over time, the banana, being a living tissue sensitive to aging, displays a decrease in capacitance. The C_s value of the banana showed a relative change of 6.76 % (first day), 9.5 % (second day), 8.93 % (third day), 5.45 % (fourth day), 4.49 % (fifth day), and 3.38 % (sixth day). Initially, at the start of the measurement, the banana was in the green stage. The relative change in C_s gradually increased, with the most significant change observed on the second and third days as the banana entered the ripening stage. As subsequent days passed, the rate of change decreased, indicating the onset of aging. These findings align with the research conducted by [8], although their study utilized a contact method instead. These various trends are accurately captured by the fitted data, which provides reliable representations of the respective samples.

The simultaneous measurements of baseline and sample capacitance of three bananas over four days are presented in Fig. S3 of the Supplementary Material, revealing the electrical characteristics of bananas during the ripening process. Initially, all three samples show a gradual increase in the C_s values and then reach a peak on the third day. This increase is correlated with the bananas transitioning from the green stage to ripe condition, during intracellular biochemical transformations that affect the dielectric properties of the fruit thus increasing the measured capacitance. Following this peak, there is a significant drop on the fourth day, likely indicative of aging and temperature reduction. Simultaneously, the baseline capacitance measurements for the corresponding days follow a similar trend, while consistently having lower values in comparison to the banana measurements. A similar trend suggests environmental factors, such as temperature and humidity, have an impact on the air's permittivity between the plates, which affects the capacitive measurement [18]. However, the measurements of bananas taken on the second and third days with the pronounced peaks and sharper slope changes on this day reveal the dominant effect of the biological charges on its capacitive properties. On day four, the slope of both banana and baseline measurements become more comparable, suggesting a stabilization in the rate of biological change within the banana and potential equilibrium between environmental influences on the capacitance values. Fig. S4 of the Supplementary Material demonstrates the direct influence of the bananas' changing mass on their electrical properties. Such mass loss is likely due to moisture loss, increase in total soluble solids [31], and metabolic changes during ripening [32]. Here, an initial rise in capacitance when the bananas lose mass, mostly from water loss, can be observed. Also in the ripening stage, during intracellular biochemical transformations conversion of starches to sugar [33] will increase the number of ions. This phenomenon enhances the polarization of the ions in the presence of the applied electric field, which allows to store more electrical charge and as a result, the capacitance increases. On the other hand, by the fourth day, ethylene production rises during ripening [34], which leads to loss of structural integrity [35] and as a result, the bananas' dielectric constant, and thus capacitance, decreased. This comprehensive representation highlights the complex relationship between the physical and electrical characteristics of bananas during their ripening cycle.

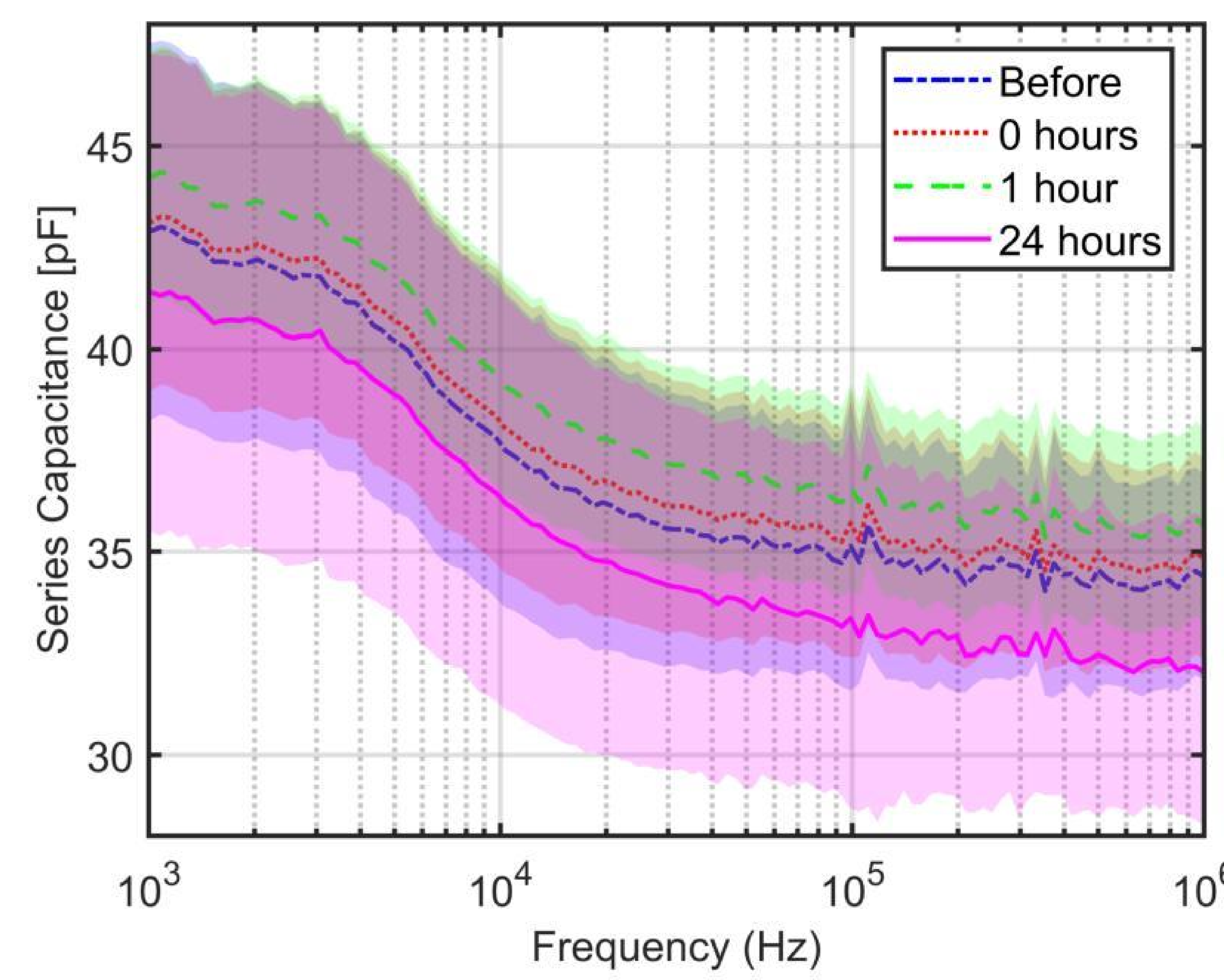

Fig. 4. Variation of raw C_s with SD for 51 nectarine fruit at selected frequencies (1 kHz–1 MHz) under four different conditions: before the mechanical damage (blue), 0 h (red), 1 h (green), and 24 h (magenta) after the mechanical damage.

B. Setup 2

Fig. 4 represents the variation of C_s in the frequency range of 1 kHz–1 MHz for 51 nectarines under four different conditions: before the impact effect, 0, 1, and 24 h after the damage. The frequency range of 10 Hz–1 kHz has been excluded for plotting purposes due to significant noise, which affects the analysis's accuracy. According to Fig. 4, while each condition displayed different C_s values, the changing trend of damaged fruit was consistent with undamaged fruit. Immediately after the damage, at the so-called 0 h, the C_s increases for the whole frequency range. This effect becomes more pronounced after 1 h. The observed changes in C_s can be interpreted from the viewpoint of impedance spectroscopy. The increase in C_s can be attributed to several factors related to the mechanical damage sustained by cell membranes. Such damage likely ruptures cell walls, leading to leakage of cellular contents such as water, ions, and enzymes [36]. Ions are the primary current carriers in an electrolyte, contributing to the overall impedance of the tissues. In the tissues shocks or stress causes cytoplasmic electrolytes to leak into the apoplast, decreasing the structure's electrical resistance to subsequent physical injury and ultimately resulting in cell destruction [37]. This result aligns with [38], [39], [40].

Furthermore, the lipid bilayer of the plasma membrane, acting as a capacitor and conductor, can be altered by mechanical stress, affecting the membrane's dielectric constant [41]. However, this variation, along with changes in internal chemical properties and physical structure, influences the tissue's electrical behavior postdamage [42].

This dynamic influences the impedance by modifying both its resistive and capacitive components, making it essential to understand the electrical behavior of plant tissues after mechanical damage. Consequently, more detailed studies are required to characterize the actual cause of this increase in capacitance. Moreover, after 24 h, the evident reduction in series capacitance suggests a more stable cellular state with tissue that resembles amalgamated tissue, higher conductivity, and the absence of the electrical isolation that is characteristic of healthy cell membranes [43].