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Analyse non-invasive du taux de sucre dans les tubercules de pommes de terre par mesures diélectriques micro-ondes

Non-invasive Analysis of Sugar Content in Potato Tubers Using Microwave Dielectric Measurements

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Mots clés: Mesures diélectriques, sonde coaxiale ouverte, pommes de terre, taux de sucre, contrôle non destructif (CND)
Index Terms: Dielectric measurements, open-ended coaxial probe, potato tubers, sugar content, non-destructive testing (NDT)

Résumé/Abstract

This study explores a non-invasive and non-destructive approach to analyzing sugar content in potato tubers using dielectric probes. By employing a dielectric measurement kit and a vector network analyzer, we characterized three potato varieties based on their complex permittivity and reflection coefficient. The results show a correlation between dielectric properties and sugar content, paving the way for an *in situ* monitoring method.

Cette étude explore une approche non invasive et non destructive pour l'analyse du taux de sucre dans les tubercules de pommes de terre à l'aide de sondes diélectriques. En utilisant un kit de mesures diélectriques et un analyseur de réseau vectoriel, nous avons caractérisé trois variétés de pommes de terre en fonction de leur permittivité complexe et de leur coefficient de réflexion. Les résultats montrent une corrélation entre les propriétés diélectriques et la teneur en sucre, ouvrant la voie à une méthode de contrôle *in situ*.

1 Introduction

The analysis of sugar content in potato tubers is a key challenge in the agri-food industry, particularly for optimizing storage and subsequent processing [1][2]. This is notably true since the interdiction of the use of anti-germinative molecules in the EU in 2020. To bypass this restriction, potato tubers are stored at lower temperature which in turn triggers the cold-induced sweetening of the tuber increasing the sugar content in that organ. Traditional measurement methods often require tissue-destructive and time-consuming laboratory analyses.

This study explores an alternative approach based on microwave nondestructive testing (MNDT). MNDT methods are attractive for biological, food and chemical applications thanks to their high sensitivity to water [3][4]. In particular, the open-ended coaxial probe can provide localized measurements with minimal sample preparation and is therefore suited for dielectric properties of heterogeneous biological materials [5][6][7][8]. Guan et al. (2004) measured the dielectric properties of mashed potatoes over 1–1800 MHz and 20–120 °C, analyzing the effects of moisture and salt content for optimizing microwave and RF pasteurization processes [9]. Zhu and Guo (2017) studied the dielectric behavior of potato starch over the 20–4500 MHz range, demonstrating how its properties vary with frequency, moisture levels, and temperature [10]. Mohamed et al. (2016) applied microwave techniques to non-destructively detect black heart cavities in potatoes, providing complex permittivity measurements from 0.5 to 20 GHz and confirming their simulation results through experimental validation [11]. Hamilton et al. (2023) conducted a comprehensive study comparing three dielectric measurement techniques—open-ended coaxial probe, broadband dielectric spectrometer, and a custom-designed stripline resonator—across a wide frequency range of 1 MHz to 20 GHz [12]. Instant mashed potato was employed as a standardized food model to assess the dielectric properties at varying moisture contents (20% to 75% by weight). El-Mohamed et al. (2017) conducted an in-depth investigation into how storage conditions affect the dielectric properties of 'Lady Rosetta' potato tubers [13]. Using an LCZ meter, they measured capacitance and conductance across frequencies ranging from 10 kHz to 1 MHz. These measurements allowed for the calculation of parameters such as complex permittivity, conductivity, and the dissipation factor ($\tan \delta$). The study revealed that both complex permittivity and conductivity decreased with increased storage time, temperature, and applied load stress.

Although several studies have investigated the dielectric properties of potato materials, most of them have focused on processed forms such as slices, starch, or mashed samples. To date, there is a lack of research specifically dedicated to the non-invasive, non-destructive characterization of whole, intact potato tubers. This distinction is essential, as the potato tuber is a biologically active system. Invasive measurement techniques, such as needle probes or destructive sampling, can disrupt cellular integrity, trigger stress responses or pathogens attack, or alter water distribution within the tissue, thereby biasing the dielectric response. In contrast, a non-invasive approach preserves the native state of the tuber, required for accurate *in situ* monitoring of its internal properties. To the best of our knowledge, the present work is the first to address this challenge by proposing a fully non-destructive methodology for complex permittivity measurement on whole potato tubers, with potential implications for storage monitoring.

Section 2 describes the experimental setup, including the measurement system, calibration procedure, and the different configurations used for analyzing the potato tubers. Section 3 presents the main results, including demonstration of the correlation between dielectric properties and sugar content, the influence of measurement configuration, and the repeatability of the method. Section 4 analyzes the results and outlines next steps toward the development of a non-invasive, real-time monitoring system for agri-food applications.

2 Materials and Methods

2.1 Measurement Setup

The proposed measurement system relies on a dielectric probe kit (Keysight® SlimForm and HighTemp) [14], used in conjunction with a vector network analyzer (VNA P5008A, Keysight®). This setup is designed to characterize the dielectric properties of biological samples across a wide frequency range, from 200 MHz to 50 GHz. The SlimForm probe is optimized for flat or slightly curved surfaces, while the HighTemp variant is suitable for higher temperature conditions, enhancing measurement versatility and reliability. While the primary objective for practical and future industrial applications is to operate at the ISM frequency only (2.45 GHz), we intentionally considered the broadband capabilities of the system to investigate the frequency dependence of the complex permittivity and penetration depth in potato tubers. Limiting the study to a single frequency would significantly constrain our understanding of the dielectric mechanisms and the interaction of electromagnetic fields with the potato tubers. By spanning a broad frequency range, we are able to capture the dispersive behavior of water, ions, and other molecular constituents—critical factors in the dielectric response of living tissues.

The probes are connected to the VNA, which records the complex reflection coefficient (S11) and enables the determination of the complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) mainly through the Keysight® Materials Measurement Suite software [14] [15]. These dielectric parameters provide valuable information about the electromagnetic behavior of the material under test (MUT). Specifically, ε' reflects the material's capacity to store electric energy, while ε'' captures dielectric losses. In tubers, these parameters are influenced by internal variables such as moisture level, ionic concentration, and molecular composition. Because sugar content modulates these internal properties, the dielectric signature offers an indirect yet sensitive method to assess sugar levels. This non-destructive and broadband approach allows for real-time monitoring of internal changes within the tubers, which is essential for quality control and biochemical analysis.

The input RF power was set to -15 dBm with an intermediate frequency (IF) bandwidth of 100 Hz and 601 measurement points. Port 1 of the VNA was connected to the Slim form coaxial probe and Port 2 to the High temperature probe, covering their respective frequency ranges (500 MHz–50 GHz for Slim Form and 200 MHz–20 GHz for High Temperature). Both probes were connected via 60 cm-length coaxial cables. The ambient temperature during the measurement ranged from 22.3°C to 22.9°C.

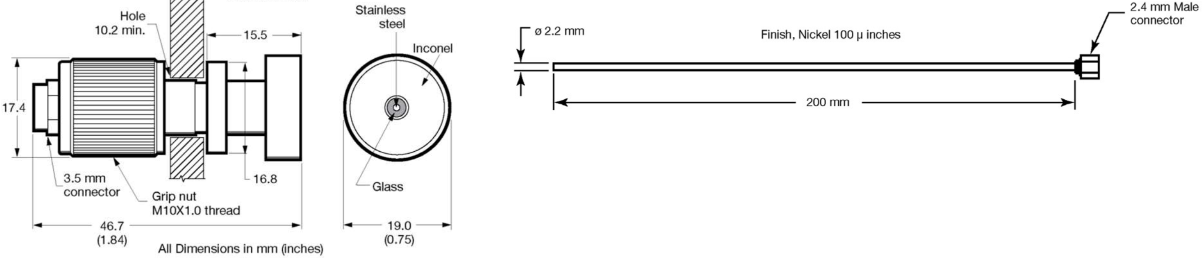

Figure 1. Drawings of both HighTemp (left) and SlimFrom (right) probes (references: Keysight N1501A-101 and N1501A-102)

To ensure consistent contact between the probe and the sample, the potato tuber was placed in a glass beaker to maintain a stable position throughout the measurement. A simple vertical adjustment system allowed for manual raising and lowering of the tuber. Custom 3D-printed spacers of 1 mm and 10 mm thickness were used to control the distance and ensure a reproducible pressure between the tuber surface and the probe. Additionally, a temperature sensor was placed near the contact zone to monitor any thermal variations during data acquisition. These setup details are depicted in Figure 2, which provides a representation of the experimental configuration.

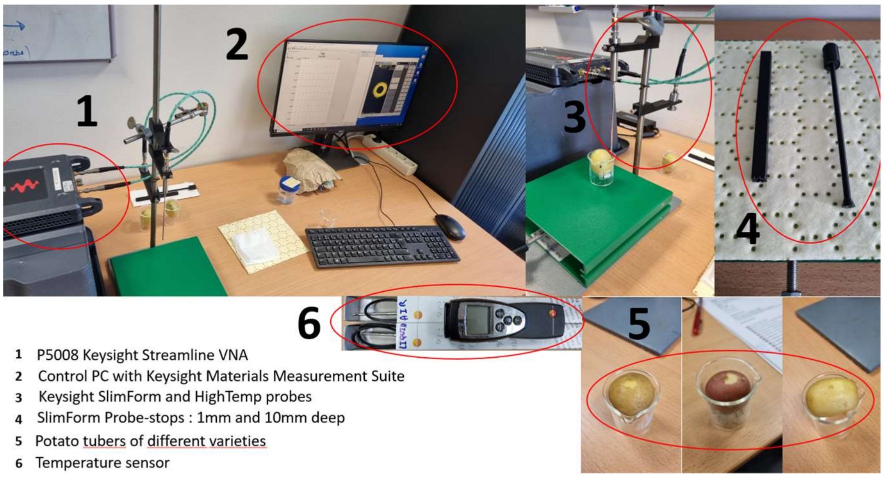

Figure 2. Measurement setup for dielectric characterization of potato tubers. The system includes: (1) Keysight P5008 Streamline Vector Network Analyzer (VNA), (2) control PC with Keysight Materials Measurement Suite, (3) Keysight SlimForm and HighTemp dielectric probes, (4) probe stops at 1 mm and 10 mm depths, (5) potato tubers from different varieties, and (6) temperature sensor for environmental monitoring. This setup enables broadband (200 MHz–50 GHz), non-destructive dielectric measurements using open-ended coaxial probe.

2.2 Reproducibility and Metrological considerations

The evaluation of measurement repeatability and reproducibility was carried out using the SlimForm probe on three different tuber varieties (Lady Claire, Désirée, Alix) of the same potato species (*Solanum tuberosum*). The protocol consisted of two distinct phases. In the first phase, the measurement setup was assembled and left untouched while three successive measurements were performed under identical conditions, this assessed the repeatability of the system. In the second phase, the probe was manually decoupled and repositioned on the tuber before each of three new measurements, allowing the evaluation of reproducibility. In both cases, care was taken to maintain consistent contact pressure using the same 3D-printed spacer. These procedures were repeated for each tuber variety. Based on the collected data, standard deviations were calculated to quantify variability. Only the results obtained with the SlimForm probe are presented in Figure 3, which summarizes the repeatability and reproducibility measurements for the three tested tuber varieties.

	Lady Claire		**Désirée**		**Alix**	
Magnitude (repeatability)	***Mean (linear)***	***σ (%)***	***Mean (linear)***	***σ (%)***	***Mean (linear)***	***σ (%)***
0.5GHZ	0.98	0.05%	0.97	0.45%	0.95	0.07%
2.45GHZ	0.95	0.11%	0.94	0.84%	0.91	0.12%
10GHZ	0.91	0.26%	0.90	1.79%	0.80	0.27%
50GHZ	0.66	0.26%	0.66	1.06%	0.63	0.04%
Phase (repeatability)	***Mean (°)***	***σ (%)***	***Mean (°)***	***σ (%)***	***Mean (°)***	***σ (%)***
0.5GHZ	-4.99	1.39%	-5.13	6.06%	-7.84	0.08%
2.45GHZ	-18.88	1.23%	-18.93	5.05%	-30.33	0.28%
10GHZ	-61.47	1.00%	-60.68	3.47%	-88.61	0.35%
50GHZ	-140.50	0.14%	-138.50	0.56%	-149.58	0.07%
Magnitude (reproducibility)	***Mean (linear)***	***σ (%)***	***Mean (linear)***	***σ (%)***	***Mean (linear)***	***σ (%)***
0.5GHZ	0.98	0.82%	0.98	0.21%	0.92	1.70%
2.45GHZ	0.95	1.46%	0.95	0.40%	0.87	2.09%
10GHZ	0.91	3.43%	0.91	0.81%	0.74	1.01%
50GHZ	0.67	4.40%	0.66	1.08%	0.62	0.41%
Phase (reproducibility)	***Mean (°)***	***σ (%)***	***Mean (°)***	***σ (%)***	***Mean (°)***	***σ (%)***
0.5GHZ	-4.93	19.34%	-4.97	5.09%	-10.08	14.13%
2.45GHZ	-18.73	17.84%	-18.61	4.86%	-38.97	13.04%
10GHZ	-61.04	14.90%	-60.50	4.21%	-102.37	8.87%
50GHZ	-139.02	3.53%	-138.87	1.00%	-151.75	3.01%

Table 1. Error analysis on the measured reflection coefficient S11 including repeatability and reproducibility.

The measurements demonstrated strong repeatability and reproducibility under varying test conditions. When the probe position was held fixed, repeated acquisitions yielded highly consistent results. Even with deliberate repositioning of the probe between measurements, the observed variations remained within acceptable limits, thereby confirming the robustness of the measurement procedure. This stability reinforces the reliability of the dielectric signatures obtained from the tubers.

2.3 Calibration Protocol

A full modified-SOL calibration was performed before each measurement campaign, following the standard procedure recommended by Keysight® for dielectric probe systems. Calibration was conducted separately for both the SlimForm and HighTemp probes using the Keysight® Materials Measurement Suite.

The calibration sequence included three standards: open (air), short (metallic shorting block), and a liquid reference. For the liquid standard, deionized water with a conductivity of less than 3.00 µS/cm (RS PRO, reference 254-3687) was used. This specific product was chosen for its consistency and compatibility with high-frequency dielectric measurements, particularly where dielectric loss becomes more significant.

This protocol allowed for the correction of systematic measurement errors and ensured reproducibility of the complex permittivity values across all configurations and varieties tested.

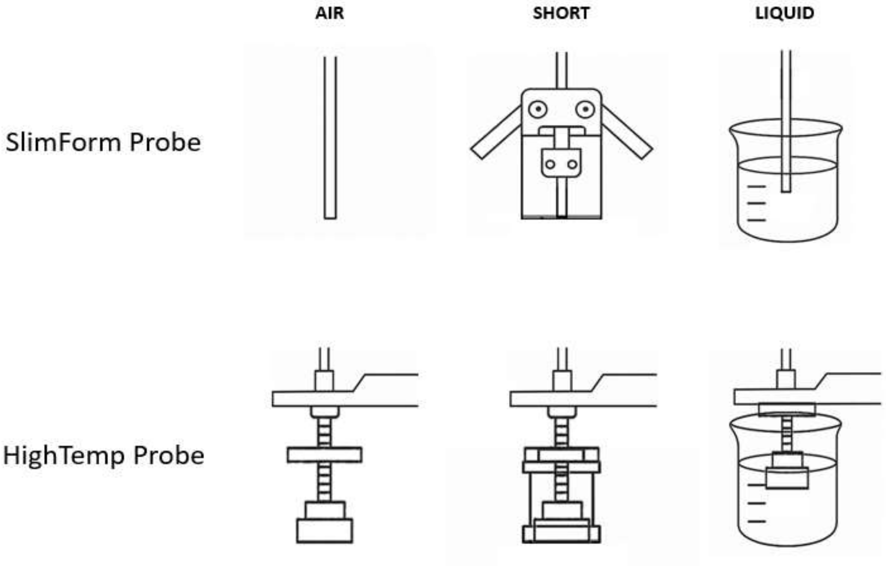

Figure 3. Calibration sequence for both the HighTemp and SlimForm probes.

2.4 Measurement Configuration

The measurement setup focused on three potato tubers varieties: Lady Claire, Désirée, and Alix. These varieties were specifically chosen because they are well-controlled within our cultivation process—we grow them ourselves and are thoroughly familiar with their behavior, especially in terms of sugar accumulation. This level of control allows us to confidently correlate the microwave measurements with their known physical and chemical characteristics.

To identify the most suitable method for obtaining reliable dielectric data, we tested three distinct measurement configurations: **Surface Measurement (Non-invasive):** In this ideal non-destructive approach, the probes were simply placed in contact with the potato tuber skin. This configuration is particularly appealing because it does not require any sample preparation. However, it introduces complexity due to the multi-layered structure of the tuber, the skin and the underlying flesh, which can influence the dielectric response. **Peeled Surface Measurement:** To isolate the dielectric contribution of the flesh alone, the tubers were peeled prior to measurement. This removes the effect of the skin but introduces a new variable: the peeled surface tends to exude moisture, which can alter the contact conditions and influence the measurement. **Inserted Probe Measurement (Invasive):** In the third configuration, the probes were inserted approximately 1 cm into the tuber to access internal dielectric properties, mimicking the conditions of an immersed probe. While this method offers deeper insight into the internal structure, it is clearly invasive and therefore not aligned with the principles of non-destructive testing.

By comparing these three approaches, we aim to balance measurement reliability with the practical constraints of non-destructive evaluation, and to better understand how surface conditions and probe placement affect the dielectric response of the potato tuber.

Both types of probes were used during the measurements: SlimForm and HighTemp probes. The SlimForm probe, due to its compact design, was mainly employed for surface measurements where minimal contact area is beneficial. While it is suitable for contact-based configurations, it is not particularly designed for deep insertion into the sample. The three previously described measurement conditions, surface contact on unpeeled tubers, contact on peeled surfaces, and insertion into the tuber flesh, were each tested using both types of probes. These configurations were applied systematically across all three potato varieties to evaluate the impact of the measurement technique on the quality of the dielectric data, particularly in terms of accuracy and repeatability.

The objective was to identify which combination of probe and measurement setup yields the most reliable data, while considering the trade-offs between invasiveness, practical feasibility, and consistency.

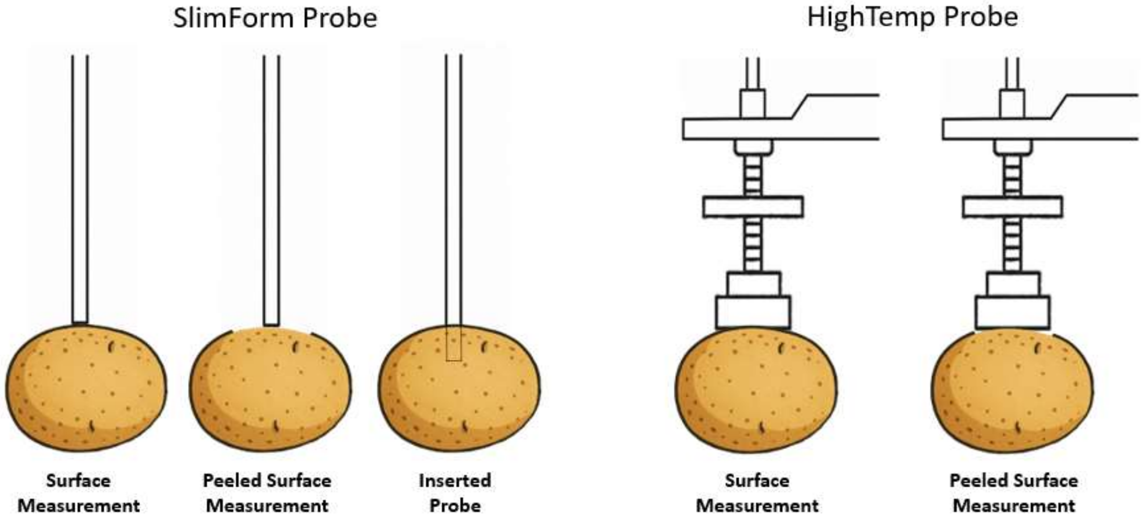

Figure 4. Measurement configurations for both SlimForm and HighTemp open-ended coaxial probes.

3 Results and discussion

3.1 Experimental results

Figure 6 illustrates the measured reflection coefficient response—both magnitude in dB and phase in degrees—of the three potato varieties (Lady Claire, Désirée, and Alix) in the frequency range from 0 to 50 GHz. In terms of magnitude, all samples show a general decline with increasing frequency, indicative of typical dielectric loss behavior. Lady Claire exhibits the highest reflection magnitude across the spectrum, followed by Désirée and then Alix, which shows the lowest values. This suggests that Lady Claire has the lowest dielectric losses, while Alix exhibits the highest. In the phase response graph, a similar trend is observed where all curves demonstrate a progressive phase shift with frequency, consistent with dispersive dielectric behavior. Again, Lady Claire and Désirée show less steep phase changes compared to Alix, whose phase drops more sharply, especially in the lower frequency range. These differences could be attributed to variations in internal moisture, sugar content, and tissue composition between the potato varieties, with Alix possibly having higher loss factors or different structural properties leading to a stronger attenuation and dispersion.

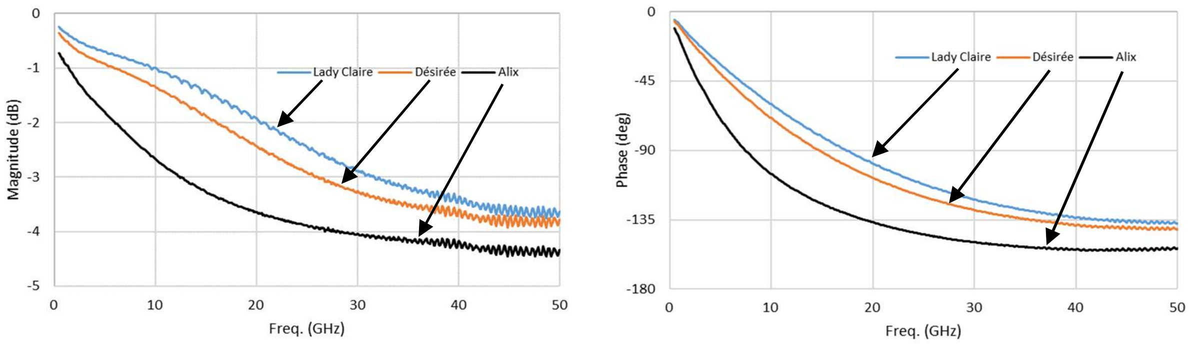

Figure 5. Measured reflection coefficient S11 (magnitude and phase) using the SlimForm probe.

From the measured reflection coefficient, dielectric spectra are extracted and presented in Figure 7.

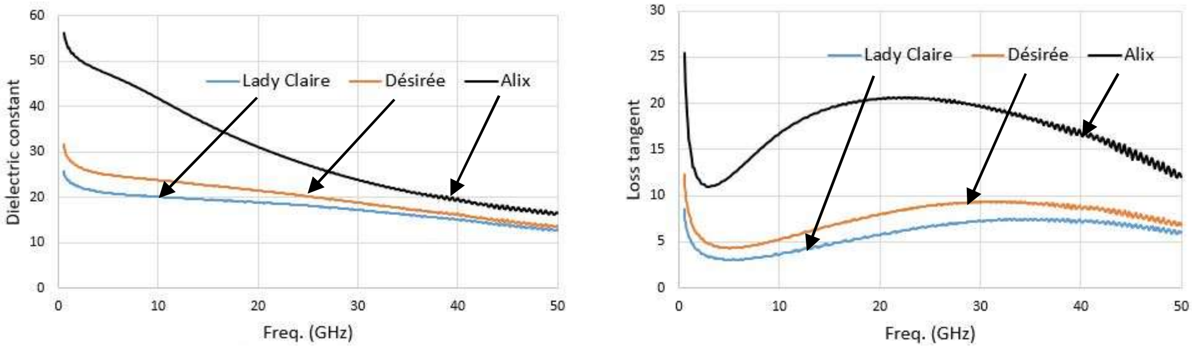

Figure 6. Extracted dielectric constant and Loss tangent from measured reflection coefficient using the SlimForm probe.

The dielectric constant plot shows that Alix exhibits significantly higher permittivity values across the entire frequency range, beginning above 50 and decreasing steadily toward approximately 25. In contrast, Lady Claire and Désirée display lower and relatively stable dielectric constants, with Désirée slightly higher than Lady Claire. This higher permittivity in Alix could be attributed to greater water content or distinct microstructural features enhancing dielectric storage capacity. The loss tangent, which quantifies the energy dissipation relative to energy storage, follows a distinct pattern among the varieties. Alix again stands out with relatively high loss tangent values, peaking above 25 at low frequencies and gradually declining yet remaining dominant throughout the spectrum. This indicates a much stronger dielectric loss mechanism, implying more significant energy absorption, possibly due to higher ionic conductivity. Conversely, Lady Claire and Désirée show lower loss tangent values, remaining below 10 over the full frequency range, with smooth curves suggesting stable, low-loss dielectric behavior. Overall, the analysis confirms that dielectric spectroscopy offers a robust method to differentiate potato varieties based on intrinsic electromagnetic properties.

Following microwave characterization, destructive analyses were performed to determine the exact sugar content in potato tubers. On the same day as the dielectric measurements, the corresponding tubers were collected and prepared for chemical analysis. Each sample was mechanically crushed to obtain a homogeneous pulp, ensuring optimal extraction of soluble sugars. The pulp was then centrifuged for 10 min at 4°C and at 16,000g and the collected supernatant was immediately boiled for 10 min to eliminate all enzymatic activities. After a new centrifugation step such as described above, the supernatant was collected for sugar quantification. Only the glucose content was measured by an enzymatic / spectrophotometric approach (adapted from Vandromme *et al* [16]) which gives a good image of total sugar concentration in the sample (glucose being the most abundant soluble sugars in such biological samples) The final results were expressed in micrograms of glucose per gram of tuber material (µg/g), providing a reference for correlation with the dielectric measurements.

Variety	Lady Claire	Désirée	Alix
Sugar concentration (µg/g)	86	200	8020

Table 2. Measured glucose concentration, expressed in µg per gram (µg/g).

The measured values of the reflection coefficient S11 (both in magnitude and phase), along with the extracted dielectric constant (ε′) and dielectric loss factor (ε′′), are given in Table 3 as functions of glucose content for selected frequencies, for Alix. The results demonstrate a clear relationship between increasing sugar concentration and the electromagnetic response. Specifically, the magnitude of S11 decreases with higher sugar content, indicating increased signal attenuation due to elevated dielectric losses. Similarly, the phase of S11 becomes more negative. The dielectric constant (ε′) increases steadily, particularly between 6.38 mg and 168.42 mg of glucose, suggesting that sugar contributes to the material's ability to store electric energy, likely through increased dipolar and ionic polarization. The dielectric loss factor (ε″) exhibits an even more pronounced rise, pointing to stronger energy dissipation mechanisms associated with higher glucose levels. These results demonstrate a strong correlation between sugar content and the dielectric properties of Alix, confirming the effectiveness of broadband microwave spectroscopy as a non-destructive method for assessing internal biochemical composition in potato tubers.

Frequency	Sugar contentration (mg)	Magnitude (dB)	Phase (deg)	ε'	ε''
0.5 GHz	2.33	-0.25	-5.00	25.64	8.49
	6.38	-0.36	-6.10	31.68	12.33
	168.42	-0.73	-10.52	56.19	25.49
1 GHz	2.33	-0.35	-9.31	23.59	5.43
	6.38	-0.49	-11.14	28.45	7.81
	168.42	-0.91	-20.04	52.50	15.07
10 GHz	2.33	-1.00	-60.46	20.09	3.64
	6.38	-1.35	-69.53	23.74	5.27
	168.42	-2.68	-105.62	41.69	16.82
50 GHz	2.33	-3.63	-137.43	12.79	5.94
	6.38	-3.78	-141.14	13.58	6.84
	168.42	-4.34	-153.72	16.63	12.00

Table 3. Comparative analysis of S11 parameters (magnitude and phase), dielectric properties (ε', ε"), and glucose concentration

3.2 High Frequency Insights

Measurements were conducted up to 50 GHz, leveraging the wideband capability of the probe system for exploratory purposes. However, results showed that meaningful dielectric variations related to tuber composition, particularly water and sugar content, are primarily observable within the lower gigahertz frequencies. This aligns with the known dielectric behavior of water and polar compounds, whose frequency response dominates in the lower GHz range. Therefore, future applications may focus on limited frequency bands, simplifying instrumentation while retaining sensitivity to key biochemical variations.

3.3 Measurement configuration influence

The measurement configuration had a significant impact on the quality and consistency of the dielectric data. Among the three tested methods, probe insertion, peeled surface, and non-invasive surface contact, only the non-invasive approach yielded stable and reliable results. Invasive methods, such as inserting the probe or peeling the skin, appeared to trigger physiological responses in the tuber tissue. As a living organism, the tuber reacts to mechanical disturbance, which likely alters its internal composition and, consequently, its dielectric behavior. These findings highlight the importance of preserving sample integrity for accurate and reproducible measurements. The fact that only non-invasive methods yield reliable results is particularly advantageous, as the ultimate goal is to develop a non-destructive, practical monitoring technique.

4 Conclusion

This study demonstrates the promising potential of dielectric spectroscopy for non-invasive evaluation of sugar content in potato tubers. By employing broadband dielectric measurements from 200 MHz to 50 GHz on multiple potato varieties and under different configurations, we observed clear and consistent correlations between dielectric properties, particularly the imaginary permittivity (ε'') and loss factor (tan δ), and the tubers' sugar concentrations. These correlations were especially evident in the Alix variety, which exhibited higher sugar levels confirmed through enzymatic/spectrophotometric assay.

Among the tested measurement configurations, only non-invasive surface contact provided stable and exploitable results. Interestingly, this limitation aligns perfectly with the intended goal of developing a rapid, non-destructive monitoring technique. The physiological reactivity of the tubers to invasive procedures such as peeling or probe insertion further reinforces the importance of preserving sample integrity during analysis.

In addition, the strong repeatability and reproducibility of the measurements—even when the probe was repositioned—underscore the robustness of the approach. This reliability paves the way for the development of an empirical model capable of estimating sugar content directly from dielectric data. Future research will aim to refine these correlations by focusing on a single frequency, specifically around the ISM band at 2.45 GHz, in order to optimize both simplicity and cost. The methodology will also be validated under real industrial conditions. Ultimately, integrating dielectric spectroscopy into processing lines could provide a powerful, real-time, and non-invasive tool for quality control in the agri-food industry.

Acknowledgement

This work was supported, in part by the French Renatech network, and in part by the CPER Hauts de France project IMITECH.

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