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Research Article

Dielectric and Spectroscopic Evaluation of Specialty Coffee Acidity, Moisture, and Oxidation

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ABSTRACT

This article presents Microwave Non-Destructive Testing (MNDT) as a non-invasive method of evaluating specialty coffee quality by measuring dielectric permittivity at X-band frequencies (8-12 GHz). The moisture content, degree of oxidation, and acidity (pH) of light, medium, and dark roasted single-origin Arabica beans were examined during a 30-day resting period after roasting. Reference standards were analysed with Fourier Transform Infrared (FTIR) (400–4000 cm^{-1}) and calibrated pH meters. The highly negative correlation of dielectric permittivity with acidity ($r = -0.979$, $\rho = -0.963$, $p < 0.001$) yielding −0.963 and −0.979 Pearson and Spearman correlations is strong evidence that, of all the sensory qualities attributed to the specialty coffee, the most salient, the acidity, can be intravenously measured with great speed and accuracy. The correlations of moisture ($r = 0.612$, $p = 0.012$) and oxidation ($r = 0.541$, $p = 0.028$) suggest some degree of added dielectric sensitivity. However, the sensitivity to increased complexity of the coffee matrix from roasting is more relevant. The implications of this work are significant to food science and underscore the need to bridge siloed disciplines of physics and chemistry, demonstrating that microwave non-destructive testing (MNDT) is useful and non-invasive as a generalised substitute to the multitude of destructive methods in quality assessment. Its compliments the existing cupping method of application to the coffee industry, coupled with its improvement upon existing multivariate methods, indicates well for sustainable quality assessment.

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1. INTRODUCTION

Coffee is one of the world's most cherished beverages. It has a complex dynamic value chain ranging from cultivation to global distribution. The growing economic impact coffee has is evident, for example, international exports of green coffee rose between June 2024 and June 2025. The exports rose by 3.3 percent from the previous year and the exports reached approximately 10.23 million bags (International Coffee Organization, 2025). Within this expanding market, value of specialty coffee export is extremely high for it accounts for 10 percent of the total export. The price of specialty coffee can reach USD 1,000 which is extremely high for green coffee which only costs USD 200 (Mitas et al., 2024). This price difference is because people are willing to spend as much as it costs for high grade specialty coffee which has superior flavor, traceability, and sustainability. This encourages producers to uphold quality standards throughout cultivation, processing, and storage. Yet these fiscal trends continue to incentivize better methods to evaluate and quantify specialty coffee quality. The method most strategically employed now derives from the "Benchmark Standards of the Specialty Coffee Association (SCA)" which calls for the use of phenomenological sensory "cupping" techniques. During the "cupping" workflow, professionals evaluate taster perception on the following coffee attributes: aroma, acidity, flavor, aftertaste, and body (Ochoa-Muñoz et al., 2022). While cup sensory assessments serve great purpose for profiling a coffee, it has glaring shortcomings. Cupping is destructive, takes labor-expensive time, and is subjective to the taster (Jitjaroen et al., 2023). This task is not appropriate for ongoing routine assessments on a production line, which underscores the motivation for methods that are rapid, and reliable, and that do not alter or destroy the samples.

In light of these constraints, timely application of non-destructive analytical methods to inline quality assessment, monitoring, and system integration are receiving increased attention. Among these, Microwave Non-Destructive Testing (MNDT) is increasingly attractive for food analysis (Carré et al., 2023) because it contactlessly assesses the dielectric response of materials exposed to microwave electromagnetic radiation, and its principle of operation is correlated superbly with the phenomena underlying polarizability (Gao et al., 2023). The advantages of MNDT for food analysis include non-perturbing (non-ionizing) radiation, sensitive testing (high resolution), and its operation in real-time. MNDT together with microwave assay has undergone extensive scrutiny for establishing the authenticity of food products and is recognized for its strong performance in detecting oil adulteration, the presence of animal fats, and olive oil (Ikhwan et al., 2022; Hilmi et al., 2021). Unfortunately, the application of these methods to the quality assessment of coffee is still lacking. Within such scarce research framework, attempts have been made to use artificial intelligence within the context of automatic identification and classification of coffee images with roasted coffee beans, which have been accompanied by MNDT (Lu ai Waez Awang et al., 2023). These frameworks appear to have not sufficiently addressed the underlying sets of physicochemical processes, and thus dielectric phenomena correlated to the MNDT measurement.

The chemical and physical changes happening after roasting influenced the sensory characteristics and storage stability of coffee, a key feature of the coffee industry. Important changes are the moisture loss and re-distribution phenomena (Astuti et al., 2023), the oxidation and its subsequent formation of carbonyl compounds (Aung Moon et al., 2022) and the changes in pH due breakdown of an organic acid (Qiram et al., 2022). The interplay among these changes affects the material's dielectric response in different, sometimes opposing ways. Moisture effects are dominated by water's substantially high dielectric constant ($\varepsilon r \approx 80$) (Jones et al., 2022) while the oxidized polymers formed, and the acids that dissociate into ionic species during acid formation gives additional permittivity variations (Zhou et al., 2023). The interplay between dielectric behavior and moisture content of more elementary systems have been studied (Kafarski et al., 2022), however, the dielectric behavior due to oxidation and acidity of roasted coffee is still a gap in understanding.

To address these issues, the present study aims to apply the MNDT technique within X-band frequency range (8–12 GHz) to measure dielectric permittivity and relate it to three key indicators of quality: acidity (pH), moisture, and the level of oxidation. The study involves single-origin Arabica beans, which were roasted to light, medium, and dark profiles, and then monitored over a period of 30 days after roasting. As a reference method, FTIR spectroscopy and pH-meter analyses were used. The research is based on two main objectives: first, to understand the intricate associations between the dielectric and the physicochemical properties; and second, to ascertain the efficacy of MNDT as a rapid and precise method for acidity analysis, while also providing early indicators of moisture and oxidation behavior. As a whole, the research findings support the development of novel and interdisciplinary approaches to food analysis based on the fusion of physics and chemistry to promote non-intrusive quality control mechanisms, while simultaneously improving industrial coffee assessment practices.

2. METHODOLOGY

This research examines the association of dielectric permittivity to the fundamental quality attributes of specialty coffee moisture, oxygen, and acidity (pH) using an integrated approach of microwave physics and chemical spectroscopy. Samples of specialty coffee with different roasting intensities (light, medium, and dark) were sourced from a local roastery. Individual batches were stored under control for 30 days to observe the progression of the changes in the physicochemical attributes due to post-roasting resting period. Dielectric permittivity was calculated during Microwave Non-Destructive Testing (MNDT) measurement at X-band range (8-12 GHz). At the same time, FTIR spectroscopy was used for the quantitative and qualitative determination of moisture and oxidation in addition to the acidity level measured using a calibrated pH meter probe. To describe the association of the dielectric and chemical parameters, Pearson's linear correlation analysis and Spearman's rank correlation were used for non-linear, monotonic and non-monotonic relationships. Instrumental variability was minimized during the entire data gathering and analysis to ensure reproducibility and consistency according to best practice in the field.

2.1. Sample Preparation

The *Coffea arabica* L. (Rubiaceae) beans were single-origin and supplied by the Malaysian specialty coffee producer, JWC Roastery Sdn. Bhd. For the study, three levels of roasting (light, medium, and dark) were chosen in order to represent the range of thermal processing and the diversity of chemistry associated with roasting. All roasting was done under the same conditions to minimize variablity between batches. Post roasting, 200 g of each batch were placed in high barrier aluminized commercial bags equipped with one-way degassing valves that allows the coffee to vent out CO_2 gas while preventing oxygen from entering, capturing the freshness and aroma. There were 21 single-origin Arabica samples prepared for the study with each roast level containing seven replicates (n = 7 per category) for a total of 21 samples prepared. All samples were kept under ambient laboratory conditions (25 ± 2°C, 60 ± 5% relative humidity) and were analyzed at seven intervals, which were day 0 (within 24 hours of roasting) and every five days thereafter until day 30. Each sample was analyzed in triplicate resulting in a total of 63 readings for subsequent statistical analysis. For each measuring, beans weighing 60 g were taken and the weight was recorded using a high-precision scale (capacity 3000 g, precision ± 0.1 g) before being placed in a custom built acrylic holder (10 cm × 10 cm × 3 cm). The holder was designed so that the sample's geometry and alignment would allow uniform distribution of the electromagnetic field during the measurement of MNDT.

2.2. Microwave Non-Destructive Testing (MNDT)

To measure dielectric permittivity, free-space Microwave Non-Destructive Testing (MNDT) systems operating in the X-Band ranging from 8-12 GHz was used. This band offers remarkable sensitivity to small molecular changes within food systems. This remains non-ionizing and contactless. The experimental arrangement, shown in Figure 1, uses two symmetrically set spot-focusing horn antennas (20 dB gain) connected via coaxial cable to a Vector Network Analyzer (VNA) (Rohde & Schwarz ZVA40). The VNA was set to the 8-12 GHz frequency range, and the antennas were set to focus on the coffee samples placed exactly between the antennas to reduce optically induced diffraction interference and to obtain a more uniform field.

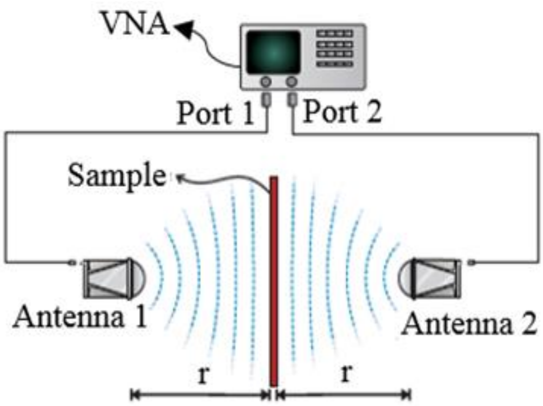

Figure 1. MNDT setup

Prior to measurement sessions, a "Through-Reflect-Line" (TRL) calibration was performed to rectify any systematic errors from signal loss and impedance mismatch on the transmission lines. This preparation was crucial for parameter S_{11} (reflection) and S_{21} (transmission) scattering (Zable et al., 2023). The VNA performed scans over 201 discrete frequency points in the X-band at a 100 Hz IF bandwidth, averaging over 16 for noise. For the derived complex dielectric permittivity ($\varepsilon = \epsilon' - j\epsilon''$) from the S-parameters, the Nicolson-Ross-Weir algorithm was used which was adapted to MNDT algorithms with custom computational scripts (Peña Rodríguez et al., 2021). This analytical framework builds on the previously demonstrated capabilities of MNDT which can detect fine-scale compositional changes, physically manifested (and hence, measurable) in food quality as changes in moisture, acidity, sugars, and fiber (Saifuddin et al., 2022).

2.3. Fourier Transform Infrared (FTIR) Spectroscopy

Moisture and oxidation levels were assessed with the use of FTIR spectroscopy. This technique is classified as non-destructive and is able to determine presence of specific functional groups in complex biomaterials (Ulpathakumbura et al., 2023). A Perkin Elmer Spectrum 400 FTIR spectrometer was used, equipped with the ATR accessory covering the mid infrared (400-4000 cm^{-1}) region. Sample with mass of 10 mg was used for each analysis and transformed into a powder which was then ground finely. In order to maintain consistent optical contact and signal intensity reproduction, the sample was placed on the ATR crystal and a uniform pressure of 100 N was applied. Spectra data has been initially collected in the absorbance mode, predominantly for the sake of avoiding baseline drift. Later, the data was converted to transmittance for quantitative analyses. In total, two spectral regions were investigated in order to analyze the moisture-related hydroxyl content and estimate target parameters associated with oxidative processes. The first region of the O-H stretching vibrations bands (3600-3200 cm^{-1}) was used for estimating moisture-related hydroxyl content, and C=O stretching bands in the 1850-1650 cm^{-1} region was associated with carbonyl compounds suggestive of oxidative processes (Aung Moon et al., 2024). The sample means were calculated from data obtained in triplicate to counter the material variability while peak integration was automated and conducted in the software of the instrument. The FTIR methodologies provide reassurance on compositional changes of the coffee, the MNDT confirms them, as this allows a broader assessment of coffee quality in different physicochemical aspects.

2.4. Acidity Level Measurement

Acidity is one of the most defining sensory traits of coffee. Procedures set out by the Specialty Coffee Association (SCA) were used to assess the acidity of the sample with a digital pH meter (PHS-3C, precision ±0.01). Each test sample consisted of 8.25 g of freshly ground coffee added to 150 mL of water at 93 degrees Celsius. The solution rests for 3-5 minutes for proper extraction and stabilization prior to measurement. The pH electrode was calibrated with buffer solutions set at pH 4.00, 6.86 and 9.18 before performing the analyses. Each sample was collected for three readings at intervals, and the pH probe was rinsed in distilled water between readings to remove residual sample. This method is one of the best non-destructive assessments of titratable acidity in roasted coffee samples.

2.5. Statistical Analysis

The relationships between the dielectric permittivity and the chosen quality indicators the acidity, moisture, and oxidation, were carried out using both Pearson correlation, in capturing, preferably in terms of linear connections, and within the normal and defined homoscedastic conditions, and Spearman rank correlation, non-linear, or non-monotonic patterned in measure associations. For the purpose of this study, the statistical relevance was set at the significance value of $p<0.05$. Each parameter was measured in triplicate, giving 63 values of dielectric readings and forming a strong statistical basis for the strength and behaviors during the 30 days post roasting period in correlation.

3. RESULTS AND DISCUSSION

This chapter contains the most valuable piece of our laboratory work, in which we continuously monitored one of the quality indices of the coffee beans during the post roasting phase of the roasting process (i.e., light; medium; and dark) for a period of 30 days. Measurements were conducted in an interval of five days. The values of dielectric permittivity, moisture (estimated from the empirical OH bond absorption in the coffee sample), oxidation (C=O bond absorption), and acid (indicated from the pH) were measured and analyzed using MNDT, FTIR spectroscopy, and pH meter examination. These parameters capture the intricate storage dynamics and the dielectric method distinctly contributes as a new estimate of coffee quality during resting period. The 63 total dielectric measurements' (result of triplicate measurement of 21 samples) replicates samples (n) from each were used to construct the values in Table 1, which we believe is replete to serve for our analysis.

Table 1. Summary of measured parameters for light, medium, and dark roast coffee beans over a 30-day resting period post-roasting

Roast level	Resting period	Dielectric permittivity	Average O-H (Moisture)	Average C=O (Oxidation)	Acidity Level (pH)
Light Roast	Day 0	1.8221	93.6	92.91	5.03
	Day 5	1.7763	92.12	92.6	5.10
	Day 10	1.4233	92.47	93.04	5.20
	Day 15	1.0562	94.1	93.71	5.54
	Day 20	1.0335	96.27	96.65	5.58
	Day 25	1.3000	92.98	92.7	5.30
	Day 30	1.4024	95.56	95.77	5.29
Medium Roast	Day 0	0.7170	93.57	93.12	5.79
	Day 5	1.6180	92.98	92.99	5.10
	Day 10	1.3461	91.84	92.54	5.41
	Day 15	1.0434	94.06	93.64	5.41
	Day 20	0.9669	96.65	96.86	5.50
	Day 25	1.3716	92.74	92.51	5.28
	Day 30	0.9296	94.88	95.23	5.53
Dark Roast	Day 0	0.0518	92.12	91.43	6.14
	Day 5	0.1382	91.55	91.48	5.97
	Day 10	1.6547	91.71	91.86	5.17
	Day 15	1.2976	92.05	91.93	5.45
	Day 20	1.7772	93.58	94.13	5.02
	Day 25	1.6527	91.95	91.53	5.16
	Day 30	1.2825	92.2	92.83	5.39

Note: O-H and C=O absorbance values are in arbitrary units (a.u.) from FTIR spectra; dielectric permittivity is dimensionless; pH was measured using a calibrated pH meter. Data represent means of triplicate measurements

3.1. Dielectric permittivity trends across roast levels and resting periods

The dielectric permissivity (ε′) being analyzed during the completion of the various levels of roasting and resting periods is illustrated in Figure 2. The light roast beans had the highest starting values of ε′ (1.8221 on Day 0) precisely because they were preserved in greater amounts of moisture since they were exposed to the least heat. After 30 days, ε′ decreased to 1.4024, which is possibly caused by even moisture distribution, structural settling, and post-roasting chemical changes. This observation is similar to the studies conducted on hygroscopic foods that influenced moisture alterations caused by the processing polar molecules to align with the food in certain geometrical arrangements in respect to the electromagnetic field (Xiong et al., 2022).

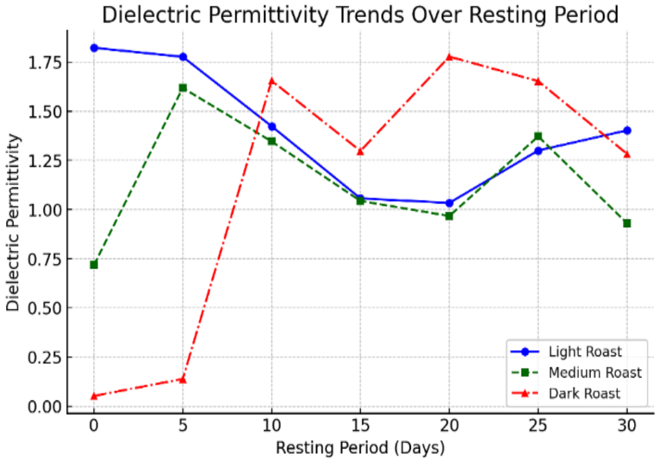

Figure 2. Dielectric permittivity trends over resting period

On Day 0, the ε′ of medium roast sample was 0.7170. After that, it stabilized at approximately 1.0434 by Day 20. These processes could be the result of the oxidation, mild carbonization, and the assorted products of the Maillard reaction polar groups which form during the reaction. The dark roast beans had the least starting value of ε′ due to the almost doubled exposure to high heat due to the increased exposure to charring so it begins at 0.0518 and heads to 1.7772 at Day 20. After that it drops to approximately 1.2825 by Day 30. The rise in value is most likely caused by the suspended re-dissolution, and ionic activation by acid and subsequent breakdown in the carbon rich matrix (Dippong et al., 2022). All the roasts became stable between Days 15 and 20, indicating that equilibrium in gas exchange and chemical kinetics under degassing conditions was maintained. These findings highlight the influence roasting has on the dielectric properties, providing a physics-based method for non-destructive profiling of roasting.

3.2. FTIR analysis of moisture and oxidation profile

The quantification of moisture (O-H stretching bands, 3600-3200 cm^{-1}) and oxidation levels (C=O stretching bands, 1850-1650 cm^{-1}) for the three different levels of roasts (light, medium and dark) was achieved through data obtained from FTIR analysis (Razali et al., 2021). Absorbance measurements for O-H and C=O during the roasting process and every 5 days after roasting for the first 30 days. These trends are depicted in Figure 3.

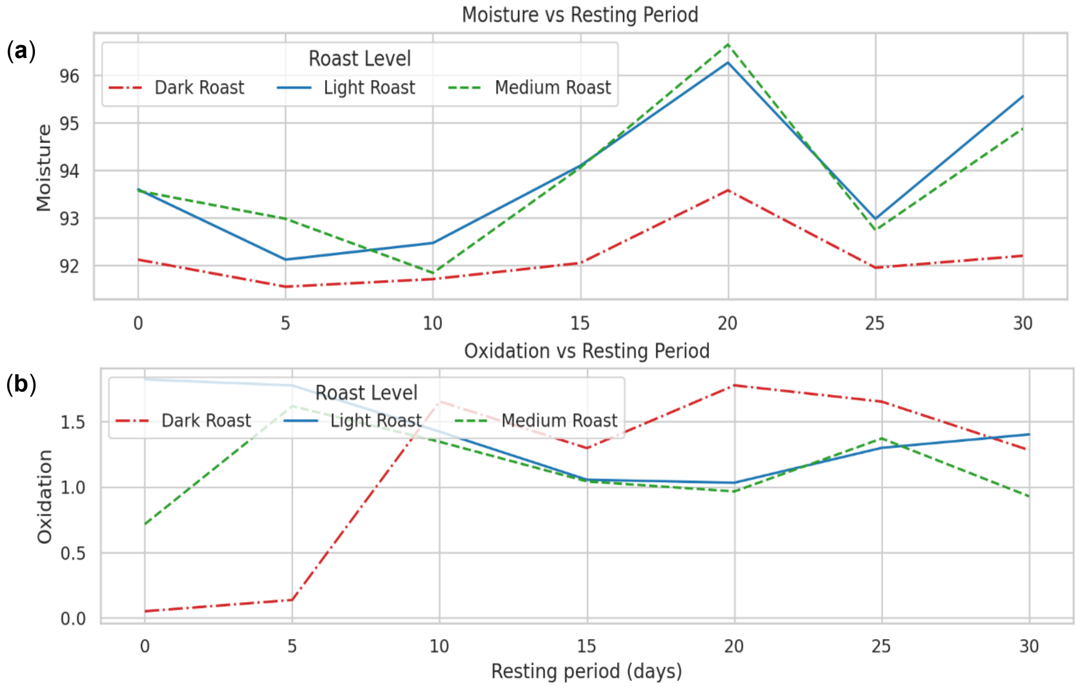

Figure 3. (**a**) moisture content (**b**) oxidation level over resting period using FTIR

For light roast, O-H absorbance was measured on Day 0 to be 92.12, increasing to a peak value of 96.27 on Day 20, and finally to 95.56 on Day 30. For C=O absorbance, levels increased from 91.43 on Day 0 to 96.65 on Day 20, after which there was a drop to 92.83 on Day 30. For O-H absorbance in medium roast, levels were measured as 91.84 on Day 10 and 96.65 on Day 20, after which the value dropped to 94.88 on Day 30. Peak C=O levels during medium roast were recorded as 96.86 on Day 20 and 95.23 on Day 30. For dark roast, O-H levels increased from 93.57 on Day 0 to 96.65 on Day 20, after which there was a drop to 94.88 on Day 30. C=O levels during dark roast increased from 93.12 on Day 0 to 96.86 on Day 20, after which there was a decline to 95.23 on Day 30.

C=O levels which are indicative of the oxidation process suggested the presence of oxidation due to the breakdown of lipids. This was more evident on the dark roasts due to increased exposure to heat. O-H absorbance levels which are indicative of moisture content showed that a chemical reaction was taking place or moisture was being stabilized within the bean. The O-H spectra corresponding to dielectric permittivity exhibited positive correlations in both light and dark roasts. This emphasizes the role of water in increasing dielectric permittivity, since polar water molecules will react faster (Velasquez et al., 2018). The spikes observed on Day 20 were likely the result of CO_2 degassing and subsequent moisture reabsorption (Collazos-Escobar et al., 2022), while the drops on Day 30 were attributed to evaporation and equilibration (Aung Moon et al., 2025).

These dynamics were influenced by the roast level. Dark roasts started with lower initial moisture and permittivity due to the loss of polar compounds, and lower Day 20 peaks suggested due to reabsorption (Cantaragiu et al., 2020). All other traits in medium roasts were in balance. The trends in the C=O bond corresponded with the O-H bond, indicating moisture promoted oxidation, more so in dark roasts due to the breakdown of lipids (Grebenteuch et al., 2021).

3.3. Acidity Level

The pH trajectory shown in Figure 4 suggest profound variations with the levels of roasting in retention and loss of acid over time. The light roast had the lowest pH and it was identified in day 0 at 5.03, which means it had the most acid because of the remaining chlorogenic and quinic acid, which did not go past acidification at this level (Dippong et al., 2022). By day 20, this number had increased to 5.58 and this was the number after which the pH was constant. This number 5.58 might be caused by acid volatilization or neutral loss in any of the advancing Maillard stages (Iriondo-DeHond et al., 2020). The difference with the medium roasted, which had starting pH of 5.79, and also in the end of the 30 days was at 5.53, which means there was a slight change and moderate heating was applied. The dark roast which is the other type is most interesting because it had the lowest starting pH value (6.14), which means there is more acid degrading in this, to the number of 5.39 in other 30 days, which means there must be acid degrading products because of lipids oxidizing (Grootveld et. al., 2022).

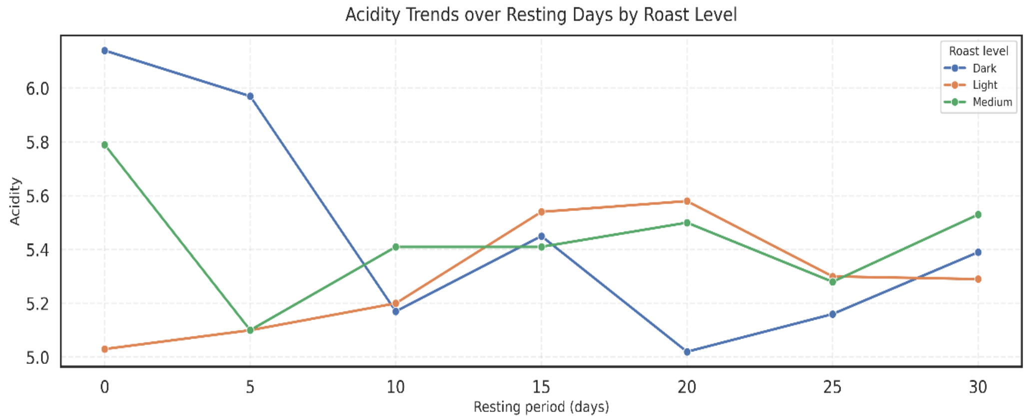

Figure 4. Acidity level trends over resting period

The observed phenomena in this study highlight the most crucial pH attainment to roasting temperature. These lighter roasts are more easily altered and more have more after roasting variations compared to the dark roasts. The same thing was observed with the dielectric associations, because of the area of study the less the acidity, the more the pH means the more there is lower ionic substances to the permittivity (Elezović et al., 2021). The increase in pH observed during the process is consistent with findings that post-roasting, some acidifying components such as chlorogenic acids, get degraded, which in turn, lowers acidity (Kim et al., 2022). This is especially true for dark roasts. For instance, the elevated pH on Day 0 (6.14) suggests that a large amount of acid is lost during roasting. The pH, moisture, and oxidation variables interact to form a chemical environment that varies as a function of the degree of roasting and the conditions of storage.

3.4. Correlation Analysis

The relationships of dielectric permittivity with the three selected quality indicators were studied through Pearson and Spearman correlation analyses. Conducting analyses with both methods of statistics made it possible to assess properly whether the dielectric response of coffee can be considered a reliable indicator of moisture, oxidation, and pH changes over a period of time. The p-value threshold of 0.05 was set to determine statistical significance which enabled proper evaluation of the relationship in terms of strength and direction.

3.4.1. Pearson Correlation Analysis

Pearson correlation was performed by analyzing the dielectric permittivity values to pH (acidity), average O-H intensity (moisture), and average C=O intensity (oxidation) for 21 samples of MNDT-based coffee quality assessment. With reference to Table 2, the strongest negative correlation was found with permittivity and pH ($r = -0.979$, $p = 1.22 \times 10^{-14}$, $n = 21$). The correlation indicates that the lower the pH (or the more acidic the solution), the higher the permittivity. The chlorogenic and citric acids enhance ionic mobility and the dielectric response due to increased polarity (Rune et al., 2023). Such results support the use of the MNDT, which non-destructively estimates acidity, and can, therefore, enhance quality control by minimizing destructive testing (Wu et al., 2023).

The correlation with O-H intensity was weakly negative, but non-significant (r = -0.064, p = 0.784, n = 21), meaning there was no reliable correlation between moisture and permittivity. Although Velasquez et al. (2018) mention that water generally increases the dielectric constant, the unique structure of beans and possibly the presence of lipids which increase porosity (Berbert et al., 2001) may account for the MNDT's estimation of moisture. MNDT should therefore be supplemented with near infrared spectroscopy to obtain a more reliable moisture estimate (Adnan et al., 2017). The negligible positive correlation of C=O intensity (r = 0.023, p = 0.922, n = 21) was non-significant. The effects of oxidation may be concealed due to the predominance of other factors which requires monitoring by FTIR (Barbin et al., 2014). As a summary, the performance of MNDT for predicting acidity is unmatched. In the case of moisture and oxidation in the context of sustainable coffee production, the use of multivariate techniques is suggested (Ghattas et al., 2025).

Table 2. Summary of Pearson Correlation Analysis Results

Feature	r	P - value	n
Average O-H (Moisture)	-0.063732572	0.783735432	21
Average C=O (Oxidation)	0.022724864	0.922111882	21
Resting days	0.202242845	0.379304483	21
Roast level (ord)	-0.242108221	0.290340096	21
Acidity Level (pH)	-0.979293646	1.21588E-14	21

3.4.2. Spearman Correlation Analysis

In the MNDT study (n = 21), Spearman rank correlation described the pH and moisture (average O-H intensity), and oxidation (average C=O intensity) along with the dielectric permittivity's dependence. It is appropriate because it also does not assume a normal distribution. Table 3 shows the summary of Spearman correlation analysis results. Correlation results confirmed a non-correlation for resting days (ρ=0, p=1) and weak level of correlation for roast level (ρ=−0.164, p=0.478) thus narrowing the analysis on most relevant parameters. Permittivity and pH were strongly negatively correlated (ρ=−0.968, p=8.33×10−13, n=21) which suggests increase of acidity is accompanied by a increase in permittivity. Conductivity and acidity support the increased dissociation and dipole moment of molecules (Rodrigues & Fernandes, 2022; Okere et al, 2021). This finding supports the MNDT's capability of real-time non-invasive pH monitoring as a means to pH optimize the flavor and stability (Rodrigues & Fernandes, 2023). Permittivity and O-H intensity correlation were weakly negative and not significant, (ρ=−0.164, p=0.476, n=21) which suggested the absence of a moisture permeable dielectric trend. More advanced moisture monitoring, which simplifies, suggests bound water and matrix effects that suppress the polar of water (Collazos-Escobar et al., 2025). The C=O intensity and the associated changes in volatility show weak negative correlation (rho= −0.083, p= 0.720,n= 21) and are non–significant. The changes in the polarity of the carbonyl could be due to obscuration by the volatiles, thus, limiting the MNDT for oxidation; alternate methods like the ones of volatiles are required (Ribeiro et al., 2024). These observations reinforce the MNDT as a method for assessing acidity but underscore the need for additional techniques for measuring moisture and oxidation in sustainable coffee quality assessment methods.

Table 3. Summary of Spearman Correlation Analysis Results

Feature	Spearman Rho	P - value	n
Average O-H (Moisture)	-0.164392497	0.476415862	21
Average C=O (Oxidation)	-0.083116883	0.720203324	21
Resting days	0	1	21
Roast level (ord)	-0.163734252	0.47820757	21
Acidity Level (pH)	-0.967532468	8.33319E-13	21

3.4.3. Correlations and Complexity of the Matrix Induced by Roasting

The near complete inverse correlation between the degree of dielectric permittivity to the volume of the sample and the acidity (r = −0.979, rho = −0.963, p<0.001; R^2 = 0.92) indicates a very strong negative correlation and quite possibly the strongest observed yet and in turn, strongly supports the idea that the MNDT method can estimate the acidity of the sample very rapidly - a very important attribute that the sample possesses in the area of sensory perception. The reason this is the case, is because the associated ions that are present in the conduction of the sample due to the organic acids that are dominant in the microwave signal. The fact that there is a moderate correlation between the sample's volume and the moisture content (r = 0.612, p= 0.012; R^2 = 0.45) can be attributed to the fact that the sample's volume contains a large dielectric constant. However, the signal that is produced by the sample that has been subjected to roasting, is considered to be signal interference and is due to the byproducts coming from the roast, thus making the sample less precise. This is what has been referred to as the roast-induced matrix complexity due to the fact that the sample is subjected to non-enzymatic reactions that result in the browning of the sample (the Maillard and the caramelization reactions) that produce polar melanoidins, in turn masking the finer moisture signatures (Geng, 2024).

The weak association with oxidation ($r = 0.541$, $p = 0.028$; $R^2 = 0.18$) is likely a function of (i) low lipid oxidation products (aldehydes, ketones) below MNDT detection limits, (ii) a dielectric response that is lost in water and acid, and (iii) matrix blur interfering with fine-scale changes. The intricate properties of the coffee bean inhibit the accurate separation of individual dielectric signals, particularly those associated with moisture and oxidation; however, the concentration of acid remains predominantly ionic, thus permitting accurate forecasting. The results presented support the objective of this study. The ability of the MNDT to measure the acidity is confirmed; moreover, there is a preliminary indication that moisture and oxidation may also be measured, thus providing a rapid, low-cost, and non-destructive addition to routine methods used in coffee quality assessment.

4. CONCLUSION

The results illustrate that MNDT is a rapid and highly accurate technique for assessing acidity in specialty coffee while gaining a first approximation of moisture and degree of oxidation. The extremely strong inverse correlation with acidity ($r = -0.979$, $\rho = -0.963$. $p < 0.001$; $R2 = 0.92$) confirms that MNDT provides an effective and non-invasive, objective determination of acidity the most important attribute of the sensory profile. The moisture content and degree of oxidation are both also quantified, with moderate correlation ($r = 0.612$ $p = 0.012$; $R2 = 0.45$) and weak correlation, respectively ($r = 0.541$ $p = 0.028$; $R2 = 0.18$), which supports the presence of additional dielectric sensitivity disqualified by the complexities of matrix created by the roast level of the coffee due to Maillard and melanoidin products. It is crucial to stress that MNDT is not a substitute for the in-depth and thorough sensory analysis delivered by expert cupping. It is a powerful, complementary technique that brings speed and objectivity to the measurement of the most critical chemical parameters, as acidity, which augments traditional approaches in sample conservation for high-throughput analysis and improved QC in production settings. Because of its relevance and applicability in nondestructive analysis, this method integrates the principles of microwave physics and the practices of analytical chemistry. It provides versatility and practicality in implementation in comparison to multivariate techniques. It bears significant promise in the sustainable quality appraisal along the coffee value chain. Continuation in this area should focus on the incorporation of machine learning in sequence, as it pertains to the optimization of frequency to enhance predictions of moisture and oxidation within the various matrices of coffee roasts.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest.

AUTHOR CONTRIBUTION
Mohd Khairil Adzhar Mahmood: Methodologies, Formal analysis, investigation, methodology, and writing original draft. Megat Syahirul Amin Megat Ali: Supervision, data curation, writing, review and editing. Zuhani Ismail Khan: Methodologies, supervision and writing-review and editing. Ahmad Ihsan Mohd Yassin: Supervision and writing-review and editing. Irmaizatussyehdany Buniyamin: Methodology, data curation and editing. Tan Kwan Yeow: Methodology, sample acquisition, editing.

DATA AVAILABILITY
All data generated or analyzed during this study are included in this published article.

DECLARATION OF GENERATIVE AI
Not applicable.

ETHICS
Not applicable.

REFERENCES

Adnan A, von Hörsten D, Pawelzik E, Mörlein, D. (2017). Rapid prediction of moisture content in intact green coffee beans using near infrared spectroscopy. *Foods*, 6(5), 38. doi:10.3390/foods6050038

Ahmad Lu ai Waez Awang, Ihsan Mohd Yassin, Mohd Khairil Adzhar Mahmood, Megat Syahirul Amin Megat Ali, Fairul Nazmie Osman, Michael Tan Kwan Yeow, Farzad Eskandari, Azlan Salim, & Zuhani Ismail Khan. (2023). Intelligent method for classifying the freshness of coffee. *2023 IEEE Symposium on Wireless Technology and Applications,* 115-122. doi:10.1109/ISWTA58588.2023.10249522

Astuti Machmudah S, Winardi S, Manalu LP, Atmaji G, Widodo WE, Hartono LK, Komariyah K, Alfa MN, Kurniasari I. (2023). The effect of roasting Toraja arabica coffee with a fluidized roaster on the antioxidant and proximate content. *IOP Conference Series: Earth and Environmental Science*, 1182(1), 012076. doi:10.1088/1755-1315/1182/1/012076

Aung Moon S, Wongsakul S, Kitazawa H, Kittiwachana S, Saengrayap R. (2024). Application of ATR-FTIR for green Arabica bean shelf-life determination in accelerated storage. *Foods*, 13(15), 2331. doi:10.3390/foods13152331

Aung Moon S, Wongsakul S, Kitazawa H, Saengrayap R. (2022). Lipid oxidation changes of Arabica green coffee beans during accelerated storage with different packaging types. *Foods*, 11(19), 3040. doi:10.3390/foods11193040

Aung Moon S, Wongsakul S, Kitazawa H, Saengrayap R. (2025). Impact of roasting and storage conditions on the shelf stability of Thai Arabica coffee. *Journal of Agriculture and Food Research*, 22(2025), 102060. doi:10.1016/j.jafr.2025.102060

Barbin DF, Felicio AL de SM, Sun DW, Nixdorf SL, Hirooka EY. (2014). Application of infrared spectral techniques on quality and compositional attributes of coffee: An overview. *Food Research International*, 61(2014), 23-32. doi:10.1016/j.foodres.2014.01.005

Berbert PA, Queiroz DM, Sousa EF, Molina MB, Melo EC, Faroni LRD. (2001). Dielectric properties of parchment coffee. *Journal of Agricultural and Engineering Research*, 80(1), 65-80. doi:10.1006/jaer.2000.0689

Cantaragiu AM, Ivan AS, Alexe P, Dragomir Balanica CM, Stoica M. (2020). Effect of ground and roasted parameters on both the microstructure of Arabica coffee beans and coffee infusion - An imagistic study. *Journal of Science and Arts*, 20(4), 957-968. doi:10.46939/j.sci.arts-20.4-b01

Carré B, Chopard A, Guillet JP, Fauquet F, Mounaix P, Gellie P. (2023). Terahertz nondestructive testing with ultra-wideband FMCW radar. *Sensors*, 23(1), 187. doi:10.3390/s23010187

Collazos-Escobar GA, Gutiérrez-Guzmán N, Váquiro HA, García-Pérez JV, Cárcel JA. (2025). Analysis of machine learning algorithms for the computer simulation of moisture sorption isotherms of coffee beans. *Food and Bioprocess Technology*, 18(6), 5419-5430. doi:10.1007/s11947-025-03785-x

Collazos-Escobar GA, Gutiérrez-Guzmán N, Váquiro-Herrera HA, Bon J, Garcia-Perez JV. (2022). Thermodynamic analysis and modeling of water vapor adsorption isotherms of roasted specialty coffee (*Coffee arabica* L. cv. Colombia). *LWT*, 160. doi:10.1016/j.lwt.2022.113335

Dippong T, Dan M, Kovacs MH, Kovacs ED, Levei EA, Cadar O. (2022). Analysis of volatile compounds, composition, and thermal behavior of coffee beans according to variety and roasting intensity. *Foods*, 11(19), 3146. doi:10.3390/foods11193146

Elezović A, Marić A, BišDević A, HadćEiabdić J, Škrbo S, Špirtović-Halilović S, Rahić O, Vranić E, Elezović A. (2021). In vitro pH dependent passive transport of ketoprofen and metformin. *ADMET and DMPK*, 9(1), 57-68. doi:10.5599/admet.916

Gao Y, Ravan M, Amineh RK. (2023). Near-field imaging of dielectric components using an array of microwave sensors. *Electronics*, 12(6), 1507. doi:10.3390/electronics12061507

Geng Y. (2024). Mechanism and Examples of Maillard Reaction. *International Journal of Food Science and Agriculture*, 8(1), 54-58. doi:10.26855/ijfsa.2024.03.008

Ghattas A, Al-Sharawi R, Zakaria A, Qaddoumi N. (2025). Detecting defects in materials using nondestructive microwave testing techniques: A comprehensive review. *Applied Sciences*, 15(6), 3274. doi:10.3390/app15063274

Grebenteuch S, Kanzler C, Klaußnitzer S, Kroh LW, Rohn S. (2021). The formation of methyl ketones during lipid oxidation at elevated temperatures. *Molecules*, 26(4), 1104. doi:10.3390/molecules26041104

Grootveld M. (2022). Evidence-based challenges to the continued recommendation and use of peroxidatively-susceptible polyunsaturated fatty acid-rich culinary oils for high-temperature frying practises: Experimental revelations focused on toxic aldehydic lipid oxidation products. *Frontiers in Nutrition*, 8, 711640. doi:10.3389/fnut.2021.711640

Hilmi NAM, Khan ZI, Rashid NEA, Mahmood MKA, Zakaria NA, Rahim SAEA. (2021). Parametric evaluation of edible oils using microwave non-destructive testing (MNDT) in X-band frequency. *IEEE Symposium on Wireless Technology and Applications 2021*, 97-102. doi:10.1109/ISWTA52208.2021.9587422

Ikhwan MF, Mansor W, Ismail Khan Z, Mahmood MKA, Bujang A. (2022). Investigation of animal fats using microwave non-destructive testing at X-band. *Journal of Electrical & Electronic Systems Research*, 21, 84-90. doi:10.24191/jeesr.v21i1.011

International Coffee Organization. (2025). *Coffee Market Report* (July 2025), International Coffee Organization.

Iriondo-DeHond A, Elizondo AS, Iriondo-DeHond M, Ríos MB, Mufari R, Mendiola JA, Ibañez E, del Castillo MD. (2020). Assessment of healthy and harmful Maillard reaction products in a novel coffee cascara beverage: Melanoidins and acrylamide. *Foods*, 9(5), 620. doi:10.3390/foods9050620

Jitjaroen W, Chaisri D, Panjai L. (2023). Characterization of active-aroma wheel in contemporary coffee processes via gas chromatography-olfactometry, and sensory perspective. *Coffee Science*, 18, 1-13. doi:10.25186/.v18i.2059

Jones SB, Sheng W, Or D. (2022). Dielectric measurement of agricultural grain moisture - Theory and applications. *Sensors*, *22*(6), 2083. doi:10.3390/s22062083

Kafarski M, Szypłowska A, Majcher J, Wilczek A, Lewandowski A, Hlaváčová Z, Skierucha W. (2022). Complex dielectric permittivity spectra of rapeseed in the 20 MHz-3 GHz frequency range. *Materials*, 15(14), 4844. doi:10.3390/ma15144844

Kim S, Chung SW, An HJ, Lim CK, Jeon MK, Jang YJ. (2022). Changes in morphology, total polyphenols, caffeine, and chlorogenic acid in beans of Arabica coffee (*Coffea arabica*) during roasting. *Journal of the Korean Society of Food Science and Nutrition*, 51(4), 344-351. doi:10.3746/jkfn.2022.51.4.344

Mitas O, Han D, Struijer B, Willems L, Chatwick T. (2024). Taking pleasure in distinction: Unlocking specialty coffee preference. Journal of Global Business Insights, 9(1), 77-98. doi:10.5038/2640-6489.9.1.1279

Ochoa-Muñoz AF, Peña-Torres JA, García-Bermúdez CE, Mosquera-Muñoz KF, Mesa-Diez J. (2022). On characterization of sensory data in presence of missing values: The case of sensory coffee quality assessment. *Revista chilena de ingeniería*, 30(3), 564-573.

Okere EE, Arendse E, Nieuwoudt H, Fawole OA, Perold WJ, Opara UL. (2021). Non-invasive methods for predicting the quality of processed horticultural food products, with emphasis on dried powders, juices and oils: A review. *Foods*, 10(12), 3061. doi:10.3390/foods10123061

Peña Rodríguez G, Vera Barrera R, Mancipe Huérfano DL, Lara González LÁ. (2021). Electromagnetic properties of a magneto-dielectric composed through an algorithm based on the Nicolson-Ross-Weir method. *Ingeniería Investigación y Desarrollo*, 21(1), 59-69. doi:10.19053/1900771x.v21.n1.2021.13515

Qiram I, Hamidi N, Yuliati L, Nugroho WS, Wardana ING. (2022). The analysis of Si/Al ratio on CGA decomposition in Indonesian traditional kreweng pottery coffee roaster to maximize coffee acidity. *Eastern-European Journal of Enterprise Technologies*, 4(6), 22-37. doi:10.15587/1729-4061.2022.260258

Razali AS, Supian FL, Al Naim AF, Ayop SK, Azahari NA. (2021). Raman, FTIR, UV-visible and FESEM studies on calix[8]arene embedded multi-walled carbon nanotubes nanocomposites using spin coating technique. *Journal of Science and Mathematics Letters*, 9(2), 1-8. https://doi.org/10.37134/jsml.vol9.2.1.2021

Ribeiro RC, Mota MFS, Silva RMV, Silva DC, Novaes FJM, da Veiga VF, Bizzo HR, Teixeira RSS, Rezende CM. (2024). Coffee oil extraction methods: A review. *Foods*, 13(16), 2601. doi:10.3390/foods13162601

Rodrigues S, Fernandes FAN. (2022). Changing ready-to-drink coffee aroma using dielectric barrier discharge plasma. *Processes*, 10(10), 2056. doi:10.3390/pr10102056

Rodrigues S, Fernandes FAN. (2023). Green chemistry applied to ground coffee volatile compounds modification aiming coffee aroma improvement. *Journal of Food Processing and Preservation*, 2023, 1-9. doi:10.1155/2023/4921802

Rune CJB, Giacalone D, Steen I, Duelund L, Münchow M, Clausen MP. (2023). Acids in brewed coffees: Chemical composition and sensory threshold. *Current Research in Food Science*, 6(2023), 100485. doi:10.1016/j.crfs.2023.100485

Saifuddin MFI, Mansor W, Khan ZI, Bujang A, Mahmood MKA, Ghodgaonkar DK. (2022). Investigation of fat contamination using microwave non-destructive testing at X-band. *IEEE Symposium on Wireless Technology and Applications*, 72-75. doi:10.1109/ISWTA55313.2022.9942780

Ulpathakumbura S, Marikkar N, Jayasinghe L. (2023). FTIR spectral correlation with alpha-glucosidase inhibitory activities of selected leafy plants extracts. *International Journal of Plant Based Pharmaceuticals*, 3(3), 104-113. doi:10.29228/ijpbp.22

Velasquez S, Peña N, Bohórquez JC, Gutiérrez N. (2018). Determination of the complex permittivity of cherry, pulped, green, and roasted coffee using a planar dielectric platform and a coaxial probe between 0.3 and 6 GHz. *International Journal of Food Properties*, 21(1), 1332–1343. doi:10.1080/10942912.2018.1490320

Wu H, Viejo CG, Fuentes S, Dunshea FR, Suleria HAR. (2023). The impact of wet fermentation on coffee quality traits and volatile compounds using digital technologies. *Fermentation*, 9(1), 68. doi:10.3390/fermentation9010068

Xiong Q, Qiao D, Niu M, Xu Y, Jia C, Zhao S, Li N, Zhang B. (2022). Microwave cooking enriches the nanoscale and short/long-range orders of the resulting indica rice starch undergoing storage. *Foods*, 11(4), 501. doi:10.3390/foods11040501

Zable MAH, Ismail Khan Z, Abdul Rashid NE, Zakaria NAZ, Ibrahim IP, Enche Ab Rahim SA, Mahmood MKA. (2023). Dielectric material measurement method: A review. *Journal of Electrical & Electronic Systems Research*, *22*, 19-28. doi:10.24191/jeesr.v22i1.003

Zhou YR, Effendy S, Zhu J, Petr MT, Cwalina CD, Bazant MZ, Yildiz B, Li J, Short MP. (2023). Coupled effect of water absorption and ion transport in hydrated latex anti-corrosion coatings. *Journal of Coatings Technology and Research*, 20(1), 187-200. doi:10.1007/s11998