming crema during espresso brewing. Crema is important in espresso due to its visual appeal, flavour protection, contribution to the mouthfeel, taste balance, and reflection of freshness. These findings highlight the importance of controlling the storage temperature to delay CO_2 loss. By avoiding excessively high storage temperatures, the retention of CO_2 can be enhanced.

Table 4: Daily Degassing Rate and Average Daily Temperature

Day	Daily Degassing Rate (ppm/day)	Average daily Temperature (℃)
1	333.14	31.5
2	191.30	31.4
3	161.67	31.0
4	127.12	29.5
5	-14.27	29.7
6	22.72	29.7
7	-40.82	29.8
8	30.40	29.5

However, after Day 4, a change in the degassing pattern was noted. The rate of CO_2 release becomes almost stagnant. These observations provide insights into the behaviour of CO_2 release during the early stages of storage and highlight the influence of storage temperature on the degassing process during the initial storage time. The correlation between the increasing daily degassing rate and storage ambient temperature, as well as pressure-driven flow, suggests their main influence on the degassing process.

3.3. Effect of Ambient Storage on the Sensory

The sensory evaluation results show a noticeable trend in the sensory properties of the coffee over the 8-day period. In the initial days, all panellists consistently rated the coffee with high scores for aroma, taste, body, acidity, and finish, indicating a good coffee experience. However, starting from Day 4, there was a significant decline in all sensory attributes when compared to the previous days ($p < 0.05$), with panellists consistently giving the lowest scores of < 2 across the board. This suggests that the coffee has lost its desirable sensory properties and experienced a degradation in quality. According to Wang and Lim (2015) and Smrke (2022), the decline in aroma, taste, body, acidity, and finish scores indicated a decrease in the overall sensory experience and the perception of freshness in the coffee, which was also obtained in this study, as shown in Figure 4 below.

Statistical analysis showed a high Pearson correlation coefficient of $r=-0.914$ between the cumulative CO_2 degassing and the overall score in the sensory evaluation. This negative correlation suggests that as the cumulative CO_2 degassing increases in the collection bag, the overall score in the sensory evaluation decreases. This can be attributed to the depletion of CO_2 inside the coffee beans, leading to a decline in the desired sensory qualities and the overall quality of the coffee. As more CO_2 was lost from the coffee over time, a corresponding decline in the perceived sensory quality was observed. This finding is in accordance with the study conducted by Wang and Lim (2015), who reported that the CO_2 degassing process could lead to losses in quality and volatile aroma compounds. Therefore, the loss of CO_2 may contribute to decreased aroma, flavour, body, acidity, and finish, as observed in the sensory scores. Since the moisture content and pH value of brewed coffee have no significant difference in this study, thus, they do not have an impact on the sensory properties. These findings emphasise the importance of controlling the CO_2 degassing rate to maintain the desired sensory properties of the studied coffee beans by monitoring the storage temperature.

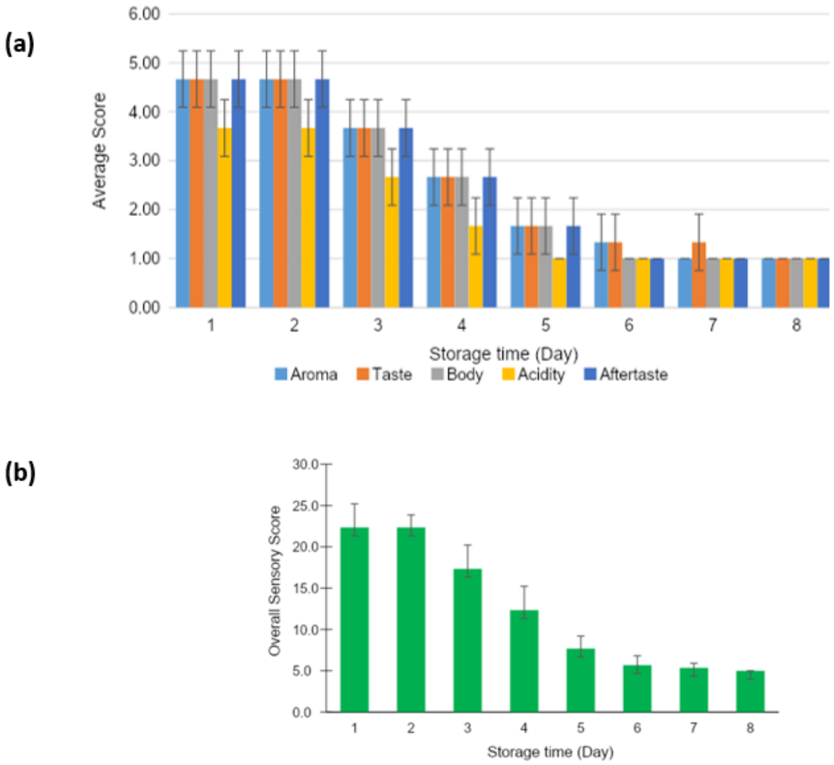

Figure 4: **(a)** Average score of sensory properties based on daily sensory evaluation results and **(b)** overall sensory score against storage time

3.4. Threshold Storage Temperature for High CO_2 Degassing Rate

According to Smrke *et al*. (2017) and Anderson *et al*. (2003), the release of CO_2 was rapid at first, with around 40% of the CO_2 present escaping within 24 h after roasting. In this study, the hourly degassing rate was further examined by analysing the hourly temperature during the first day after roasting and the corresponding degassing rate. It was found that the degassing rate reached 100.71 ppm/h when the storage temperature was 30.7°C, as early as the third hour of monitoring. Subsequent hours also showed an increasing trend in the degassing rate. According to Anderson *et al*. (2003), at this timeframe, the CO_2 diffusion has a strong temperature dependence, which subsequently affects the pressure-driven flow mechanism. Temperature affects CO_2 diffusion because it impacts the speed at which gas molecules move. Higher temperatures generally increase the kinetic energy of gas molecules, causing them to move more quickly. As a result, when the temperature is higher, the rate of CO_2 diffusion tends to be faster. The pressure difference between the inside and outside of the beans sets up a pressure gradient, driving the flow of CO_2 out of the beans (Anderson *et al*., 2003; Barrera-López *et al*., 2022). Based on Figure 5 below, it was deduced that for the sampled beans, the threshold temperature that accelerated the CO_2 degassing was 30.7°C. It was important to monitor the storage temperature of the freshly roasted product, not to exceed 30.7°C. By keeping the temperature below the identified threshold value, it would be possible to delay the deterioration of the freshness of the sampled beans caused by CO_2 degassing. This, in turn, extends the timeframe during which the coffee maintains its freshness, allowing for a prolonged and enjoyable brewing experience.

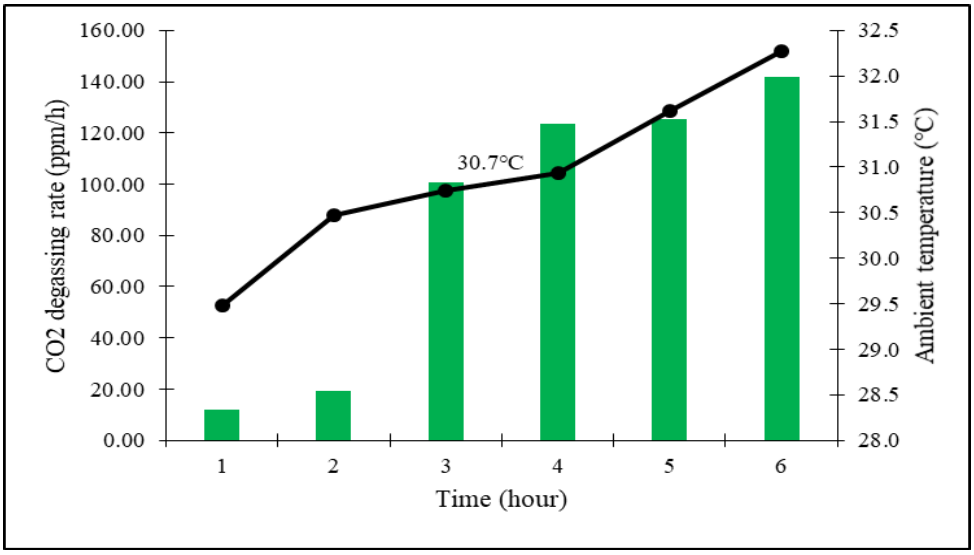

Figure 5. Correlation between CO_2 degassing rate and temperature against time to determine the threshold storage temperature

3.4. Development of IoT-Based Monitoring System for Storage Temperature

This section proposed a storage temperature monitoring system, as in Figure 6, based on IoT, which was suitable for small coffee roasters or small coffee shops. In principle, the proposed system would collect the data on the temperature from the storage area that accommodated the freshly roasted coffee beans. When the temperature approaches 30.7°C, the system would detect this as a deviation and send an alert to the inventory department. The inventory department would perform the necessary corrections to prevent further acceleration in the CO_2 degassing and further deterioration of coffee freshness. Examples of corrective action include:

1. Decrease ambient temperature using a ventilation system (air conditioning controller)
2. Shift the freshly roasted beans to the cooler storage area.
3. Perform brewing as soon as possible

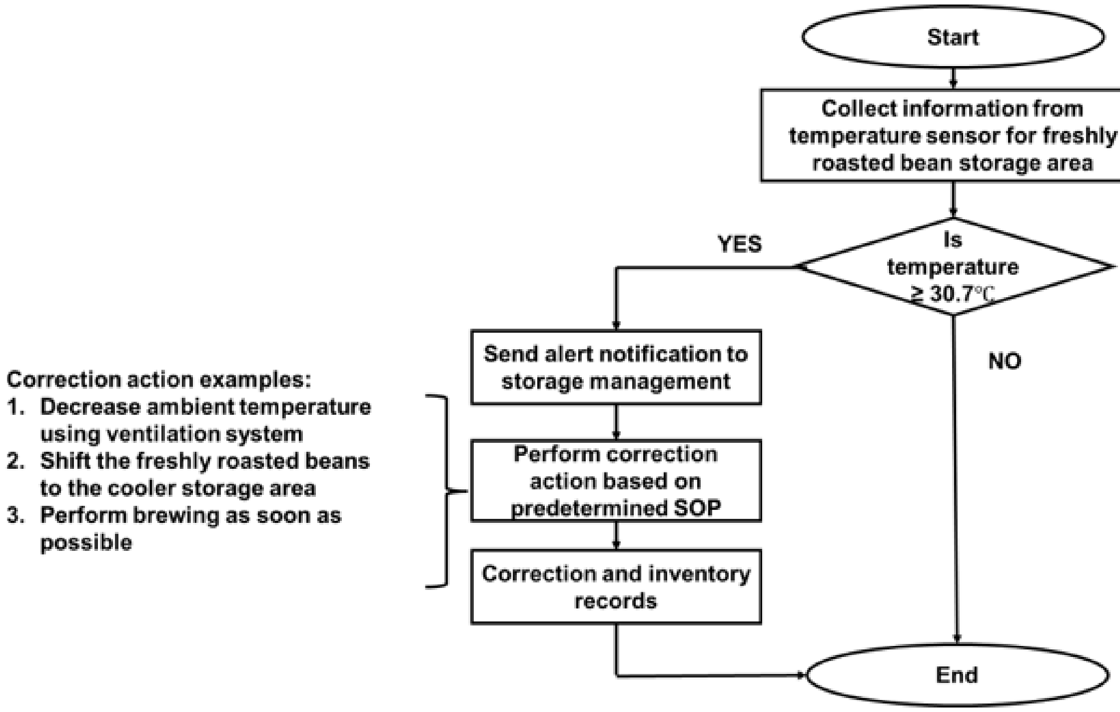

Figure 6. Framework for Temperature System Monitoring of Freshly Roasted Coffee Bean

The developed IoT architecture for monitoring the ambient storage temperature is presented in Figure 4.6. The system's architecture consists of:

- Temperature sensor
- Arduino IDE
- NodeMCU with ESP8266 onboard
- Wi-Fi network
- ThingSpeak IoT platform, ThingSpeak API, ThingSpeak channels, and ThingSpeak visualisation and analysis tools, as well as alert notification via email sent by ThingSpeak.

The IoT architecture above is depicted in Figure 7. All the components formed four modules in the system, which were 1) sensor, 2) connectivity, 3) data processing and 4) application layer. The first layer of the IoT system consists of a sensor, which is the SCD30

Grove sensor (Cytron Technologies, Malaysia). This sensor was employed to measure the temperature of storage. The sensor established communication with a connected NodeMCU, which has been programmed using the Arduino IDE. This communication took place through the I^{2}C interface, which stands for Inter-Integrated Circuit. The I2C protocol enables multiple peripheral pins to communicate with one or more microcontroller chips. The NodeMCU serves as a microcontroller and incorporates a self-contained Wi-Fi networking solution. This feature allows it to read real-time temperature from the sensor and transmit the data to the ThingSpeak server via a Wi-Fi network (communication module). The measured temperature will be sent to the ThingSpeak channel using the API key and the ThingSpeak channel. As programmed, the data transmission occurs at intervals of 20 s to ensure a continuous stream of data. In the data processing layer, the IoT platform ThingSpeak is utilised to collect, analyse, and visualise the measurement temperature obtained from the sensor. If a predefined condition is met, such as exceeding a certain temperature threshold, the system can trigger a reaction by sending alert notifications to the user through various channels, including email, SMS, or other accessible means via a mobile phone. The application layer enables users to visualise real-time temperature from anywhere and at any time using devices such as phones, tablets, or laptops. If the temperature exceeds 30.7°C, a predefined corrective action is implemented following the Standard Operating Procedure (SOP) as in Figure 7. On the other hand, if the storage temperature remains below 30.7°C, no action is required.

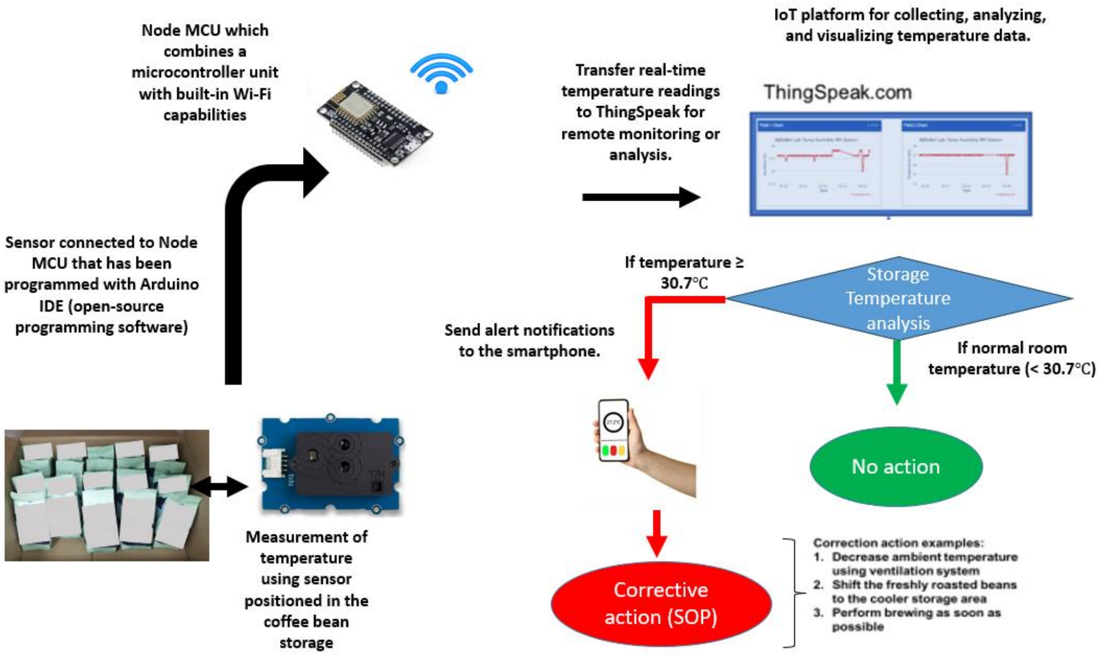

Figure 7. Proposed IoT Architecture of the roasted coffee bean storage monitoring system

3.5. Performance of the Designated IoT-Based Storage Monitoring System

Real-time monitoring allows for continuous tracking of critical parameters like temperature, humidity, and CO_2 levels, ensuring that optimal storage conditions are maintained to preserve coffee freshness. With remote accessibility, users can access this data from any location via web or mobile interfaces, enabling proactive management of storage conditions without the need for on-site presence. The system also provides alerts and notifications, which automatically inform users when parameters deviate from set thresholds, allowing immediate corrective actions to prevent quality degradation. Additionally, the system's performance evaluation reveals insights into response time and energy efficiency. Response time analysis indicates a 21s interval for ThingSpeak to receive data, implying a 1s transmission from the sensor, considering additional processing and storage time. Energy analysis highlighted a total power consumption of 6.231×10^{-3} kW, necessitating recharging of the power bank every 5.94 h to sustain continuous operation. In terms of security, ThingSpeak ensures authentication and authorisation through user accounts and API key authentication, safeguarding data integrity. Data encryption using HTTPS protocols enhances data transmission security, complemented by the option to share data securely. Furthermore, the system facilitates historical data analysis and visualisation, empowering users to derive insights from graphical representations, facilitating informed decision-making.

4. Conclusions

While ambient storage temperatures between 26.5 to 32.5°C show minimal impact on moisture content and pH for the studied coffee beans, rapid CO_2 degassing occurs within the initial four days post-roasting, reaching equilibrium by Day 8. Higher storage temperatures accelerate CO_2 degassing, affecting coffee freshness and aroma, corroborated by sensory evaluations showing declining attributes. A temperature threshold of 30.7°C signals accelerated CO_2 degassing for the studied coffee beans, prompting the need for temperature control measures. An IoT-based storage monitoring system, detecting deviations and issuing alerts, has shown potential in maintaining optimal storage conditions for the roasted coffee beans. It is important to recognise that the IoT system settings will vary depending on factors such as bean type, preparation methods, storage techniques, and packaging types. Therefore, it is essential to first study how these parameters affect coffee quality before proceeding with the development and configuration of the IoT system for monitoring. Understanding these variables will ensure that the system is tailored to maintain optimal storage conditions and preserve the freshness of the coffee. Future enhancements could be considered for automated corrective actions and integration with wider supply chain management systems for coffee industries, especially during transport.

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