https://doi.org/10.31436/iiumej.v27i2.3969

Quantitative Assessment of Coffee Quality Using Microwave Non-Destructive Testing

MOHD KHAIRIL ADZHAR MAHMOOD[1,2], ZUHANI ISMAIL KHAN[1*],
MEGAT SYAHIRUL AMIN MEGAT ALI[1], AHMAD IHSAN MOHD YASSIN[2],
NORZIATON ISMAIL KHAN[3], TAN KWAN YEOW[4]

[1]*Microwave Research Institute, Universiti Teknologi MARA, Shah Alam, Malaysia*
[2]*Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia*
[3]*Faculty of Accountancy, Universiti Teknologi MARA, Shah Alam, Malaysia*
[4]*JWC Roastery Sdn Bhd, Puchong, Malaysia*

**Corresponding author: zuhai629@uitm.edu.my*

(Received: 3 October 2025; Accepted: 22 February 2026; Published online: 10 May 2026)

ABSTRACT: The geographical origin, processing, roast level, and post-roasting resting time affect coffee quality in multiple ways. The traditional quality assessments in the coffee industry (sensory and chemical analyses) are subject to analysts' biases and are destructive, requiring the coffee to be destroyed to run tests. This analysis uses Microwave Non-Destructive Testing (MNDT) to study the dielectric characteristics of specialty coffee (Coffea arabica L.) associated with roasting and resting period. Coffee beans were roasted to produce light, medium, and dark roasts, and the beans were tested for dielectric properties over 30 days in 5-day intervals. The dielectric permittivity was negatively correlated with the level of roasting ($r = -0.590$, $p = 0.005$) and the resting period ($r = -0.483$, $p = 0.027$). The multiple linear regression showed strong predictive ability ($R = 0.762$, Adjusted $R^2 = 0.534$), explaining the effects of roasting and resting period, and their combined effect on the coffee's dielectric properties. This study shows, for the first time, how MNDT can be applied to the coffee industry to evaluate and assess coffee quality.

ABSTRAK: Kualiti kopi dipengaruhi oleh pelbagai faktor seperti asal geografi, teknik pemprosesan, tahap panggang dan tempoh rehat selepas dipanggang. Kaedah tradisional bagi penilaian kualiti, termasuk penilaian deria dan analisis kimia, terdedah kepada subjektiviti dan keperluan ujian yang merosakkan sampel. Kajian ini menggunakan kaedah Microwave Non-Destructive Testing (MNDT) bagi menilai sifat dielektrik kopi istimewa (Coffea arabica L.) yang dipengaruhi oleh tahap pemanggangan dan tempoh rehat selepas dipanggang. Sampel kopi ini dipanggang pada tahap terang, sederhana dan gelap, dengan sifat dielektrik yang diukur selama 30 hari pada selang 5 hari. Keputusan menunjukkan korelasi negatif ketara antara kebolehtelapan dielektrik dan kedua-dua tahap panggang ($r = -0.590$, $p = 0.005$) dan tempoh rehat ($r = -0.483$, $p = 0.027$). Model regresi berganda menunjukkan keupayaan ramalan yang kuat ($R = 0.762$, R^2 Terlaras = 0.534), memberi kesan gabungan pemanggangan dan tempoh rehat pada sifat dielektrik. Penemuan ini menggariskan potensi MNDT sebagai alat berskala, bukan invasif bagi penilaian kualiti kopi, menyumbang kepada amalan pemprosesan lebih baik dan kawalan kualiti dalam industri kopi.

KEYWORDS: *Specialty coffee, Coffee quality, MNDT, Dielectric permittivity, Multiple regression*

1. INTRODUCTION

Coffee is a widely loved drink worldwide. It has a wide variety of tastes and aromas. The complexity and variety of flavors arise from factors such as where the coffee is grown, how it is processed after harvest, and the specifics of its cultivation and harvest. Coffee is grown all over the world. It is a major world crop. The most widely grown and most traded species is Coffea arabica, or Arabica, which accounts for 57.4% of the world's coffee production. The other 42.6% is produced by Coffea robusta [1]. Coffee that is of "specialty" quality has "uniqueness" as a result of an excellent aroma and flavor. This quality is given to coffee that has received a score of 80 or higher on a 100-point scale from the Specialty Coffee Association (SCA) [2]. Specialty coffee is for consumers with high, specific requirements for aroma, taste, sweetness, acidity, and body [3]. Other factors, like soil, altitude, and processing, are important, but roasting is the most important. Coffee roasting has three levels: light, medium, and dark.

Different roasting times and temperatures produce distinct profiles of aroma compounds and therefore different flavors [4]. Being able to control roasting conditions is crucial for achieving desired flavors. In terms of roasting, the levels of acidity in coffee vary, and more highly roasted beans have lower acidity [5]. Additionally, it was noted that Arabica beans have lower acidity than Robusta beans [6].

Still, examining the coffee after roasting and determining quality is difficult. Evaluating coffee quality has primarily relied on cupping, a subjective sensory analysis, and also includes destructive chemical analyses [7]. Despite widespread consensus that cupping is the best sensory evaluation tool, it is highly subjective and therefore difficult to scale [8]. Chromatography is very thorough but inefficient for large-batch testing and is also considered destructive [9]. Given these issues, it is evident that the specialty coffee market needs better quality control. Dielectric properties without changing the product. An example is evaluating coffee without destroying the sample. To do this, the dielectric properties of the coffee are evaluated, which means the internal properties of the sample. The internal properties are governed by the degree of roasting and the resting period of the coffee beans, which together determine coffee quality. The lack of interest in this area is due to the lack of work on developing the equation that relates the two dielectric characteristics of materials, which is the main hindrance to the many practical uses of MNDT in the coffee industry. Within the coffee industry, among the many dielectric properties, two are of utmost importance, and two are closely related to the key quality parameters of roast coffee and post-roast resting time [10]. MNDT is the first to easily and quickly close the gap between the old analytical methods and the modern approach to the coffee industry.

This study examined the relationships among roast intensity, specialty coffee resting time, and dielectric permittivity over 30 days. The electrical properties of the coffee beans are fundamentally related to the amount of water, their chemical constituents, physical structure, and more, and these characteristics undergo drastic changes when the beans are roasted and then stored. Researchers have examined various aspects of coffee, such as its chemical composition and taste, but little research has examined how these variables affect the electrical properties of coffee using accurate, non-destructive methods.

This study looks at the electrical permittivity of coffee at varying degrees of roasting: light, medium, and dark. It attempts to relate the roasting, aging, and microscopic structural properties of the coffee. Over 30 days, we studied the rapid aging processes of coffee, such as oxidation, loss of carbon dioxide, and moisture movement, which can significantly affect the final quality.

We believe our study to be the first of its kind in coffee research, as we have, for the first time, combined varying degrees of roasting, different resting time intervals for coffee samples, and measurements of electrical properties using Microwave Non-Destructive Testing (MNDT). Past research on coffee quality has focused on sensory and chemical analyses. There has been little research on the electrical properties of coffee and how MNDT at different degrees of roasting and resting affects them.

This project develops a new technique for determining how roasted coffee beans undergo chemical and physical changes during storage. We demonstrate the first use of microwave-based technologies to monitor these changes in real time. We describe the first use of microwave-based technologies to monitor these changes in real time. We also describe the first use of microwave-based technologies for real-time, non-destructive, and simultaneous evaluation of coffee quality. We also describe the first use of microwave-based technologies to evaluate the quality of coffee and other beverages. Traditional approaches to coffee quality evaluation involve chemical analysis, spectroscopy, and even destructive sampling. The use of MNDT offers the first opportunity to evaluate beans without contact and without destruction during sampling. The multiple regression modeling framework we created strengthens MNDT's predictive analytical power for coffee. The statistical models developed for neural networks identified the critical roasting and aging times that determine the predictive patterns for coffee analysis. The neural networks identified critical patterns in roasting and aging dielectric permittivity and developed a predictive framework for coffee analysis. This methodology aids in implementing quality control systems that provide operational feedback by developing MNCT-based sensors for in-line roasting and real-time coffee monitoring. This research represents the first step in applying MNDT to the coffee industry, with a focus on operational precision. This research provides the industry's first opportunity to use MNDT.

This paper is organized as follows: Section 1 outlines the various methods for evaluating the quality of coffee; Section 2 outlines the proposed methods for research on MNDT; Section 3 discusses the findings of the experiments conducted; and Section 4 discusses the future research and development of the MNDT tools for assessing the quality of coffee.

2. PROPOSED METHOD

The aim of the approach is to employ MNDT as a new tool for assessing coffee quality, specifically during the critical period of resting days after roasting. The present work provides a scientific study of MNDT and demonstrates its novelty and convenience compared with common quality evaluation approaches. Antenna-based free-space MNDT was chosen for non-contact assessment, in contrast to invasive probes, which require contact between the probe and the materials under test.

MNDT uses electromagnetic waves to investigate the interior characteristics of materials without any physical change or damage to the test object. This technology can be used for quality control of coffee to determine critical parameters such as moisture, dielectric properties, and the structure of the bean during resting.

Reflection, transmission, dielectric constant, loss factor, and complex permeability, which depend on temperature and frequency, are assessed by the MNDT method at the microwave spectrum. The principal equations to determine these parameters are as follows [11]:

$$X = \frac{S_{11}{}^2 - S_{21}{}^2 + 1}{2S_{11}} \tag{1}$$

$$\Gamma = \chi \pm \sqrt{\chi^2 - 1} \tag{2}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{3}$$

$$\mu_r = \frac{1 + \Gamma_1}{\wedge(1 - \Gamma)\sqrt{\frac{1}{{\lambda_0}^2} - \frac{1}{{\lambda_c}^2}}} \tag{4}$$

$$\varepsilon_r = \frac{{\lambda_0}^2}{\mu_r}\left(\frac{1}{{\lambda_c}^2} - \left[\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right]^2\right) \tag{5}$$

In this context, Γ is the reflection coefficient, T is the transmission coefficient, μ_r is the permeability, λ_0 is the free space wavelength, λ_c is the cutoff wavelength, and ε_r is the permittivity.

With proper calibration, the measured values can be related to other material properties, such as defects and moisture content. Free-space measurements are the cornerstone of making MNDT easily accessible for early detection, as they are non-invasive, repeatable, and obtainable in harsh environments, including heat, cold, and complex electromagnetic fields [12].

MNDT is considered in this work as its attributes for which the material is to be evaluated, with no damage in the sample, to sense the value of the dielectric material. The analysis is performed using Microwave Non-Destructive Testing (MNDT) to determine the degree of roasting, rest periods, and the dielectric permittivity of coffee samples. They use a range of X-band frequencies from 8 GHz to 12 GHz, with 3000 data points. First, the MNDT is calibrated with the Through-Reflect-Line (TRL) calibration standards. The measurement is performed on 2 ports (Port 1 and Port 2) because the calculation of dielectric permittivity requires S11 and S21 data. After completing the calibration, the samples are inserted into the acrylic holder, followed by the preparation of the samples above, which were centrally positioned on the spot focusing horn lens. Results were then stored for subsequent analysis. s2p file extensions.

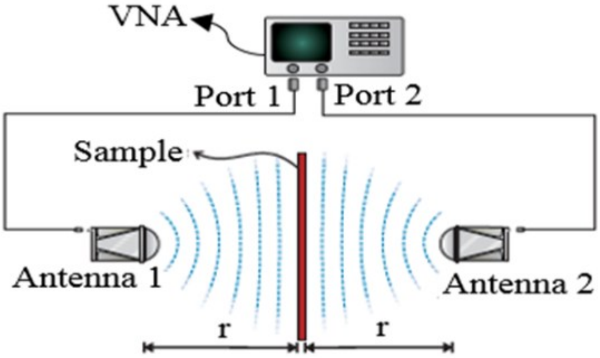
An accurate calibration is important to relate the measured values to known material properties of practical interest, such as flaws and moisture. Calibration ensures the validity and accuracy of measurements by minimizing errors and making results repeatable and comparable across varying conditions. Free-space measurements are non-contact and, if properly calibrated, MNDT methods have the potential to deliver accurate and repeatable results, even under extreme environmental conditions such as heat, cold, and complex electromagnetic backgrounds [13].

This technique eliminates secondary contamination and is advantageous for material analysis. Additionally, MNDT is an important part of materials science and includes a sensor, testing methods, and measurement technologies for detecting damaging cracks and water content in materials using microwave techniques [14]. In recent studies on the conversion of sludge from water-treatment plants into pre-carbonized material, MNDT has been used to assess temperature changes and heating duration [15]. The theory has also been investigated in other disciplines, such as civil engineering, where the material studied has included concrete, and it has applications in food technology. MNDT has been used by researchers to measure the state and characteristics of fruits and animal fat [16].

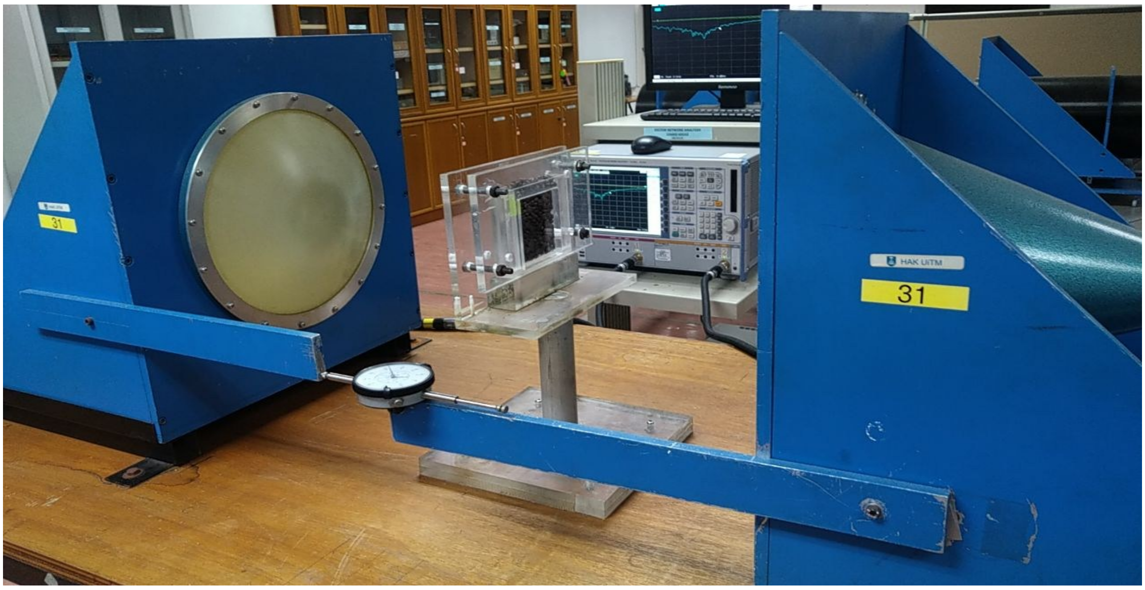
In this work, MNDT is used to assess the object's edibility without directly damaging it, as a convenient method for dielectric characterization of coffee samples. The evaluation is based on the determination of roasting intensity, resting time, and the samples' dielectric permittivity. Measurements are made using X-band (8 - 12 GHz) microwaves with 3000 data points. The X-band (8-12 GHz) offers the best compromise between the ability to penetrate and the ability to resolve in the dielectric measurement of coffee, as the wavelengths within this range are able to cause enough interaction at the bean microstructure level and not too much attenuation, which is a problem in the lower bands, i.e., S-band. S-band is too focused on penetration and bulk material measurement, while X-band is more sensitive to the moisture and structural variations within individual coffee beans [17]. The MNDT system is calibrated using a TRL method prior to measurements, a common experimental approach in microwave measurements to account for systematic errors introduced by the measuring system. The TRL calibration compensates for phase shift, reflection loss, and distortion introduced by the measurement system in the signal path. This process is carried out by the following process:

- *Through Standard*: The system can be calibrated by connecting both ports (Port 1 to Port 2) directly (no sample) to acquire the baseline of the transmission properties.
- *Reflect Standard*: A reflective load (usually a short) is connected to the system to measure its reflection response.
- *Line Standard*: A known-length transmission line is inserted to provide phase information for calibrating the frequency band of interest.

This MNDT setup can accurately determine the scattering parameters (S11 and S21) required for dielectric permittivity calculations once the TRL calibration is complete.



(a)



(b)

Figure 1. (a) MNDT setup (b) Close-up of samples inside the sample holder

Figure 1 above shows a configuration used in the MNDT. The configuration uses a 2-port Vector Network Analyzer (VNA), with ports 1 and 2 connected to the spot-focused antenna. Spot-focusing horn lens antennas were employed to focus the microwave beam on the sample, mitigating environmental effects in a non-anechoic setup. A sample holder located in the center of the antennas is used to retain the samples to be measured. The calibrated ones are used to cup the coffee samples as per the sample preparation instructions. The holder is placed in the center to take the best signal samples in the interactive spot-focusing horn lens. The S-parameters (S11 for reflection and S21 for transmission) are recorded to assess dielectric properties. The recorded measurements are stored in .s2p format in preparation for analysis.

MNDT is efficient and scalable. It is also the most accurate of the methods discussed. The microwave penetration of the coffee beans' molecular structure enables rapid and accurate scanning of the bean's core. This method is particularly useful during post-roast resting periods, when the coffee undergoes vital chemical and physical changes that enhance flavor. It is only during this period that MNDT can track changes in the bean's core, unlike conventional methods that rely on subjective taste testing. Additionally, precise TRL calibration has been developed to allow for accurate and consistent measurements of MNDT. This allows for reliable assessment of the coffee's roasting level, its electrical permittivity, and the aging period. The ability to measure material properties without damaging the material, coupled with precise calibration, enables MNDT to advance materials science and food technology.

2.1. Research Methodology Overview

Figure 2 describes our methodology used in this research. The flowchart describes the individual components of our computational system. For example, the collection of raw data leads to dielectric property calculations, then to statistical analysis. This provides a solid foundation for our system, allowing us to study how the electrical properties of coffee vary with roasting level and storage duration.

Our data analysis systematizes the following steps: 1. Sample preparation, which includes clarification of raw coffee roast classification, detailed weighing, and MNDT measurement; 2. Import of the recorded data into the MATLAB program; and 3. Execution of the data analysis.

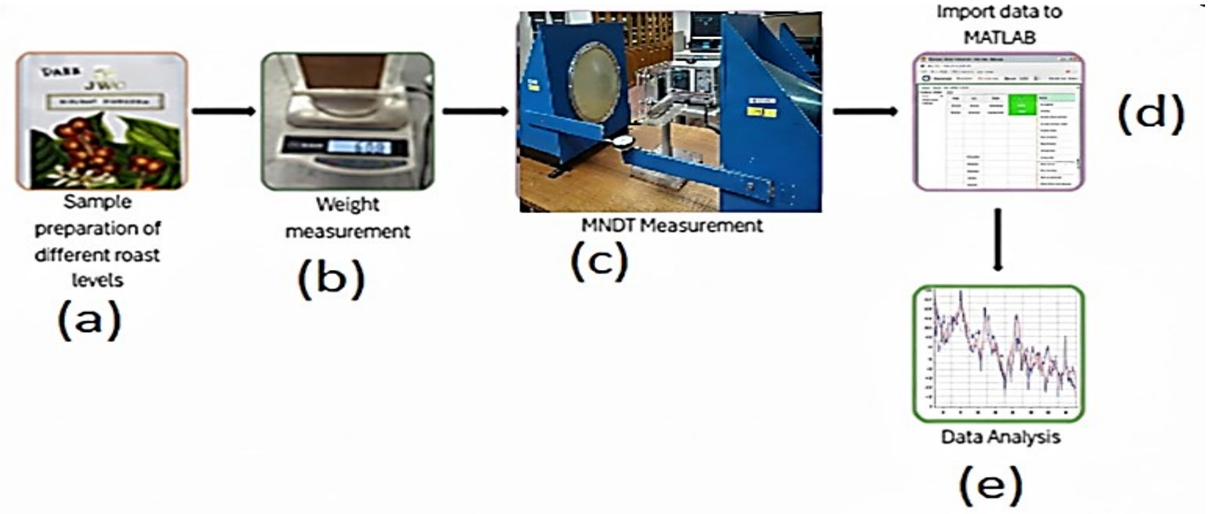


Figure 2. Research methodology overview (a) sample preparation (b) weight measurement (c) MNDT measurement (d) import data to MATLAB (e) data analysis

2.1.1. Sample preparation

Specialty coffees (Coffea arabica L. Rubiacea) of different roast levels were selected from JWC Roastery (Malaysia) to represent different roasting levels (light, medium, dark) and provide a sufficiently wide base with which to examine the impact of the resting period after roasting.

The coffee samples, kept in their original commercial packaging, were packaged in 200-gram units and were not opened until the day of each measurement. The measurement process was organized over a 30-day period, with data collected every 5 days from day 0 until day 30. This methodology proved to be complete in following up on quality reports and in the dynamic assessment of the coffee.

For each measuring point, a 60 g subsample was taken from the original 200 g packaging and placed in a pre-cleaned acrylic sample holder. A calibrated digital scale was used for weighing. Special attention was paid during preparation to avoid air gaps in the sample holder, which could affect measurement precision. Sample density was controlled by using the same grind size (espresso grind), a fixed-volume acrylic holder, and precise weighing, thereby mitigating density-related skew.

Following these preparations, the coffee sample was measured for MNDT (Figure 1(c)). The experiment was repeated for all 7 samples at the times when the specific roast level was tested. Following the same standardized procedure allows consistent sample prep and handling, and therefore reliable, reproducible measurements comparable across different roast levels and resting periods.

2.1.2. Weight Measurement

To maintain consistency, the sample's accurate weight was ensured using a calibrated digital scale. Samples were weighed under controlled conditions to minimize environmental impact, including temperature and relative humidity. The digital scale was calibrated periodically to ensure accuracy, and all measurements were recorded accurately.

2.1.3. MNDT Measurement

Microwave non-destructive testing (MNDT) was done at X-band frequency with 3000 data points between 8 GHz and 12 GHz. Antennas (spot-focusing horn lenses) were 30 cm apart, with the sample centered. The VNA used is Rohde & Schwarz ZVA40, and the power was set at 0 dBm. Measurements were performed using a calibrated VNA and the two-port free-space measurement technique. Measurement errors were reduced using the Through-Reflect-Line (TRL) calibration to eliminate sources of error that could affect measurements. Each coffee sample was placed in the same acrylic holder to ensure uniform testing conditions. The S-parameters (S11 and S21) obtained were analyzed using the Nicholson-Ross-Weir method to extract the dielectric permittivity. The systematic method used ensures that other researchers can replicate the study.

2.1.4. Data Analysis

The raw S-parameters were imported into MATLAB, where a custom NRW-based script was used to extract dielectric characteristics for each coffee sample. During the preliminary stage of the work, the focus was to extract the critical S11 and S21 values, which are used to determine the reflection and transmission coefficients, respectively. The S12 and S22 parameters were omitted because they were irrelevant to our work on dielectric permittivity.

Teflon standards operated as our quality control checkpoint. These materials allowed us to validate our NRW calculations for dielectric constants. After we validated our method, we imported the cleaned dataset into SPSS to perform the statistical analysis.

Our analysis was done in two major parts. First, we performed a correlation analysis to assess the relationships among roasting intensity, resting time, and dielectric permittivity. These relationships highlighted the critical parameters of coffee's physical and chemical composition. Second, multiple regression analysis to determine the individual and collective contributions of roast level and coffee age to electrical conductivity. This two-pronged approach demonstrated the complexity of the interplay between these factors in determining coffee's dielectric behavior.

3. RESULTS AND DISCUSSION

Our primary findings focus on the interplay among roasting intensity, aging time, and electrical characteristics. These findings have undergone rigorous statistical analysis and align with the scientific literature.

Our findings provide further insight into the interaction of roasting intensity and post-roast aging on the coffee dielectric values. The greater the roasting intensity, the lower the dielectric permittivity. The decrease in permittivity is attributed to structural changes in the solid matrix and to the amount of moisture present. The dielectric permittivity also decreases, indicating that moisture content and/or chemical changes in the matrix interact with and influence the matrix's electrical composition during the month-long aging process.

3.1. Results

The findings also corroborate earlier studies on the non-destructive assessment of food quality, particularly those using dielectric and spectroscopic techniques. While dielectric techniques are useful for determining some chemical constituents in food (such as acidity and bitterness), their application is usually limited by high cost and the level of expertise required. In such situations, the MNDT technique offers a more viable and effective solution, as it provides a high-quality analysis of the food's bulk properties. Our findings show that MNDT can provide a high-quality analysis of coffee without the need for expensive, highly sophisticated spectroscopic equipment.

Since dielectric permittivity governs energy absorption and transmission, it is an important factor in understanding its role in the interaction between coffee and microwave signals. The coffee samples' dielectric permittivity is shown over a 30-day resting period, illustrated in Figure 2. The results indicate differences in dielectric properties across roast levels (roast level 1: light roast, roast level 2: medium roast, roast level 3: dark roast), suggesting that roast level significantly influences coffee dielectric properties. These properties change over the first 30 days due to moisture redistribution and oxidation, providing a better understanding of the changes coffee undergoes after roasting. The analysis focused on the permittivity (dielectric constant) maximum, which correlated strongly and negatively with roast level and resting period, thereby fulfilling the study's purpose of combining quantitative quality evaluation with MNDT. While the loss tangent was derived from measured S-parameters and is noted as less informative, it is consistent with the literature, in which the dielectric constant is the predominant metric for moisture/structural variation in roasted coffee [18].

In this study, multiple analytical methods are used to ensure a thorough and comprehensive evaluation of the dielectric permittivity measurements. One of these methods, the Nicholson-Ross-Weir (NRW) method, is applied to the raw S-parameter data from the MNDT experiment.

The NRW method is recognized for its ability to derive values of the complex dielectric constant from microwave measurements involving incident and reflected power. It allows measurement of the dielectric constant with sufficient precision to classify roast levels and track the permittivity of coffee samples over time.

Using data compiled from the first roasting stage (day 0) to 1 month (day 30), the Pearson method was applied to determine the relationship between the dielectric permittivity of coffee and the number of days from roasting. This method analyzes the degree and type of relationship between two continuous variables. The analysis results in a coefficient (r) that ranges from -1 to 1. The closer the number is to 1, the stronger the positive relationship, and the closer it is to -1, the stronger the negative relationship. If r is near zero, that indicates no relationship. The next step was to use multiple regression modeling to evaluate the effect of different independent variables on the dependent variable, as shown in Table 2. This method simultaneously estimates the effects of multiple independent variables on a dependent variable. By doing so, the accuracy of the prediction is improved, making it more precise than that of a one-variable linear predictive model.

3.2. Discussion

Our study examines the effect of different roasting degrees and bean maturation periods on the electrical properties of specialty coffee beans. The application of heat during the roasting process causes a myriad of important chemical reactions and structural changes to the coffee beans, affecting their moisture content, cellular structure, and electromagnetic properties. The subsequent staging process involves several changes, including oxidation, carbon dioxide degassing, and moisture movement, all of which restructure the beans' electrical properties. Such information is important, as it helps coffee professionals and researchers to improve their roasting and bean storage techniques without compromising the quality of the beans.

MNDT is a new tool for coffee evaluation that can be used alongside the established sensory evaluation techniques. The conventional approaches assess the beans through the human senses of smell, taste, and touch, and these assessments vary from individual to individual. Unlike conventional approaches, MNDT provides both a quantitative and an electrical measure, which is guaranteed to yield the same result regardless of who performs the evaluation. This method integrates the art of coffee making with the science of precise measurements and brings to the coffee industry a reliable, scalable quality assurance tool that does not replace the human element but works alongside it.

The speed at which technology is advancing in food science and food material analysis is mirrored by the MNDT system implemented for coffee assessment. The system provides real-time measurement of the dielectric response of aging coffee beans and determines the optimal rest period to achieve the desired taste and product stability. This system can help specialty coffee producers achieve product consistency and reduce the waste from coffee bean storage, thereby increasing the shelf stability of their products. In food science, the use of microwave technology to measure electrical properties and correlate them with chemical changes provides additional tools to answer questions about the chemical changes occurring in food materials during microwave heating.

The commercial prospects are considerable. Automated quality assessment of the industry-level coffee supply chain is possible with MNDT technology. On-farm processing will have more consistent batches and shelf-life forecasting. Bean-to-cup operational streamlining will be achieved, and producers and consumers will have access to the same excellent quality coffee. All coffee supply chain processes will be transformed. The technology can be used to quickly and non-invasively measure the degree of roast and the effects of aging on coffee, thereby increasing transparency in specialty coffee. This will create a system of connected knowledge using metrics to inform producers and consumers. We consider the outcomes of this research in the context of industrial innovation and scientific advancement.

3.2.1. Dielectric permittivity

Dielectric analysis has been used in many evaluations of food products. Existing literature has demonstrated that MNDT can be used to measure moisture content and structural changes of different food matrices. This illustrates the technique's reliability and flexibility. Our results also support the reliability of MNDT in assessing coffee quality.

Dielectric analysis has many applications in food systems. This study documents changes in the physical and chemical composition of roasted coffee over time and their impact on MNDT. We document changes in the dielectric properties of roasted coffee samples as a function of roasting level and aging duration. The results show that the dielectric permittivity decreases with higher roasting levels and longer rest times.

Figure 3 illustrates the measurements of dielectric permittivity for coffee samples of varying roast levels (light, medium, dark) and for varying time intervals (Day 0 to 30 days after roasting). All dielectric permittivity values decrease consistently as the roast level changes from light to medium to dark roasts. With light roasts, the dielectric permittivity values are much higher than those recorded for medium plus dark roasts. This phenomenon was consistent across all time intervals from day 0 to day 30, with a negative correlation between coffee roast level and dielectric permittivity. For instance, on day 0 (roasting day), light roast samples recorded a value of 1.14 compared to 1.04 and 1.05 for medium and dark roasts, respectively. This decreasing pattern was consistent across the time intervals. Our results showed consistently decreasing dielectric permittivity values as time advanced across all roast levels. In light roasts, this pattern was notably clear as the dielectric permittivity value plummeted from 1.14 on day 0 to 1.05 by day 25, a decline of almost 0.1 in just 25 days. The findings are consistent with those detailed in [19].

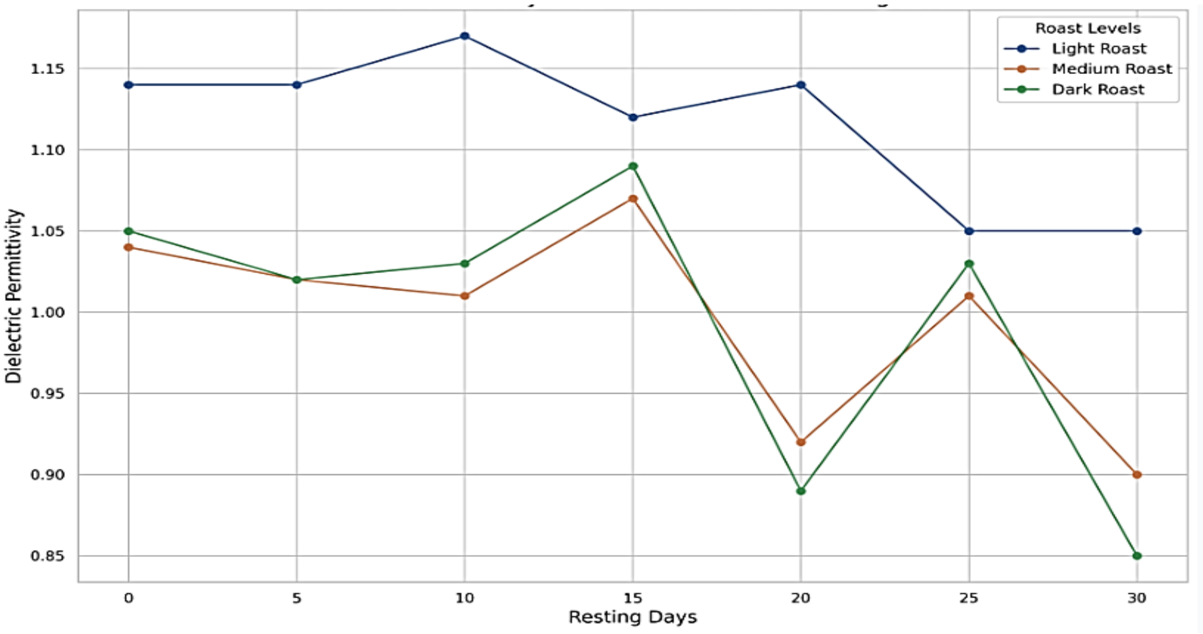


Figure 3. Dielectric permittivity of coffee at different roasting levels

We observe a decline in dielectric response for both darker roasts and longer resting periods, indicating interactions with roasting intensity and aging. There are two additional factors that contribute to these effects: the degree of roasting and the resting period. This time-related permittivity behavior, consistent across all roast levels, is especially pronounced in medium and dark roast samples, with a steady decrease until day 30.

The decline in permittivity is noticeably more pronounced for dark roasts than for light roasts. Between day 0 and day 25, dark roast samples show a significant reduction (from 1.05 to 0.85), while light roasts exhibit more modest changes (from 1.14 to 1.05). These results show that both the degree of roasting and the time since roasting are important factors in determining the dielectric properties of coffee.

The results show that the combination of dark roasting and longer aging periods for coffee decreases dielectric permittivity values, helping elucidate the physical and chemical changes that occur during roasting and aging. These results corroborate those in [20] regarding the moisture content and its relationship with the roast level: as the roast level increases from light to dark, the moisture content decreases, and the dielectric permittivity and loss tangent values are lower.

Roasting level became the most influential factor impacting dielectric permittivity. Higher roasting temperatures decompose the cellular structure of coffee beans, breaking down their structural matrix and reducing their moisture content. These structural and compositional alterations reduce the coffee beans' dielectric capacity, as indicated by the decreasing permittivity values associated with increased roasting. There was a strong negative correlation between dielectric permittivity and roast level ($r = -0.590$, $p = 0.005$), signifying that roasting reconfigured the physicochemical properties of the coffee beans. The correlation suggests that the alterations from roasting fundamentally influence the dielectric properties of the beans.

In addition to the roast degree, the 30-day resting period was found to be one of the factors causing a decrease in dielectric permittivity. With time, the degassing, moisture loss, and oxidative reactions tend to impair the dielectric properties of coffee beans. The greatest changes in dielectric permittivity were observed for darker roasts, indicating that the degree of roasting increases the effects of aging. The dielectric permittivity and the coffee aging period showed a moderate correlation ($r = -0.483$, $p = 0.027$), indicating that the electrical properties of coffee change as it ages, albeit modestly. This pattern reflects the changes that occur in the beans and the physical and chemical properties of the beans that continue to evolve, and are not limited to roasting.

In summary, the effects of the roasting and aging days on the dielectric properties of the coffee are better understood. The effects illustrate the unique, distinguishing impacts of roast level and aging processes, and how they contribute to the evolution of coffee.

3.2.2. Pearson correlation analysis

This study employs Pearson correlation analysis because it effectively measures the strength and direction of linear relationships between two continuous variables. In this study, the focus was on the relationships among roast levels and resting periods and their effects on dielectric permittivity. Since dielectric permittivity is a quantitative, continuous variable, using Pearson correlation was most effective in measuring the relationship. This method is effective in identifying research trends and guiding future studies.

Table 1 data show a significant inverse relationship between post-roast day storage and coffee dielectric permittivity ($r = -0.483$, $p = 0.027$). This shows that the more post-roast days, the lower the dielectric value, indicating a negative relationship. A correlation coefficient of -

0.483 is interpreted as a moderate inverse linear correlation. This may result from the loss of volatile compounds, fluctuations in moisture, and chemical reactions that occur during storage. The first 10 days post-roasting showed the most significant reduction in permittivity, after which it stabilized. This means that during the initial days of storage, the coffee undergoes the most significant changes, such as degassing and oxidative reactions. After that initial period, the rate of dielectric drop declines, indicating little to no change, which implies the chemical reactions have reached equilibrium.

Table 1. Pearson correlation analysis

Variable 1	Variable 2	Pearson Correlation	Significance (2-tailed)	N
Days	Roast	0	1	21
Days	Dielectric Permittivity	-0.483	0.027	21
Roast	-0.59	-0.59	0.005	21

The correlation between the level of roast and the dielectric permittivity of coffee is statistically significant and negative (r = -0.590, p = 0.005). Thus, the higher the roast level of coffee, the lower the coffee dielectric permittivity. This can most likely be attributed to the destruction of some cellular structures and the loss of moisture 'trapped' within them during roasting at very high temperatures. Because the moisture content in cellular structures is a significant factor affecting the dielectric properties, loss of moisture in the darker roasts contributes to a decrease in dielectric permittivity. A correlation coefficient of -0.590 represents a strong negative linear relationship between the two variables. The two negative correlations are significant at the 0.05 and 0.01 levels. Hence, there is a definite strong relationship between the roast level and the dielectric permittivity of coffee, and lower roast levels will correspond to higher dielectric permittivity and tangent loss. Roasting coffee leads to changes in its chemical composition, caused by the breakdown of polysaccharides, proteins, and lipids. These breakdown products of organic compounds cause a change in the material to behave in a way that the dielectric permittivity is lower than before. The darker the roast, the more intense the heat, and the greater the loss of the dielectric properties.

These findings provide a solid foundation for understanding coffee's dielectric properties in relation to roasting and aging processes. The inverse relationships/correlations show the declining dielectric permittivity of coffee as the roasting and aging processes continue to alter the beans. This information is a starting point for understanding how roasting processes can be improved, the changes in a coffee's electrical properties during storage, and the development of new methods to assess coffee quality non-destructively using the dielectric properties of a coffee sample.

The numerous relationships presented here do not imply a cause-and-effect pairing, and therefore, exploratory research would be required to identify the cause-and-effect relationships and determine the mechanisms involved. Sample size, a lack of control for confounding variables, uncontrolled variables, measurement precision, and measurement bias may have a significant effect on the correlation and the strength and significance of the relationship

The correlations among aging period, roasting level, and dielectric permittivity provide insight into the relationships involved, and ultimately demonstrate the value of dielectric measurement in understanding, controlling, and improving the processes associated with coffee and its storage.

3.2.3. Multiple regression analysis

The multiple regression analysis in Table 2 builds on previous Pearson correlation findings and aims to develop a more robust model to explain variation in the dielectric permittivity of coffee. These relationships are vital for improving roasting methods, maintaining freshness and quality consistency (enabling non-destructive quality assessment), and accounting for variations in the coffee's dielectric properties. In this analysis, both post-roast aging (days) and roasting degree (intensity) are included as independent variables and are quantified individually and in combination, helping explain variations in the dielectric properties of coffee.

Table 2. Multiple regression analysis

Metric	Value
R	0.762
R-square	0.338
Adjusted R-square	0.314
Std. Error of the estimate	0.0605
F	12.462
Resting days	-0.483
Roast level	-0.59

Table 2 presents the regression analysis of dielectric permittivity as the dependent variable, with post-roast aging (Days) and roasting degree (Roast) as the independent variables. The regression analysis summary indicates a multiple correlation of R = 0.762, indicating a strong linear relationship with the model's independent variables. It is also noted that the adjusted R-squared is 0.534, implying that the combination of the independent variables, post-roast aging and roasting degree, explains 53.4% of the variation in the dielectric permittivity of coffee.

The ANOVA table shows that the model is significant ($F = 12.462$, $p < 0.001$), indicating that at least one predictor is significant in predicting the dielectric permittivity. The regression coefficients are explained more by the predictor variables. The beta value represents the strength of the relationship between the dielectric permittivity of coffee, the number of days since roasting (resting period), and the roast level.

- *Resting period (Days)*: The standardized coefficient of -0.483 has a p-value of 0.005, with a significant level at $p<0.01$, suggesting that an increase in the number of days since roasting (resting period) is associated with a significant decrease in dielectric permittivity, after controlling for the effect of roast level.
- *Roast level (Roast)*: The standardized coefficient of -0.590 has a p-value of 0.001, with a significant level at $p< 0.01$, indicating that an increase in the roast level is associated with a significant decrease in dielectric permittivity, after controlling for the effect of the number of days since roasting (resting period).

Both predictor variables (Number of Days and Roast) significantly contribute to the regression model, with the roast level having a slightly stronger negative association with dielectric permittivity than the number of days since roasting (resting period). Therefore, in general, it can be inferred that the dielectric permittivity of coffee is strongly dependent on resting period and roast level, with the darker roasts and longer resting period having lower dielectric permittivity than the lighter roasts. With these two predictors, the multiple regression model explains a large fraction of the variation in dielectric permittivity, indicating their usefulness for modeling and predicting changes in the dielectric properties of coffee during roasting and aging.

The results of multiple regression analyses indicate that both roasting and aging periods have independent, significant contributions to the variance explained, and that their combined effect explains a significant portion of the variance (Adjusted $R^2 = 0.534$). With the p-value under 0.01, the independent yet inclusive characteristics of the independent variables confirm the predictors' roles in the complexity of coffee quality.

The most significant predictor was roasting. This is attributed to the structural and compositional changes induced by roasting. Multiple studies have shown that coffee roasting induces changes to a coffee bean's moisture content, its cellular makeup, and the carbonation that develops during roasting. These changes also affect the beans' coffee's electromagnetic response and explain why the roast level is one of the most significant predictors of the coffee's dielectric response.

The resting period was the weakest predictor, but it was still significant in the model. This indicates that this period is important and should not be neglected during coffee post-roast processes if good-quality coffee is to be achieved and maintained. The resting period is the time during which volatile compounds equilibrate, and pressure is allowed to equilibrate (internal and external pressures equalize). During the resting period, dielectric permittivity values may change significantly.

Our research emphasizes the significance of tracking resting duration across study or business operational data collection. This tracking establishes consistent benchmarks for the quality of the coffee beans. The relation of roasting and post-roast aging strongly influences coffee's dielectric response and illustrates the integration of roasting and post-roast aging into quality frameworks.

There are strong statistical grounds for the model, validating further work on the many relationships arising from the interplay between processing variables and coffee attributes.

3.2.4. Research contribution

Our findings align with existing literature on the dielectric properties of food systems, particularly the studies on the effects of moisture on the permittivity of foodstuffs. Coffee exhibits hygroscopic behavior, leading to large differences depending on storage temperature and environmental conditions, and the identified trends suggest that dielectric permittivity may serve as a useful indicator of the degree of freshness and quality of coffee. This study builds on existing knowledge of the effects of roasting and aging on coffee quality indices.

From a commercial perspective, the study offers a time frame. In the first two weeks post-roasting, dielectric properties should reflect changes in coffee freshness and quality. In coffee science, this study also enhances the application of MNDT. The findings show that, compared with established protocols, the method can better support sensory evaluations that involve subjectivity and variability. MNDT provides objective and measurable metrics of the desired quality attributes, which may facilitate the first degree of automation in the coffee value chain.

Our research demonstrates that MNDT has significant potential as an innovative technology for understanding and assessing coffee quality. These findings also demonstrate that MNDT is reliable, scalable, and non-destructive for evaluating the quality of post-roasted coffee in commercial roasting facilities. Measuring changes in dielectric properties would help coffee roasters and researchers obtain precise, quantifiable metrics to assess optimal roasting profiles and storage durations. The proposed solution has the potential to be integrated into the coffee roasting and packaging industry through highly automated, high-speed systems that align with and meet industry needs.

Our research also illustrates the importance and necessity of understanding and evaluating the roasting intensity and resting time of coffee beans in order to develop and implement dielectric-based quality assessment methods. MNDT technology can serve as a quality control instrument in the coffee roasting industry to address a wider range of problems, such as optimizing the storage of roasted coffee beans. This will help provide product quality uniformity in different batches.

Rather than relying on subjective sensory analysis, which can vary by evaluator, the MNDT method uses objective measurement, thereby enhancing its objectivity. MNDT provides a comprehensive service, whereas the other methods provide qualitative analysis. MNDT is also the most practical method for operational monitoring of quality control measures, as it significantly reduces the need for destructive testing, lowers manpower requirements, lowers operational costs, and enhances the preservation of coffee samples. The combination of these practical aspects makes MNDT a very innovative system for the coffee quality control industry.

3.2.5. Study Limitations and Future Directions

This study offers the first look into the dielectric properties of roasted coffee. Additional studies will be needed to consider the numerous other factors that affect dielectric permittivity. Future studies will include other coffee varieties (e.g., Coffea robusta) and different roasting and processing profiles to broaden the generalizability and validate the proposed method.

There is also a need for further mechanistic studies to determine the chemical and structural factors that differ within coffee and lead to different dielectric properties. This would assist in understanding the aging of coffee, the roasting process, and the underlying factors driving changes in coffee quality.

The proposed method has been developed without considering real-world industrial applications, and as such, it has been implemented with multiple limitations. There is a need for further studies that demonstrate real-world applications of the proposed method, show real-time tracking and monitoring during roasting and storage, and enable its full potential in the coffee industry. This will allow further refinements to the proposed method and simplify its use by farmers to determine the quality of harvested coffee. These findings continue to demonstrate the potential of dielectric permittivity as an indicator of coffee quality, solidifying the case for the continued development of dielectric permittivity-based quality control methods and for improving the quality of coffee specialty production.

4. CONCLUSION

The research has shown that roast level and time since roast (resting period) affect the dielectric permittivity of the coffee samples. Correlation analysis and the multiple regression model have shown strong negative relationships for the predictor variables against the dielectric permittivity measurements. In regression analysis, it explained around 58.1% of the variation in dielectric permittivity, which may lend some validity to considering it a predictor. The findings seem to affirm that the lower dielectric permittivity values of dark roasts and longer resting periods are due to different chemical/structural aspects of the coffee that change during roasting and resting. Mechanisms underlying the changing relationships and dielectric permittivity values for potential non-destructive quality control in the coffee industry need to be investigated further. In addition, other factors, such as the variety of beans, growing conditions, and bean processing, may need to be studied to assess their dielectric properties. Ultimately, measuring dielectric permittivity and integrating it into existing quality control systems may simplify and enhance the sustainability and profitability of the coffee supply chain, including processing, storage, and quality assessment.

ACKNOWLEDGEMENT

The author would like to thank JWC Roastery Sdn Bhd and Microwave Research Institute for providing the infrastructure, assistance, and sample provisions.

REFERENCES

[1] E. R. Guimarães, P. H. M. V. Leme, D. C. De Rezende, S. P. Pereira, and A. C. Dos Santos, "The brand new Brazilian specialty coffee market," *Journal of Food Products Marketing*, vol. 25, no. 1, pp. 49–71, Jan. 2019, doi: 10.1080/10454446.2018.1478757.

[2] A System to Assess Coffee Value: Understanding the SCA's Coffee Value Assessment [https://static1.squarespace.com/static/584f6bbef5e23149e5522201/t/667182ffdde8a5081afc2d8c/1718715138872/SCA+-+A+System+to+Asssess+Coffee+Value+-+June+2024+(Secured).pdf]

[3] D. A. Campo-Ceballos and C. A. Gaviria-López, "Optimising consumer acceptability of Cauca specialty coffee through roasting profiles on acidity and body sensory attributes," *Czech Journal of Food Sciences*, vol. 41, no. 1, pp. 64–72, 2023, doi: 10.17221/181/2022-CJFS.

[4] M. Gancarz *et al.*, "Impact of coffee bean roasting on the content of pyridines determined by analysis of volatile organic compounds," *Molecules*, vol. 27, no. 5, Mar. 2022, doi: 10.3390/molecules27051559.

[5] E. B. Tarigan, E. Wardiana, Y. S. Hilmi, and N. A. Komarudin, "The changes in chemical properties of coffee during roasting: A review," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Feb. 2022, doi: 10.1088/1755-1315/974/1/012115.

[6] S. E. Yeager, M. E. Batali, J. X. Guinard, and W. D. Ristenpart, "Acids in coffee: A review of sensory measurements and meta-analysis of chemical composition," *Crit. Rev. Food Sci. Nutr.*, vol. 63, no. 8, pp. 1010–1036, 2023, doi: 10.1080/10408398.2021.1957767.

[7] S. D. Rodrigues *et al.*, "Sensory Q-grader evaluation of fermented Arabica coffees by yeast (*Saccharomyces cerevisiae*) and lactic bacteria (*Pediococcus acidilactici*) cultures," *Coffee Sci.*, vol. 15, no. 1, pp. 1–9, 2020, doi: 10.25186/.v15i.1690.

[8] L. L. Pereira, W. S. Cardoso, R. C. Guarçoni, A. F. A. da Fonseca, T. R. Moreira, and C. S. ten Caten, "The consistency in the sensory analysis of coffees using Q-graders," *Eur. Food Res. Technol.*, vol. 243, no. 9, pp. 1545–1554, Sep. 2017, doi: 10.1007/s00217-017-2863-9.

[9] S. Eticha and T. Bedassa, "Determination of caffeine in coffee samples by high performance liquid chromatography and ultra violet-visible spectrophotometry methods from Wollega, Ethiopia," *Int. J. Biochem. Biophys. Mol. Biol.*, vol. 5, no. 1, p. 8, 2020, doi: 10.11648/j.ijbbmb.20200501.12.

[10] A. Salim *et al.*, "Classification of coffee roast levels using multi-layer perceptron on MNDT S-parameters," in *Proc. IEEE Symp. Wireless Technol. Appl. (ISWTA)*, 2022, pp. 88–92, doi: 10.1109/ISWTA55313.2022.9942782.

[11] A. M. Nicolson and G. F. Ross, "Measurement of the intrinsic properties of materials by time-domain techniques," *IEEE Trans. Instrum. Meas.*, vol. 19, no. 4, Nov. 1970.

[12] W. Herr, Ed., *CAS–CERN Accelerator School: Advanced Accelerator Physics*. Geneva, Switzerland: CERN, 2014, doi: 10.5170/CERN-2014-009.

[13] M. A. Farag, A. Zayed, I. E. Sallam, A. Abdelwareth, and L. A. Wessjohann, "Metabolomics-based approach for coffee beverage improvement in the context of processing, brewing methods, and quality attributes," *Foods*, vol. 11, no. 6, p. 864, Mar. 2022, doi: 10.3390/foods11060864.

[14] Y. Sun, X. Wang, C. Zhang, and M. Zuo, "Multiple regression: Methodology and applications," in *Highlights in Science, Engineering and Technology*, 2023, pp. 542–548.

[15] M. A. H. Zable *et al.*, "Investigation on dielectric properties of sludge waste from water treatment using microwave non-destructive testing (MNDT)," *Int. J. Integr. Eng.*, vol. 15, no. 3, pp. 163–169, 2023, doi: 10.30880/ijie.2023.15.03.016.

[16] A. L. W. Awang *et al.*, "Intelligent method for classifying the freshness of coffee," in *Proc. IEEE Symp. Wireless Technol. Appl. (ISWTA)*, 2023, pp. 115–122, doi: 10.1109/ISWTA58588.2023.10249522

[17] R. Tao, L. Xu, X. Bai, and J. Chen, "Principles, applications, and future evolution of agricultural nondestructive testing based on microwaves," *Sensors*, vol. 25, p. 4783, 2025, doi: 10.3390/s25154783.

[18] R. Torrealba-Meléndez, M. E. Sosa-Morales, J. L. Olvera-Cervantes, and A. Corona-Chávez, "Dielectric properties of beans at different temperatures and moisture content in the microwave range," *Int. J. Food Prop.*, vol. 19, no. 3, pp. 564–577, 2016, doi: 10.1080/10942912.2015.1038565.

[19] N. Makul, "Dielectric permittivity of various cement-based materials during the first 24 hours hydration," *Open J. Inorg. Non-Met. Mater.*, vol. 03, no. 04, pp. 53–57, 2013, doi: 10.4236/ojinm.2013.34009.

[20] P. D. Chauhan, D. H. Gadani, and V. A. Rana, "Effect of moisture content variation on dielectric properties of various plant leaves at microwave frequencies," *Sci. Rep.*, vol. 14, no. 1, Jun. 2024, doi: 10.1038/s41598-024-64266-3.