Dual-Pin Impedance Probe for Crop Quality Estimation using the RF Return Loss Method

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***Abstract*—This paper presents a significant advancement in the RF return loss method for crop quality characterization by introducing a dual-pin probe, designed to address the limitations of traditional coaxial probes. The dual-pin probe enhances the measurement process by providing a larger probe-to-sample contact area, which improves accuracy and repeatability, particularly for inhomogeneous crop samples such as cassava. In this study, return loss measurements were correlated with dry matter content determined through the oven-drying method. The results revealed a strong correlation, with a linear regression analysis at 27 MHz yielding an R^2 value of 0.8214. This indicates that the dual-pin probe significantly enhances the reliability of non-destructive dry matter content estimation. The proposed method offers substantial advantages for the rapid and precise assessment of food quality, making it a valuable tool for applications in the agricultural and food processing industries.**

***Index Terms*—Impedance spectroscopy, food and crop quality estimation, cassava, return loss.**

I. Introduction

Impedance spectroscopy, or electrical impedance spectroscopy (EIS), is a versatile technique employed across scientific and engineering disciplines to analyse the electrical properties of complex systems over a spectrum of frequencies. This method offers a non-invasive and non-destructive means to evaluate both organic and inorganic materials, including food products [1], [2]. By analysing the impedance spectrum of food samples, EIS provides valuable insights into their composition, texture, and freshness, making it a promising tool for rapid and accurate food quality assessment that is also cost-effective compared to conventional methods [3]. A derivative application of EIS, RF return loss, measures the reflected RF power after transmitting an RF signal into a sample, offering a rapid and cost-effective means to characterise organic materials [4], [5], [6].

Of particular interest is estimating the starch content in cassava (*Manihot esculenta*), a key tropical root vegetable and primary food staple in sub-Saharan Africa [7]. Cassava's industrial demand is tied to two main quality parameters: the root dry matter and starch content. The accurate estimation of both indices is crucial for farmers, food processors and other stakeholders in the value chain. Higher dry matter and starch content increases market value, directly impacting farmers' economic returns [8]. Furthermore, rapid, non-destructive estimation of both root dry matter and starch is essential to enhance supply chain efficiency and supports the livelihoods of those dependent on this versatile crop. Both indices have a strong linear correlation such that one can be reliably estimated from the other [9].

However, the application of EIS in food quality assessment faces challenges due to its inherent non-specificity and the heterogeneous nature of food samples. This is particularly pronounced in crops like cassava, where the conventional narrow coaxial probes are not effective in providing accurate and consistent measurements [10], [6]. The limited probe-contact of the coaxial probe area requires multiple measurements and complex averaging processes, which is time-consuming and error-prone, especially through tissue damage at the probe-sample interface. To address these limitations, this paper introduces a novel dual-pin probe designed to replace traditional coaxial probes in impedance spectroscopy applications. By significantly increasing the sample-contact area, the dual-pin probe enhances measurement reliability and accuracy for heterogeneous samples like cassava roots, thereby simplifying the measurement process while improving overall precision in food quality assessment [5], [6].

The outline of the paper is as follows: Section II outlines the design theory and application of return loss measurement to the characterisation of organic materials using the dual-pin probe. Section III describes the measurement setup, detailing the equipment and methodology adopted for the experimental validation of the probe. Section IV presents the results and discussion, including return loss plots for the cassava samples used to validate the method, an analysis of the correlation between return loss measurements and dry matter content, and a discussion of the merits of the dual-pin probe. Section IV concludes the paper.

II. Design Theory

Commonly used EIS probes can be categorised into three main classes based on the measurement method employed: the

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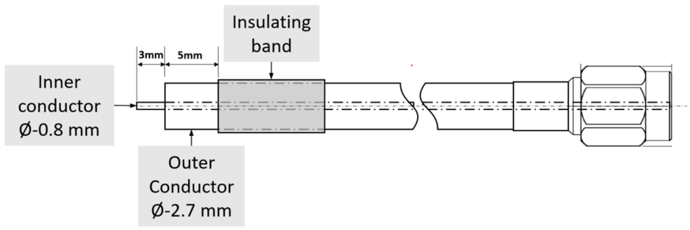

Fig. 1. Open-ended (semi-rigid) coaxial probe [6]

microwave-resonance method [11], the short-circuit waveguide method [12], and the reflection method [5], [10]. The most commonly used method is the reflection method, particularly with the open-ended coaxial probe configuration, shown in Fig. 1 [5], [10]. In this method, an electromagnetic signal is sent through the probe, and the reflected signal is analysed to determine the impedance properties of the material at the probe tip. The open-ended coaxial probe is preferred for its ease of use, versatility, and ability to provide direct contact measurements without the need for complex sample preparation [5], [10]

This method of estimating the dry matter content of cassava is based on the measurement of the return loss (also referred to as the S11 parameter) of the samples and correlating it to the dry matter values obtained through the oven-drying method. The magnitude of the return loss of a sample under test (SUT), RL_{SUT} is given by [13]:

$$RL_{SUT} = \frac{V^-}{V^+} \tag{1}$$

where V^+ is the incident voltage wave being injected into the SUT and V^+ is the reflected voltage wave coming back from the SUT. It is an essential parameter for evaluating the performance of RF and microwave components and has also been used to characterise organic materials.

$$RL_{SUT} = \frac{Z_{in} - Z_{SUT}}{Z_{in} + Z_{SUT}} \tag{2}$$

where Z_{in} is the input impedance from the signal source and Z_{SUT} is the characteristic impedance of the SUT [14]. One of the factors that determines Z_{SUT} is the dielectric constant, ϵ_r also known as the relative permittivity of the sample, which is a measure of how much a material can store electrical energy in an electric field compared to a vacuum, affecting the speed of electromagnetic waves traveling through the material and, consequently, the wavelength and impedance. The characteristic impedance is inversely proportional to the square root of the dielectric constant [14].

Inserting an open-ended coaxial probe into an SUT alters the dielectric constant around the probe, impacting the characteristic impedance, propagation velocity, and reflection characteristics of the probe-SUT system. [14], [5]. The study of this relationship can provide insight into the electrochemical properties of the material. For instance, by measuring the changes in return loss and Z_{SUT} the dielectric constant and, consequently, the electrochemical properties of the material may be inferred. This is useful in fields such as food science,

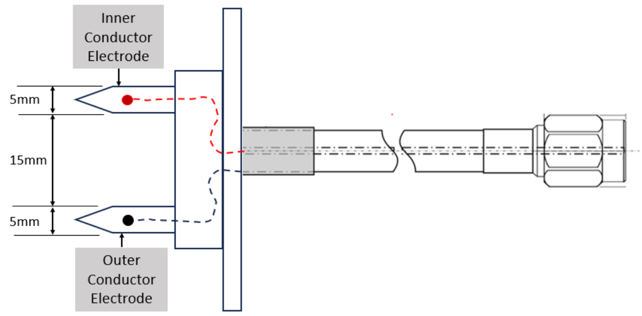

Fig. 2. Dual-pin probe: The inner and outer conductors of the coaxial cable are connected to the respective pins of the dual-pin probe, enhancing the contact area with the sample for more accurate impedance measurements.

agriculture, and medical diagnostics [15], [16], [3], [17]. Also, the dielectric constant of organic materials is highly sensitive to moisture content. Hence, by inserting the probe into different materials and measuring the resulting changes in ϵ_{eff} (i.e. the effective dielectric constant of the probe-sample system) and Z_{SUT}, and RL_{SUT}, the moisture content of samples can be determined, which is critical for quality control in food processing and storage [18]. Furthermore, in medical applications, the dielectric properties of tissues can provide insights into their physiological state. For instance, cancerous tissues often have different dielectric properties compared to healthy tissues [19].

However, the open-ended coaxial probe has some limitations. First, the typically narrow structure of the probe means that there is often a relatively small surface area of contact between the probe and the SUT. For applications that require a precise contact point, which is typical for biomedical application, this may be considered an advantage. However, when dealing with relatively large masses of inhomogeneous samples then the limited surface area would require probing multiple times to achieve a representative impedance value, or the mounting of several probes to achieve a simultaneous effect. The first approach is time-consuming, and the other option complicates the design. Another, perhaps less obvious, limitation of the narrow-form coaxial probe is that the high ratio of probe tip dimensions to the SUT contact surface can lead to major disruptions of the food material being tested, such as the breaking of the cell walls or pooling of fluid in the contact area, which reduces the sensitivity of the measurement system and may render the measurement inaccurate [6], [10]. To address these limitations, a dual-pin probe, with pictorial diagram shown in Fig. 2, is introduced.

III. Experimental Setup

The return loss measurements were conducted using a Keysight FieldFox Microwave Analyser N9917A, a vector network analyser, coupled with the purpose-made dual-pin probe (Fig. 2. The measurement setup is shown in Fig. 3 This setup was used to measure the one-port reflection coefficient of cassava samples across a frequency range of 30 kHz to 100 MHz. The probe was carefully inserted into

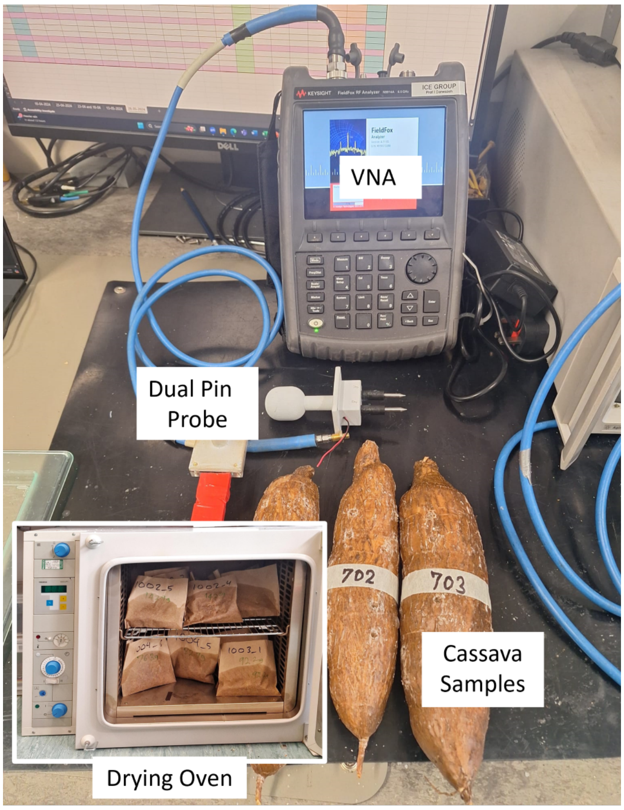

Fig. 3. Return loss measurement setup with the dual probe attached to a N9914A Keysight Firefox VNA. Inset show the oven-drying setup, using a Heraeus UT 6060 laboratory oven

each sample to ensure good contact and accurate reflection coefficient readings. The probe was inserted right through the skin into the flesh of the root. Furthermore, to ensure that the frequency spectrum recorded is representative of the sample being measured, each cassava sample was probed four times at four different points around the root to minimise the effect of the inhomogeneous distribution of the dry matter and starch.

Following the measurement of return loss, the samples were cut into small pieces and placed in a paper bag and weighed using a Kern EMB 500-1BE digital scale (d = 0.1g). These values were recorded as the sample wet weights. The samples were afterwards placed in a Heraeus UT 6060 laboratory oven for drying at an average temperature of $90°C$ until a constant weight was reached, indicating the complete removal of water. The dry matter content was then calculated as the ratio of the dry weight to the initial fresh weight of the sample.

$$\text{Dry Matter (\%)} = \frac{\text{Dry Weight}}{\text{Wet Weight}} \times 100 \tag{3}$$

The dry matter content for each sample was obtained through this means, against which the return loss measurements was correlated, as described in Section IV.

IV. Results and Discussion

Figure 5 shows the return loss plots for 11 fresh cassava samples (labelled Sample 1 to Sample 11), with increasing values of dry matter content. Sample 1 has the lowest dry matter content of this set, with a dry matter percentage of 33.76%, while Sample 11 has the highest dry matter content at 42.46%.

In this experiment, return loss measurements at 27 MHz were found to provide the highest level of dry matter predictability. A simple linear regression analysis of the return loss data at this frequency yielded an R^2 value of 0.8214, indicating a strong correlation between return loss measurements and dry matter content. This high R^2 value demonstrates that return loss measurements at 27 MHz can reliably predict the dry matter content in cassava samples using the proposed dual-pin probe.

Moreover, there is a well-established strong linear relationship between dry matter and starch content. Consequently, this method is also applicable for estimating starch content using existing empirical equations relating dry matter to starch content. Typically, laboratory estimation of starch content involves grinding, mixing, and sieving cassava dry matter through a 180-mesh screen, followed by analysis using the standardized Ewers Polarimetric Method [20]. Although this specific estimation process was not conducted in this experiment, the empirical relationship between dry matter and starch content described in [9] can be employed to estimate starch content from the obtained dry matter measurements.

$$\text{Starch Content} = \frac{\text{Dry Matter} - 4.35}{1.04} \tag{4}$$

This finding supports the potential of using return loss measurements with the dual-pin impedance probe for non-destructive estimation of dry matter and starch content in agricultural products. This method offers several advantages, including rapid measurement and the ability to analyse samples without altering their physical state, which could be particularly beneficial in agricultural and food processing industries where quick and accurate determination of dry matter content is essential. In the cassava industrial context, the accurate and rapid estimation of starch content enabled by this method can enhance the efficiency of the supply chain, improve market transparency, and support better decision-making for all parties involved.

However, it is important to acknowledge the small sample size as a limitation of this experiment. The analysis was based on 11 samples, which might not fully capture the diversity of the broader cassava population. The next phase of this ongoing experiment would include a larger and more diverse set of samples to validate and refine the predictive model. Additionally, exploring the influence of other factors, such as sample temperature and heterogeneity, on return loss measurements could further enhance the accuracy and robustness of the proposed method.

V. Conclusion

This study has demonstrated the potential of using a dual-pin probe for non-destructive estimation of the dry matter content in cassava. By addressing the limitations of traditional coaxial probes, such as limited contact area and the challenges posed by inhomogeneous samples, the dual-pin probe provides a more reliable and accurate measurement method. The return loss measurements at 27 MHz showed a strong correlation

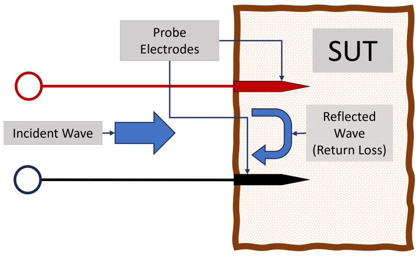

Fig. 4. Circuit pattern diagram for one-port measurement using dual-probe electrode

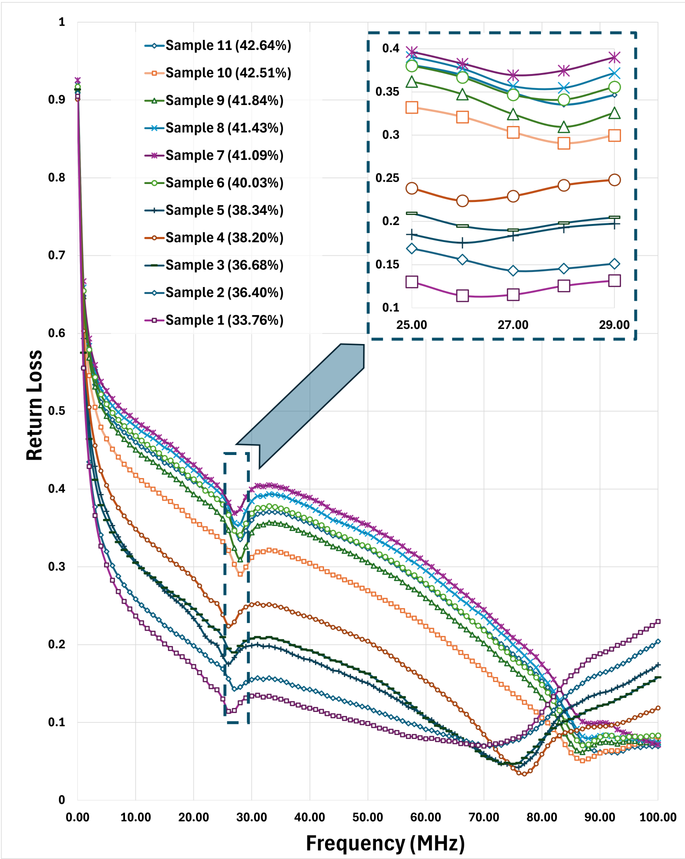

Fig. 5. Return loss plots for 11 fresh cassava samples, labeled Sample 1 through Sample 11. The plots display the variation in return loss with increasing dry matter content, where Sample 1 has the lowest dry matter percentage and Sample 11 has the highest.

with dry matter content, as indicated by an R^2 value of 0.8214, underscoring the effectiveness of this approach.

The use of the dual-pin probe enhances the representativeness of the impedance measurements, reduces the need for multiple probing, and minimises errors due to sample tissue damage. These improvements make the method particularly suitable for rapid and precise assessment of agricultural products, offering significant advantages for food quality analysis in both research and industry settings. With further validation, this technique could be widely adopted in agricultural and food processing industries, enabling improved quality control measures.

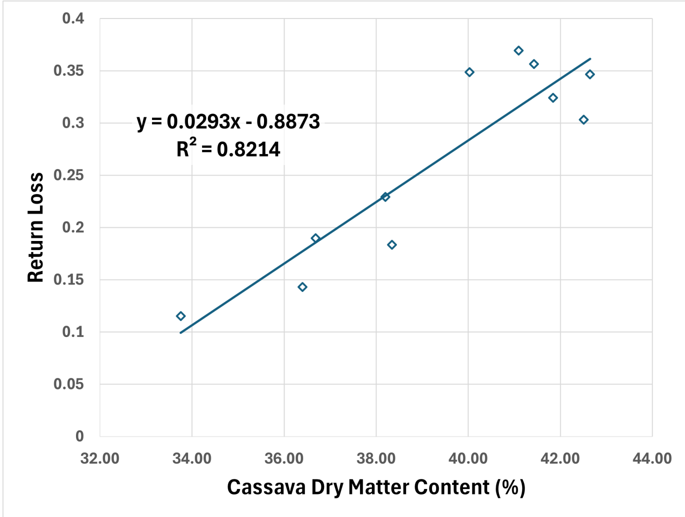

Fig. 6. Return loss at 27 MHz versus dry matter, indicating a strong predictive relationship with an R^2 value of 0.8214.

TABLE I
PERCENTAGE CASSAVA DRY MATTER CONTENT VS RETURN LOSS MAGNITUDE AT 27 MHZ

	Cassava Dry Matter (%)	Return Loss Magnitude
Sample 1	33.76	0.1153
Sample 2	36.40	0.1431
Sample 3	36.68	0.1900
Sample 4	38.20	0.2294
Sample 5	38.34	0.1835
Sample 6	40.03	0.3488
Sample 7	41.09	0.3693
Sample 8	41.43	0.3566
Sample 9	41.84	0.3243
Sample 10	42.51	0.3033
Sample 11	42.64	0.3466

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