B. Setup 2

For subsequent research, the focus shifts to a comprehensive mechanical damage study of 51 nectarines. The measurements are conducted over a wider frequency range of 10 Hz–1 MHz over 200 logarithmically spaced frequency points in the two-electrode configuration, in line with [22], [23]. According to the size of the nectarine sample (on average 66.7 mm), the distance between the plates is increased to 100.7 mm. To assess if the setup can distinguish the effect of mechanical damage on the nectarines a simple pendulum with a platform and a bob acting as a ball hammer was fabricated [24], [25]. The platform was constructed at the equilibrium position of the pendulum to hold the fruit sample. The bob was designed to replicate the bruising injury of fruit falling from a height of 30 cm, and it expresses its behavior as a partially elastic body Fig. S1 of the Supplementary Material. The weight of the bob was calculated according to the average weight of nectarines (152.25 g). It is important to note that the weight of the bob was negligible compared to the average weight of the fruit (3.72 g). The bob of the pendulum was let go at a height of 36 cm, mimicking the impact and bruising injury of a fruit falling. This collision is considered to be elastic which both kinetic energy and momentum are conserved. To calculate the impulse energy transferred from the pendulum to the sample, the changes in kinetic and potential energy before and after the collision need to be considered

$$E_{\text{impulse}} = E_{\text{final}} - E_{\text{initial}}. \tag{2}$$

Single measurements of impedance and temperature are taken before the impact, immediately following the impact (0 h), 1 h, and finally after 24 h had passed to study the time-dependent electrical property changes due to damage. Also, a one-way ANOVA was performed to evaluate statistical differences between damaged and undamaged fruits, utilizing Fisher's least significant difference method. The differences were calculated for an appropriate level of interaction ($p \leq 0.05$) [26]. Results were reported as the mean and standard deviation (SD) of the mean. Furthermore, this configuration allows the investigation of probable temperature effects on damage identification through the analysis of series capacitance values. This investigation improves our understanding of how the system responds to various circumstances and provides direction for further studies.

III. Results and Discussion

A. Setup 1

Fig. 2(a) shows the variation of normalized C_s and C_p (see Fig. S2 of the Supplementary Material) with their equivalent circuit for a banana tested over seven days at frequencies from 5–200 kHz, in 15-point increments. For the specified samples and frequency range, the plot provides insights into the behavior of both C_s and C_p. As shown in Fig. 2(a) the capacitance decreases over time due to sample aging, as also observed in [27]. In addition, it is clear how the peak heights in the figure, reflect temperature fluctuations. Such behavior can be observed in more detail in Fig. 2(b), where the temperature fluctuation closely follows the daily C_s one. Higher peaks indicate greater temperature variations, particularly in the initial days. As

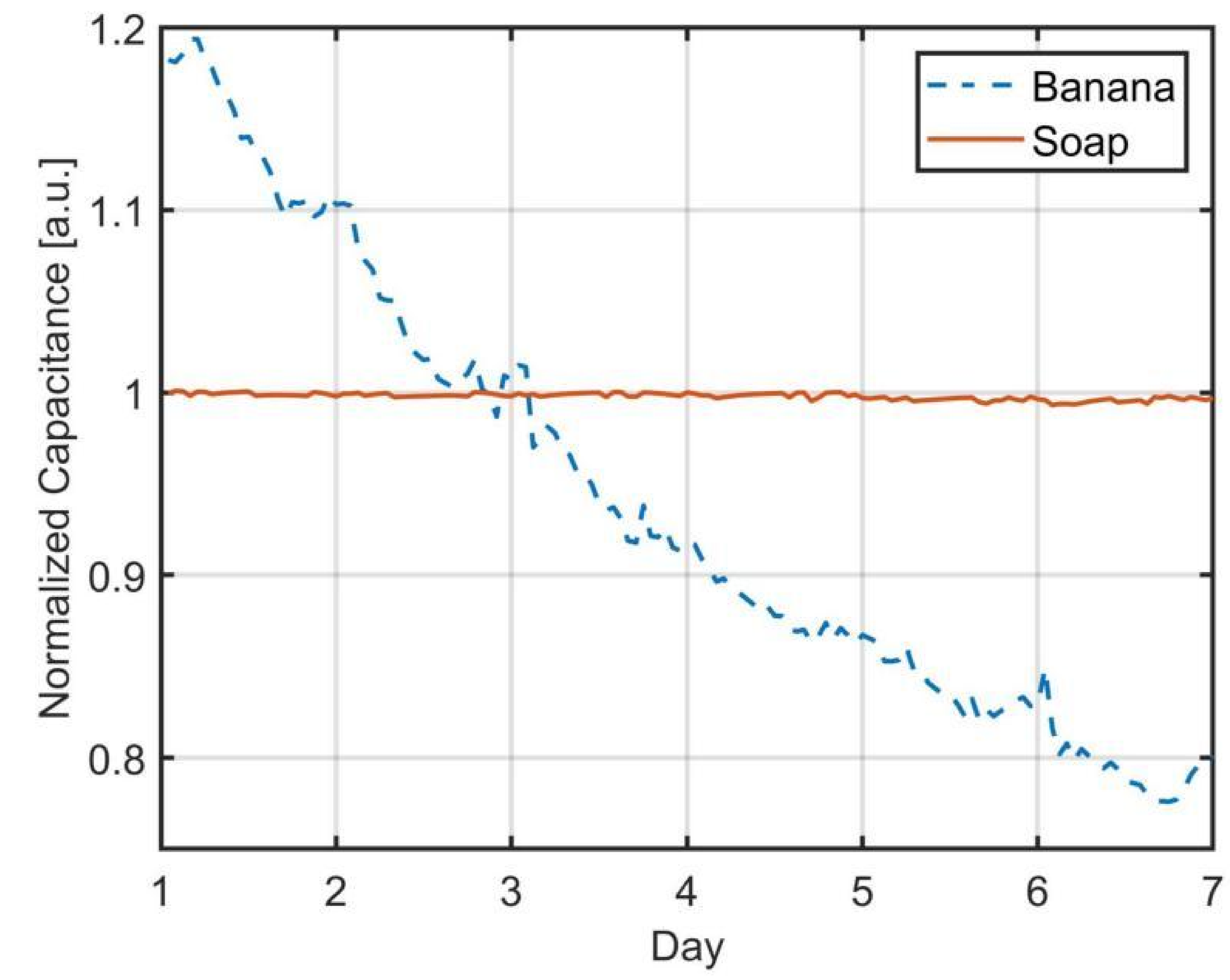

Fig. 3. Comparison between the normalized and fitted data of banana and soap for six days.

temperature stabilizes, peak heights decrease. The decline in peak heights during the banana's last stage is likely due to a reduced permittivity of the sample under test [27]. Based on the observed similarity in the behavior of C_s and C_p across the six frequencies studied over multiple days, we concluded that a single frequency can provide equivalent outcomes. For this reason, the analysis presented in this study refers to the frequency $f = 45$ kHz for C_s. The data analysis of both the fruit and soap samples is conducted using the same methodology.

Fig. 2(b) shows the relationship between temperature and raw C_s data over the initial 24 h, excluding the first six data points. This representative section indicates temperature impacts the dielectric constant of the materials (i.e., air and sample under test), which in turn affects capacitance. Such behavior can be explained by the fact that the mobility of polar molecules is increased at higher temperatures, which raises the dielectric constant of the measuring materials [28]. Compensation for the data based on temperature is needed to mitigate the effect of temperature on the samples. A linear regression model was fitted to the first 18 data points (excluding the first six data points), yielding an r-squared value of 97.76 % and 96.57 % in banana and soap, respectively.

As shown in Fig. 2(c), the impact of temperature on the normalized data can be successfully compensated. The series capacitance decreases over time, indicating the aging of the sample. The decrease in series capacitance over time in the fruit can be attributed to factors, such as water content. During the ripening process of fruits, the water content gradually decreases, leading to an increase in impedance [29]. This decrease in water content is one of the factors contributing to the decrease in capacitance. However, it is important to note that the value of capacitance is not solely determined by water content but is primarily influenced by the degradation of the cell membrane. From an electrical perspective, the decrease in capacitance over time can be attributed to the degradation of the capacitive behavior of the cell membrane of the biological sample. This degradation allows for easier passage of current through the intra and extracellular space of fruit [30].

Fig. 3 compares the normalized and fitted data for banana and soap over six days. The behavior of the two samples diverges significantly. While the soap demonstrates consistent stability