Towards Detection of Fruit Ripening and *Moniliophthora Roreri* in Cocoa Using a Capacitive Sensor

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Abstract. This study presents the design and development of a non-invasive sensor for measuring the capacitance of cocoa fruits to detect ripening stages and the onset of fungal disease caused by Moniliophthora roreri. Capacitance is recognized in the state of the art as an effective physiological indicator due to its correlation with moisture content, cell development, and glucose levels in fruit. Based on this premise, the hypothesis was that capacitance measurements are directly related to fruit ripening and fungal infection. The sensor system features an electronic circuit that generates a 10V peak output at a frequency of 1 kHz, integrated with a Sauty Bridge for real-time capacitance measurements without harming the fruit. The device is lightweight, user-friendly, and energy-efficient. The experiments were carried out under controlled conditions using the CNCH13 cocoa variety to standardize the measurements. The preliminary results confirm a strong correlation between capacitance levels, ripening stages in healthy fruits, and the presence of fungal disease. The prototype developed effectively measures capacitance, providing a reliable method for assessing the physiological state of cocoa fruits.

Keywords: Capacitance, Cocoa ripening, Sauty bridge, Moniliasis

1 Introduction

The quality and yield of cocoa trees (Theobroma cacao) are vital to the sustainability of the chocolate industry and the livelihoods of millions of farmers worldwide [1]. A constant challenge is the early detection of the stages of ripening of cocoa fruit and diseases, such as moniliasis caused by the fungus *Moniliophthora Roreri* [2]. This pathogen causes significant economic losses and reduces the quality of the final product, which emphasizes the need to implement effective and non-invasive surveillance methods. Capacitance, defined as the ability of the system to store charge, has been shown to be a promising index to assess the physiological state of agricultural fruits [3][4][5]. Previous research has shown that yield is influenced by factors such as moisture and cell density [6][7][8], which change during ripening and under conditions of fungal disease [9][10][11][12]. However, commercial instruments for measuring the capacitance magnitude are not designed to measure capacitance in fruits, which limits their use in agriculture. In this context, this work proposes a non-invasive sensor based on Sauty bridges [13] to measure the capacitance of cocoa pods, designed for agricultural environments with low power consumption and real-time measurements. Experiments with landrace and CNCH13 varieties have revealed a correlation between yield, ripening, and the presence of *Moniliophthora Roreri*, suggesting that this technology can optimize production, reduce losses, and improve the quality of cocoa. The study describes sensor design, test methods and results, highlighting technical challenges and opportunities for improvement, as well as its potential application in precision agriculture and other crops.

2 Materials and Methods

The central concept of this study is to select and build a device that can make reliable capacitance measurements on cocoa fruits to try to detect ripening points and fungal diseases in cocoa pods. Figure 1 shows the flow chart that explains how the data was collected, how it was processed, and how the characteristics were extracted for the final measurement system.

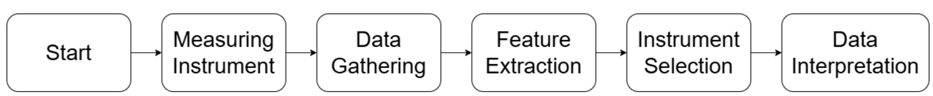

Fig. 1: Flowchart of the study

2.1 Measuring Instrument

To initiate measurements on the cocoa fruits, an initial LCR740 meter was used, this equipment is totally analogical, and in its capacitance measurement it works with the sauty bridge balancing principle [13] at a frequency of 1KHz and 584mV, as can be seen in Figure 2.

The second instrument used was an LCR meter, specifically the Meterman LCR55. This device displays measurements numerically and measures capacitance by injecting the system with a 630 mV sine wave at a frequency of 1 kHz. LCR meters were chosen for the initial measurements as they are widely available and accessible to the public. See Figure 2.

To simulate a capacitor with cocoa fruit as dielectric material, parallel curved plates of 316L stainless steel were used; at first the plates were manufactured

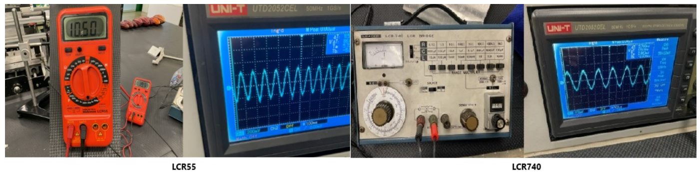

Fig. 2: LCR740 meter and its characterization of 584mV peak and 1kHz and Meterman LCR55 meter and its characterization of 630mV peak and 1kHz

with a diameter greater than the average cocoa fruit; it was evident that the first measurements with cocoa fruit using these plates were not accurate or repeatable, since the electric compo was lost in a larger surface than the area of the fruit. The measuring points where the clamps are connected are at the top and bottom of the plates, as can be seen in Figure 3.

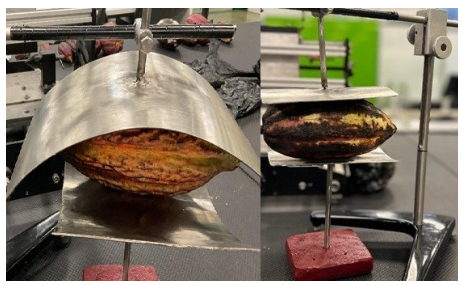

Fig. 3: Curved parallel plates with a diameter larger than average cocoa fruit and Curved parallel plates with average cocoa fruit diameter.

As can be seen in the wave and voltage characterizations of the two LCR meters, how can see en the Figure 2 and Figure 3, both have similar waves and voltages, therefore the measurements made with these devices were similar even with their similar measurement deviations, so it is selected among the different principles of capacitance measurement the sauty Sauty bridge [13], since it is used to measure capacitance, if only capacitance is to be measured, that is, if resistance ESR (Resistance Series Equivalent) is not to be measured [14]. As shown in Figure 4, the Sauty bridge is used [13]. The Sauty bridge is used to measure the capacitance of an unknown capacitor by comparing it with a known reference capacitor. The Sauty bridge is a Wheatstone bridge configuration adapted to measure capacitance. It consists of two branches, one with the unknown capacitor (C-COCOAFRUIT)and a resistor (POT), and the other with a reference capacitor (C3) and a resistor (R2).

An alternating current (AC) signal is applied to the bridge. The bridge is in equilibrium when the ratio of the impedances in one branch is equal to the

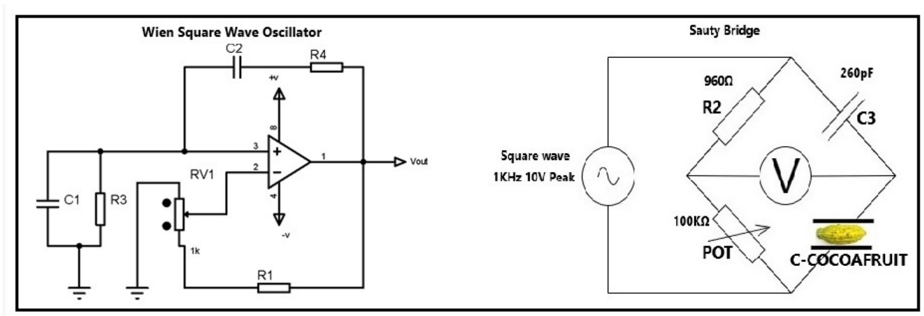

Fig. 4: Block diagram of the final system used

ratio of the impedances in the other branch. Mathematically, this is expressed as shown in equation 1.

$$R2 = \frac{POT * C_3}{C - COCOAFRUIT} \tag{1}$$

To perform the capacitance measurement, the resistors (POT) and (R2, fixed known value) are adjusted until the balance detector (in our case an oscilloscope) indicates zero signals, the unknown capacitance can be determined. $C - COCOAFRUIT$ using the relation shown in equation 2.

$$C - COCOAFRUIT = C_3 * \frac{R_2}{POT} \tag{2}$$

Figure 3 shows a graphical approach to the final measurement system where it can be seen that $C - COCOAFRUIT$ is shown as a capacitor.

The Sauty bridge operates with a sine wave. For the initial measurements, a signal generator was used, while a Wien bridge oscillator was employed for subsequent measurements after finalizing the measurement system [15]. The Wien bridge oscillator is a circuit that generates sine waves using an operational amplifier and a feedback network composed of resistors and capacitors. The basic circuit of the Wien bridge oscillator includes an operational amplifier in a non-inverting configuration, with the feedback network consisting of two resistors and two capacitors arranged in a bridge. The oscillation frequency of the circuit is determined by the values of the resistors and capacitors in the feedback network. The formula for calculating the oscillation frequency can be seen in equation 3.

$$f = \frac{1}{2 * \pi * R * C} \tag{3}$$

Where $R_1 = R_3 = R_4$ y $C_1 = C_2$

To keep the oscillation stable, it is necessary to adjust the gain of the amplifier. This is done with the potentiometer RV1(Variable resistor). In this case the gain was adjusted to the maximum to generate a square wave of 1KHz and 10V peak, the complete measurement system can be seen in Figure 4.

2.2 Data gathering

These measurements are made with the two LCR meters, the LCR740 and the LCR55, using the curved parallel plates without optimization, two measurements are made for each fruit, both with Monilia and fruits at different stages of ripening, results that indicate that the equipment are not appropriate for measuring capacitance in these cocoa fruits. The results obtained are highly variable and atypical. In fruits at different stages of maturation, the capacitance values ranged from a maximum of 16.8 nF to a minimum of 1.7 nF, while in contaminated fruits, the values ranged from 57.9 nF to 0.2 nF. Figure 5 shows the selected samples.

Fig. 5: Local variety cocoa fruit at diferent stage of ripening and cocoa fruit contaminated whit monilia

For the following measurements, different types of varieties were used, CNCH13, CNCH12 [16][17] and local varieties, two (2) contaminated fruits and eight (8) fruits with different ripening stages. For these measurements a signal generator was used as a sine-wave generator for The Sauty bridge in order to vary the frequency at 100Hz, 300Hz, 500Hz and 1KHz at 1V, 2.5V, 4V and 5V in a sine wave, the results show scattered data and no apparent correlation between the different combinations of frequency and voltage. For the capacitance measurements of the fruits in figure 6, the system shown in Figure 4 is used, with a 10V square wave and using optimized parallel curved plates.

The results obtained in the cocoa fruit measurements, which can be seen in Figure 5, were satisfactory, the average measurements were between 1.7 nF and 2.2 nF and their maximum standard deviation was a maximum of 0.52 nF, which indicate a low capacitance in healthy fruits with different stages of maturation.

For the last measurements, 10 cocoa fruits, 2 contaminated fruits and 7 healthy fruits with different stages of maturation as shown in Figure 6.

The same measurement system was used as before, with ten (10) measurements taken for each fruit, rotating the fruit between measurements. For fruits 3 and 5, outliers were identified. In fruit 3, the mean capacitance including the outlier was 31.23 nF; after correction, the mean increased to 34.95 nF. Similarly, in fruit 5, the mean with the outlier was 71.92 nF, which was corrected to 35.04 nF. The results are conclusive: healthy fruits showed average capacitance measurements ranging from 1.8 µF to 2.4 µF, while contaminated fruits exhibited averages between 34.8 µF and 40.4 nF. This demonstrates a clear distinction between healthy fruits at different stages of maturation and contaminated fruits.

Fig. 6: Cocoa fruits CNCH13 contaminated and healthy fruits and Cocoa Fruits of different variants

2.3 Feature extraction

The measurements from the fruits shown in Figure 6 yielded the following conclusions: healthy cocoa fruits at different stages of ripening exhibited low capacitance values, typically less than 5 nF, while contaminated fruits showed significantly higher capacitance values, exceeding 30 nF, as summarized in Table 1. and Table 2.

Table 1: Measurement results for cocoa fruits of different variants

Samples	**Average in nF**	**Standard deviation in nF**
Fruit 1	2.10	0.5216
Fruit 2	2.25	0.5201
Fruit 3	1.99	0.3136
Fruit 4	1.72	0.271
Fruit 5	2.25	0.4971

Table 2: Measurement results for cocoa fruits CNCH13 contaminated and healthy fruits

Samples	**Average in nF**	**Standard deviation in nF**
Fruit 6	2.44	0.5946
Fruit 7	1.89	0.4068
Fruit 8	34.58	0.1619
Fruit 9	2.10	0.4534
Fruit 10	40.43	0.4188

2.4 Instrument selection

For the initial measurements, commercially available instruments commonly used for general purposes were selected: the LCR740 and LCR55. These instruments were utilized to obtain reference measurements and establish starting points for the capacitance measurement. Following the initial measurements, it was decided to proceed with the Sauty bridge system, using a 10V square wave excitation, as described in the system details. The complete setup is shown in Figure 7.

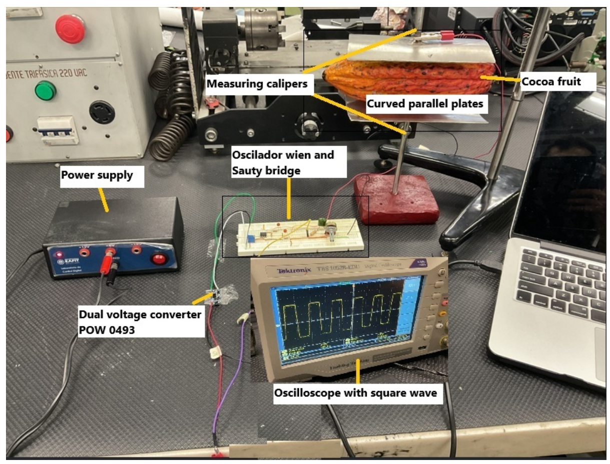

Fig. 7: Selected measurement system

3 Results

This section corresponds to the final part of the proposed methodology, Data Interpretation. The data obtained with the fruit sample that can be seen in Figure and the fruit data in Figure 10 are conclusive data for these samples taken; the box and whisker graphs ratify the analysis that indicates the presence of fungal diseases [18] in cocoa fruits whose capacitance measurements are greater than 30 nF and in healthy fruits with different stages of maturity yield measurement data below 5 nF, as shown in the graphs shown in Figure 8 and Figure 9.

The boxplot Figure 8 represents the distribution of capacitance (in nF) in five types of cocoa fruits. types of cocoa fruits. A remarkable variability in the values is observed, suggesting differences in the electrical properties of the fruits. suggesting differences in the electrical properties of the fruits. In the plotted values of the values plotted for Fruit 3 and Fruit 5 show significantly higher capacitance compared to the other fruits. Fruit 1 Fruit 2 and Fruit 4 show much lower values and less scatter. The Capacitance of Fruit 1, Fruit 2 and Fruit 4

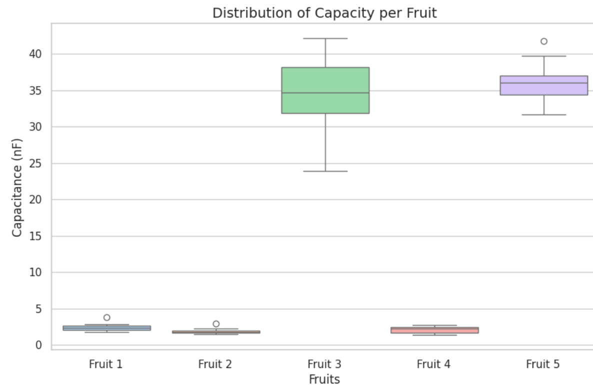

Fig. 8: Standard scatter plot Cocoa fruits of different variants

samples varies in a range of approximately 0 nF to 5 nF. approximately 0 nF to 5 nF with a narrow distribution and less variability in the measurements.

variability in the measurements. Fruits with high Fruit 3 and Fruit 5 show values ranging from 25 nF to 41 nF, with a median close to 35 nF, in both cases, the variability is notably significantly higher in comparison with the other fruits. It is inferred and can be visualized in image 8 that the fruits with high capacitance (Fruit 3 and Fruit 5) correspond to samples contaminated with fungal diseases, therefore, the capacitance could be correlated with the capacitance could be correlated with the presence of pathogens, that the increase in capacitance may be due to structural changes in the fruit tissue structural changes in the fruit tissue, such as increased moisture content, alterations in electrical permeability and dielectric changes. If fruits with low capacitance (Fruit 1, Fruit 2 and Fruit 4) are healthy, then capacitance could be low capacitance could be an indicator of uncontaminated fruit and its low variability in these fruits suggests that their internal structure is more homogeneous. structure is more homogeneous.

The boxplot Figure 9 shows the distribution of capacitance (nF) in five variants of cocoa fruits: fruit 6, fruit 7, fruit 8, fruit 9 and fruit 10, the capacitance in all variants is in a range between approximately 1.5 nF and 4.0 nF showing differences in the dispersion of the data between variants, suggesting that certain fruits have greater variability in their capacitance values also observing outliers in several samples, indicating the presence of some measurements significantly different from the general trend. The existence of outliers, but within the expected capacitance ranges, show that the fruits have similar electrical characteristics as the samples measured are from healthy cocoa fruits. The measurements of fruits with relatively high variances could be due to factors related to their ripening stage, slightly changing their chemical composition, increasing or decreasing their dielectric capacitance.

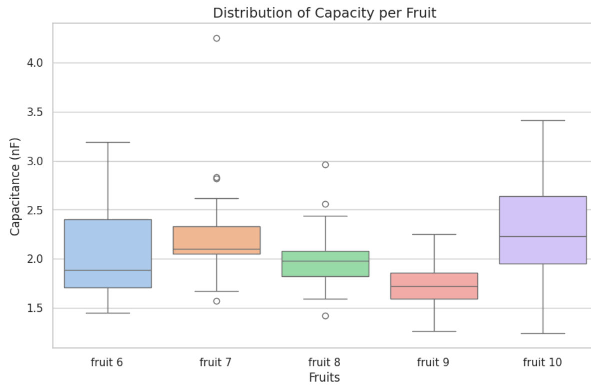

Fig. 9: Standard scatter plot Cocoa fruits CNCH13 contaminated and healthy fruits

4 Conclusions

The developed sensor successfully measures capacitance in cocoa fruits through non-invasive means. The current prototype operates effectively with a 10V square wave signal. Future optimizations will focus on the implementation of the system on a micro controller with digital measurement display capabilities. Research has demonstrated a correlation between capacitance measurements and both ripening stages and fungal infections in cocoa fruits. This relationship is particularly evident when comparing healthy fruits with those infected with *Moniliophthora Roreri* (Monilia), suggesting that capacitance measurements can serve as reliable indicators for both fruit maturity and disease presence. The sensor has demonstrated effectiveness in detecting *Moniliophthora Roreri* infections in selected cocoa fruit samples. This capability significantly enhances the value of the device as a monitoring tool for the management of cocoa crop health. For future work and system improvement, the measurements from the Sauty bridge can be transferred to a microcontroller and visualized on a display, making it a portable device for use in different locations.

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