Capacitive Impedance Analysis for Noncontact Assessment of Fruit Quality and Ripening

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***Abstract*—This article presents a comprehensive examination of the development of a non-contact measuring technique for determining fruit quality. Capacitance measurements were performed on soap (reference), banana, and nectarine samples across a frequency range of 5 Hz–200 kHz for banana and soap, and 10 Hz–1 MHz for nectarine. The data analysis revealed consistent trends in series capacitance (C_s), indicating its suitability for future investigation. Additionally, temperature compensation improved data accuracy. Compensated capacitance data, obtained through linear fitting coefficients from the first 18 hours of data, showed distinct trends in banana samples, with a reduction of 6.76% on the first day and an additional 3.38% on the last day, illustrating the impact of aging. In contrast, the soap reference sample exhibited constant capacitance behavior over time. The response of the system to the presence and absence of the fruit sample and the effect of mass loss of the banana fruit on the Cs trends were also examined. The system's capacity to differentiate between undamaged and damaged samples was demonstrated after the investigation was expanded to include 51 nectarines. Following the impact damage, C_s significantly increased, particularly one hour later, aligning with biochemical changes associated with mechanical damage. ANOVA, a type of multivariate analysis, highlighted the system's efficacy. The system demonstrated preserved damage detection even 24 hours after impact, despite temperature variations. This study provides valuable insights into non-contact measurement methods for potential industrial use, considering the effect of temperature and sample-specific analysis in the accurate evaluation of fruit quality.**

***Index Terms*—Aging, banana, bioimpedance, capacitance, fruit quality, mass loss, mechanical damage, nectarine, nondestructive techniques, temperature compensation.**

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I. Introduction

FOOD quality is one of the most important aspects to be considered to protect human health. Among the various food items to be inspected, fruits play a key role. Furthermore, the reduction of fruit waste through its correct quality evaluation is especially relevant in the agri-food industry to reduce financial loss [1] and to improve food security and sustainability. Fruit sorting methods taking into consideration both internal and external qualities and flaws are essential throughout all postharvesting stages. In this context, significant challenges arise from mishandling, freezing, and transportation-related damages [2], [3]. To address this, the industry employs sorting techniques to identify unsuitable fruits for market or storage. To date, accurate determination of fruit quality is based on both destructive and nondestructive methods. While destructive methods typically require long times and are not appropriate for large-scale measurements, nondestructive procedures provide instantaneous outcomes and are more desirable.

Nondestructive quality detection technologies for postharvest products can utilize optical and electrical properties. Optical techniques, such as colorimetry [4], imaging [5], and spectroscopy, provide insights into the internal structure of fruit through interaction with light. Alternatively, the interaction of an electric field with the fruit presents a new approach to the measurement of fruit quality. Electrical impedance spectroscopy (EIS), also called bioimpedance, allows measuring the passive electrical properties of a sample in response to an applied electromagnetic field [6]. While both approaches offer fast and efficient measurements, bioimpedance represents a low-cost and promising approach compared to conventional optical methods. Such impedance measurement techniques can be classified as contact and noncontact. Extensive research has been conducted on non-destructive contact methods for fruits, such as bananas [7], apples [8], [9], strawberries [10], and mangoes [11]. However, with the increasing demand for real-time fruit quality detection in industrial settings, the development of fast, nondestructive, and noncontact detection systems has become crucial [12].

While EIS is typically measured using electrodes in direct contact with the device under test (DUT), capacitive noncontact measurements can also be performed. In this approach, electrodes are not connected to the sample; instead, the changes