High-Throughput Starch Content Estimation using RF Return Loss: Theory, Analysis and Test Instrument Design

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***Abstract*—This paper explores the application of radio frequency (RF) return loss measurements to estimate starch content in cassava, from the theoretical framework to the development of a portable test instrument utilising this method. The design evolution of the portable instrument for starch content estimation, employing RF reflectometry, is described, together with the calibration of the instrument against known starch content samples in the field. This design progression, from a basic hardware platform for proof of concept to versions with wireless connectivity, user interface enhancements, rechargeable batteries, and a focus on cost reduction and mass production suitability, has the potential to benefit farmers and further advancements in food quality assessment. Uploading of measured data from this instrument to the cloud, by means of a custom smartphone app, is also described.**

***Index Terms*—Equivalent circuit modelling, food and crop quality estimation, cassava, electrical impedance spectroscopy, return loss, food technology, food sustainability, reflectometer, IoT, PSoC.**

I. Introduction

Impedance Spectroscopy, often referred to as electrical impedance spectroscopy (EIS), is a technique used in various scientific and engineering fields to study the electrical behaviour of complex systems over a range of frequencies. It offers a non-destructive and non-invasive means to assess the quality of both organic and inorganic materials, including food [1], [2]. By analysing the impedance spectrum of food samples, this method unveils valuable insights into the composition, texture, and freshness of the sample [3]. Consequently, impedance spectroscopy has emerged as a promising tool for food quality analysis, providing a rapid, accurate, and cost-effective alternative to conventional methods [4]. A derivative of the impedance spectroscopic method is the use of the Radio Frequency (RF) return loss, which is a measure of the amount of RF power reflected when an signal is injected into a sample [5], [6], to characterise food and other organic materials [7]–[11]. This paper describes research on the use of the RF return loss method of estimating starch content in cassava roots, specifically.

Cassava is a starchy root vegetable that provides staple food to 800 million people globally [12]. The tropical crop is highly valued because of its peculiar climate resilience, drought tolerance and relative resistance to weeds and insect pests [13]. The bulk of dried cassava root consists of carbohydrates, over 80% of which is pure starch [14], [15]. Pure cassava starch is typically constituted of 16–18% of amylose and 82–84% amylopectin [16]. In [8] the viability of starch content estimation in cassava using RF return loss measurement was demonstrated. The return loss was shown to be a good predictor of both the dry matter and starch content in a cassava sample. The utility of the return loss method for the quality characterisation of cassava has also been verified for cassava flour suspensions and fresh roots [9].

The motivation for the developments described in this paper is the development of a robust, reliable, and low-cost test instrument that could be mass-produced and distributed to cassava farmers, with the goal of contributing to a wider effort to improve productivity and farm incomes in the cassava sector. Hence, precise electrical circuit modelling for the frequency response of cassava flour, based on return loss measurements of suspensions is presented, demonstrating the viability of this technique. Furthermore, the design evolution of the device from early proof of concept demonstration to a fully functional, connected, handheld device is presented.

II. Theoretical Framework

A characteristic impedance of 50Ω has been observed to be common in food samples [17]. In cassava, experiments revealed that high dry matter and starch content in fresh root samples, corresponded with lower measured return loss at frequencies around 30 MHz, indicating a closer match to 50Ω in samples with high dry matter and starch content. This observation provided the basis for the application of RF return loss measurements as a viable means for estimating the dry matter and starch content in cassava root samples, with 50Ω reference [8]–[11].

III. Experimental Setup for Measurement and Model Extraction

Cassava flour obtained by finely grinding peeled and dried cassava chips was dissolved in deionised water at quantities of 5g, 7.5g, 10g, 12.5g, 20g and 30g. The cassava flour in this form is a composite that retains the constituents of raw cassava, which is primarily starch (which is non-conductive [18]) but also includes water-soluble, electrically conductive, constituents such as potassium and sodium [19]. As a control experiment, the return loss of deionised water, which is used as the solvent in these experiments, was also

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measured. The return loss measurements were carried out using a Keysight FieldFox Microwave Analyzer N9917A (a vector network analyzer - VNA [20]) and a specially designed coaxial probe to measure the return loss from 30 kHz to 500 MHz (measurement setup is shown in Fig 1). All the samples were thoroughly stirred before each measurement was taken.

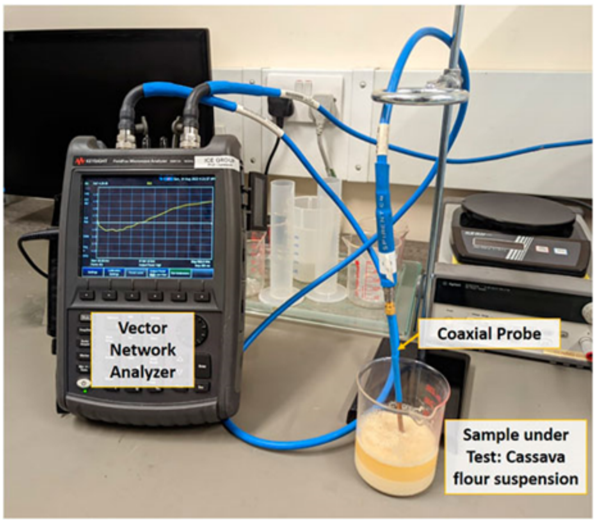

Fig. 1. Measurement setup for testing samples with different concentration levels of cassava flour and starch.

The return loss plots from 30 kHz - 500 MHz from the measurement of the cassava flour composite and extracted pure cassava starch are shown (solid lines) in Fig. 3. Also included Fig. 3 is the return loss of deionised water (black solid line). The increase in the magnitude of the return loss (dB) with increased concentration of the cassava flour may be observed.

An equivalent circuit consisting of resistances and capacitances has been developed to model the frequency response curves in Fig. 3. This model is a modification of the classical 1969 Hayden's equivalent electric circuit model [21] and the double-shell equivalent electrical circuit model [22], which were developed to model the electrical response of plant tissue. The equivalent model developed is shown within the dotted lines in Fig. 2 with the voltage source V_s representing the single port excitation from the VNA for the frequency response measurement as shown in the setup in Fig 1. C_s, C_d and R_d were found to be associated with the starch content in the cassava flour, while R_s models the losses associated with the soluble conductive components of the cassava flour.

The values for the components in the model, at different levels of cassava flour concentration, are shown in Table I. Fig. 3 compares the frequency response plots from the extracted equivalent circuit (dashed lines) against the measured frequency response (presented in solid lines). The model matched the measured response within a 1% margin of difference across all the measured frequencies. R_s is found to be the dominant contributor to the overall frequency response and reduces with increasing flour concentration, reflecting the increase in the conductivity of the suspension. Importantly, C_s, C_d and R_d, which are associated with the starch component of the cassava flour, contribute to the overall frequency profile, with extracted values and effects

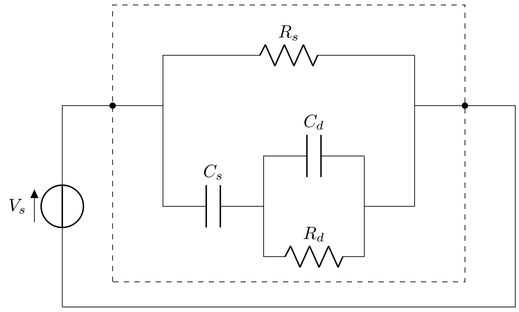

Fig. 2. Equivalent circuit of cassava flour suspension. The component values for different concentrations is shown in Table I

only changing slightly with changing the concentration of the cassava flour.

TABLE I
PARAMETERS FOR THE CASSAVA FLOUR EQUIVALENT CIRCUIT

Flour Conc.	Equivalent Circuit Parameters			
	C_1 (pF)	C_2 (pF)	R_1 (Ω)	R_2 (Ω)
5g	15	500	1	315
7.5g	15	500	1	236
10g	15	550	1	185.5
12.5g	15	500	1	150
20g	15	550	1	101.2
30g	14.3	500	0.5	76.7

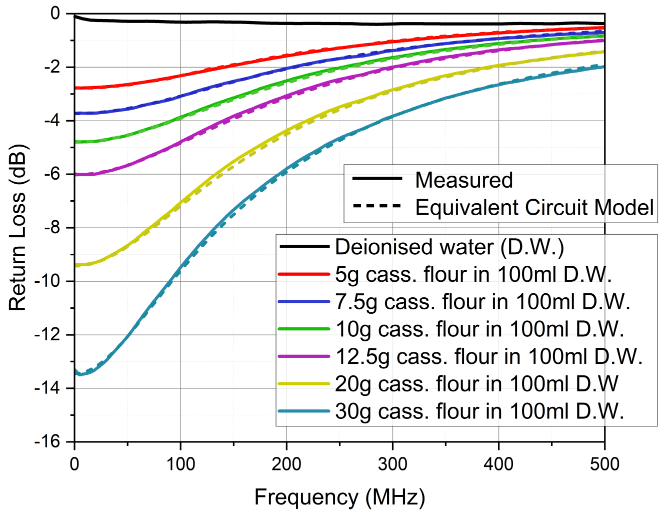

Fig. 3. Return loss plots of suspensions of 5g, 7.5g, 10g, 12.5g, 20g and 30g of extracted cassava (cass.) flour in 100ml of deionised water (solid lines) with plots of corresponding equivalent circuit model (dashed lines).

From Fig. 3, it may be observed that the magnitude of the return loss increases with increasing cassava flour concentration, with the difference clearly discernible up to 300 MHz. A fundamental understanding that pure starch, at room temperature, does not dissociate into ions when suspended in water, hence it does not conduct electricity [18] is quite helpful in interpreting this observation. First, it may be inferred that the changing electrical impedance is due to the presence of dissolved, conductive substance(s) present in the cassava flour and not the starch component (which is non-conductive) [10]. In addition to this, it is also inferred that the return loss approach to measuring starch content actually measures the water-soluble conductive components that are present in the cassava flour, which is proportional to the starch content, thus providing a good measurement proxy.

IV. Test Instrument Development

A. Hardware Development

Following the establishment of the link between RF return loss and starch content in cassava flour suspensions, a portable test instrument was designed to allow field measurement of starch content in fresh cassava roots, using the RF return loss method. Several versions of the instrument have been developed, all comprising four basic elements: a simple RF reflectometer, an RF signal source (frequency synthesizer), a low-cost microprocessor and some form of display. The hardware platform evolved over several iterations, which are described in some detail in [11]. Here we will only summarise the first ”proof-of-concept” version and the most recent iteration of the platform, which we will refer to as ”version 3”.

B. Proof-of-concept Hardware (Version 1)

The first generation of hardware was a minimum viable platform intended to prove the concept of a battery-operated portable instrument able to measure starch content of cassava using the RF return loss method. The architecture of this instrument was described in detail in [8] and consisted of an RF signal source (frequency synthesiser module), a reflectometer (to measure RF power reflected from the cassava sample), simple data processing and a rudimentary display consisting of an array of 5 LEDs to indicate a range of return loss values calibrated to represent starch content in 5 bands, from low to high. The processor used was an ATmega328 in the form of an Arduino nano module [23] and the whole device is powered using four standard AAA alkaline batteries. This version 1 hardware platform is shown in Fig. 4. The probe used consists of a rigid coaxial probe connected to the instrument via the SMA connector (at the left-hand edge of the board in Fig. 4). The probes are described in more detail in [8].

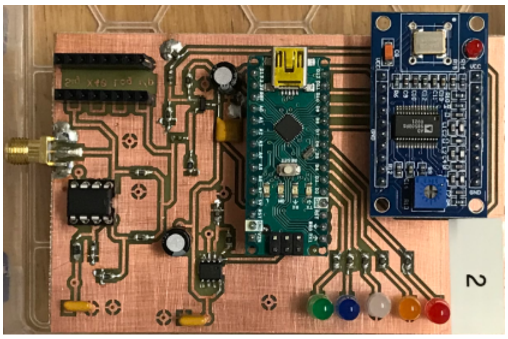

Fig. 4. Version 1 hardware platform

C. Test Instrument Calibration

The version 1 test instrument was calibrated at the International Institute of Tropical Agriculture (IITA) in Nigeria, using a range of cassava root samples taken from 4 different varieties of cassava with known starch content ranging between 6% and 22%. The roots were cut into proximal, mid and distal sections and the starch content of each section was determined using the Oven Dry Matter (ODM) method described in [8]. Empirical formulae presented in [24] were applied to the ODM results to arrive at actual starch content percentages. The version 1 test instrument was used to test each sample using the coaxial probe [8] and the readings generated by the ATmega323p internal Analog to Digital Converter (ADC) were recorded. Average ADC readings are shown in Table II, together with the corresponding ODM measured starch content for the sample set and the specific LED thresholds that were set during this test. A maximum ADC reading of 1024 represents a return loss of less than 3dB, i.e. more than half the incident RF power is being reflected back from the Sample Under Test (SUT). This corresponds to a high starch content ($> 20\%$) and will be indicated by the green LED being activated. An ADC reading below about 100 corresponds to a return loss of over 20dB which will indicate that over 99% of incident RF power is being absorbed by the cassava sample. This corresponds to a low starch content ($< 5\%$) and will be indicated by the red LED being activated. Extensive discussion and results of these field tests are presented in [8], [9]

TABLE II
VERSION 1 CALIBRATION DATA

ADC reading	Starch content	LED on
0 to 100	$< 5\%$	Red
100 to 270	$> 5\%$ to 10%	Amber
270 to 420	$> 10\%$ to 15%	White
420 to 760	$> 15\%$ to 20%	Blue
760 to 1,024	$> 20\%$	Green

D. Improved Test Instrument Platform

After the concept was proven and the version 1 platform was calibrated, work focused on enhancing the functionality, connectivity, and manufacturability of the test instrument. A version 2 instrument was developed using a more powerful processor and built in display. The version 2 instrument is described in [11]. The current version 3 instrument represents a significant evolution in power and functionality over both version 1 and version 2. The processor being used in the current version is a Cypress PSoC 6 processor, [25], which is an ARM-based ”system on a chip” device allowing the integration of some of previously external components. For example, we now use the PSoC to generate a 6MHz reference signal which is multiplied up to 30 MHz using an external frequency multiplier. This enabled the replacement of an expensive frequency synthesiser module with much cheaper components. An external op-amp gain stage has also now been absorbed into the PSoC. In addition to the 5 LED bar-graph display, the updated hardware includes an OLED display that displays the measured starch values as well as other data.

Perhaps the biggest functional improvement with version 3 hardware is the addition of Bluetooth Low Energy (BLE) wireless connectivity, a functionality built into the PSoC 6 processor module. This allows data to be collected on a mobile device, such as a smartphone, and uploaded to the cloud as required. An internal Real-Time Clock (RTC) allows starch data readings to be time-stamped in the instrument (when no smartphone connection is available) and an external temperature sensor has been added to measure probe temperature, which is included in the dataset of each starch reading.

The updated hardware platform is powered from a rechargeable LiPo battery, with built-in battery charging via a standard micro USB connector, and power management circuitry to supply a standard 5V and 3.3V supplies to the electronics irrespective of the state of the battery. An option to allow battery charging from a solar cell is also available in the latest version.

The version 3 hardware platform, with plastic enclosure open, is shown in Fig. 5.

Fig. 5. Improved hardware platform (version 3)

E. Internet and Cloud Connectivity

The Bluetooth (BLE) capability built into the version 3 instrument allows for connection to the internet via a smartphone app for the purposes data storage, analysis and further uploading to a cloud platform. An Android smartphone app was developed as a dedicated tool for this purpose. The app connects to the instrument and receives a measured data record every time the "test" button on the instrument is pressed. Each data record transmitted from the instrument contains the following:

1) Device ID
2) Firmware version
3) Starch content (reflectometer reading)
4) Ambient temperature
5) Time/date stamp (local RTC value)
6) Battery level

Geolocation data is added to each data record by the smartphone app, and the RTC on the instrument is re-synchronised every time it is connected to the smartphone. Since there is no geolocation capability in the instrument itself, only location where the data has been uploaded to the smartphone can be recorded, not the location where the measurements were necessarily taken.

When the smartphone is connected to a Wi-Fi service or a cellular data service, the data can be transferred to a designated cloud platform, enabling data accessibility from any global location and facilitating logging and further analysis. Each actuation of the test button on the instrument prompts an immediate transfer of the current measurement data record, plus any data records that have been stored in the instrument since the last BLE connection and data upload to the smartphone was made. In scenarios where internet connectivity is absent, the smartphone app temporarily retains the time-stamped data records, uploading them to the cloud once a connection is re-established. Fig. 6 shows the version 3 instrument, in it's case, alongside a smartphone displaying the smartphone app.

Fig. 6. Version 3 starch measuring instrument together with smartphone App

V. Conclusion

This paper presents a new electrical equivalent circuit model for cassava and sheds new light on the use of the electrical property of return loss to characterise cassava quality, specifically with regard to measuring the starch content of cassava roots. While starch is non-conductive, the content of charged ions in the raw composite cassava flour (Potassium, Phosphorus, Calcium etc) appears to be correlated with the amount of starch in the cassava. This provides a potential marker for estimating the starch content of cassava, which is important for the design of quality measurement devices based on the return loss method. The paper also outlines the evolution in design philosophy for a portable test instrument for collecting starch content data in the field and uploading to the cloud. The overall aim is to create a cost effective solution, which is easy to use. The instrument reported here will become part of a larger ecosystem for monitoring the health and yield of Cassava. Moreover, this research opens up new avenues for further research in the field of cassava quality assessment.

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