in capacitance between two capacitor plates are detected. Noncontact capacitive measurements are influenced by variables, such as plate size, distance, sample characteristics, and ambient temperature. The latter, in particular, alters the permittivity of materials between plates, greatly influencing the measured capacitance. Notably, impedance and capacitance in capacitors have an inverse relationship: at higher frequencies, capacitive impedance decreases, leading to increased current flow. It is essential to comprehend this connection to properly interpret the impedance measurements produced by noncontact capacitive methods [13]. In particular, several noncontact methods have been employed for fruit quality evaluation. For instance, the ripening of bananas has been assessed using a noncontact approach with parallel plates to measure the fruit's dielectric properties [14]. Another study used a noncontact approach to test the quality characteristics of bananas based on their dielectric properties, proving the method's effectiveness for determining ripeness and quality changes [15]. The firmness of apples was evaluated noncontact by utilizing a parallel plate capacitor [16]. In addition, the device is used to acquire conductivity spectra from different biological test specimens [17].

Noncontact detection systems offer several advantages allowing them to be suitable for industrial purposes, including the ability to measure multiple fruits simultaneously, noninvasively, and with real-time data acquisition. This study aims to develop a noncontact measurement technique to assess fruit quality. The proposed system design is presented in Section II, which includes the design requirements, system architecture, circuit design, measurement specifics, setups, and calibration. The measurement is performed in the frequency range of 5 Hz–200 KHz every hour for seven days consecutively on two samples, banana and soap (reference sample) to investigate the aging effect, as described in Section II-A. Furthermore, in this section, the response of the system to the presence and absence of the fruit is studied over four days of measurement on three bananas, to fully investigate the temperature effect. Here, the same samples were also employed to investigate the effect of the fruit mass loss on the recorded C_s values. In Section II-B, an extension of the investigation is provided by studying 51 nectarines in the frequency range of 10 Hz–1 MHz, focusing on the ability of the system to detect mechanical damage. Outcomes in Section III-A demonstrate that C_s value of the banana declined by 6.76 % on the first day and further decreased by 3.38 % on the last day of measurement in contrast with the reference sample, soap whose C_s behavior was constant over time. Also, in this section, a comprehensive comparison with relevant studies is provided. The consequence of Section III-B reveals that even after 24 h, the system can effectively distinguish damaged samples. Moreover, multivariate analysis, in particular analysis of variance (ANOVA), demonstrates how effectively the system performs to distinguish samples that are undamaged from those that are damaged, especially 24 h later. These results support the suggested noncontact measuring method, demonstrating successful biological sample aging and damage assessment with the potential for sorting on production lines. Finally, Section IV concludes this article, summarizing findings and discussing future directions for improving the method and outlining potential future possibilities for the method's development and industrial use.

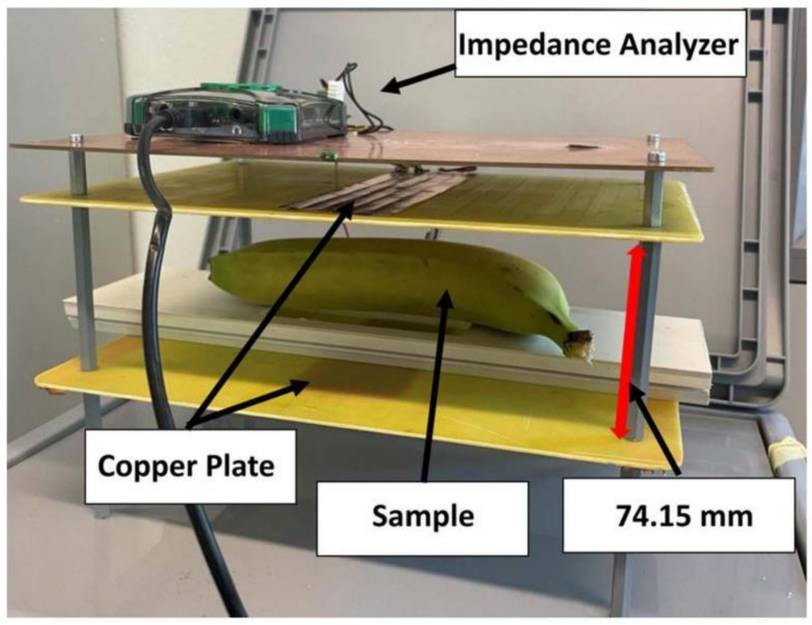

Fig. 1. Capacitive setup includes an impedance analyzer, two copper plates within a distance of 74.15 mm, and a sample under test (i.e., a banana in the figure).

II. Materials and Methods

Fig. 1 illustrates the measurement system setup, including all its components. The system is composed of two 300 mm × 200 mm parallel copper plates, with an unplasticized polyvinyl chloride (UPVC) stage containing a hole to safely hold the sample under test in between the plates. The hole in the stage is precisely sized to match the width of the plates, ensuring that only the segment of the fruit directly interacts with the electric field. The selection of UPVC material was based on its observed lack of effect on the electric field during experiments. The upper plate is fixed at the same height as the UPVC stage to maintain consistency in the air gap on both sides of the sample, satisfying Gaussian law. Also, the setup was enclosed in a plastic box to reduce the influence of the surrounding environment on the measurements. The sample's shape is one of the many elements that determine capacitance. Because of the plates' small dimensions compared to the sample, shape-dependent variations in readings are minimized. This is because the electric field lines between the plates are more uniform when the plates are smaller than the sample, preventing the sample's shape from seriously distorting the electric field [18].

For acquiring the bioimpedance data, a semiportable impedance analyzer (Digilent Analog Discovery 2) operating across different frequency ranges is used. To have a better signal generated by the impedance analyzer, the feedback resistor and the system voltage are considered to be the maximum values that can be selected on the software, 1 MΩ, and 5 V_{P-P}, respectively. Since the capacitance also depends on temperature, after placing the samples between two plates, simultaneous measurements of the temperature inside the box and capacitance were carried out. The temperature data were acquired using a Pico TC-08 Data Logger. The system's capacitance in the first approximation can be estimated by fitting the impedance data to an equivalent circuit.

The samples that were studied in this experiment are four bananas, a bar of soap, and 51 nectarines that were obtained from a single vendor (Eurospar) at the neighborhood store. Two settings were employed for the two different experiments, according to the type of sample. The first setup was used to study the aging effect of bananas and soap, while the second setup was employed for damage detection. The height of the setup was