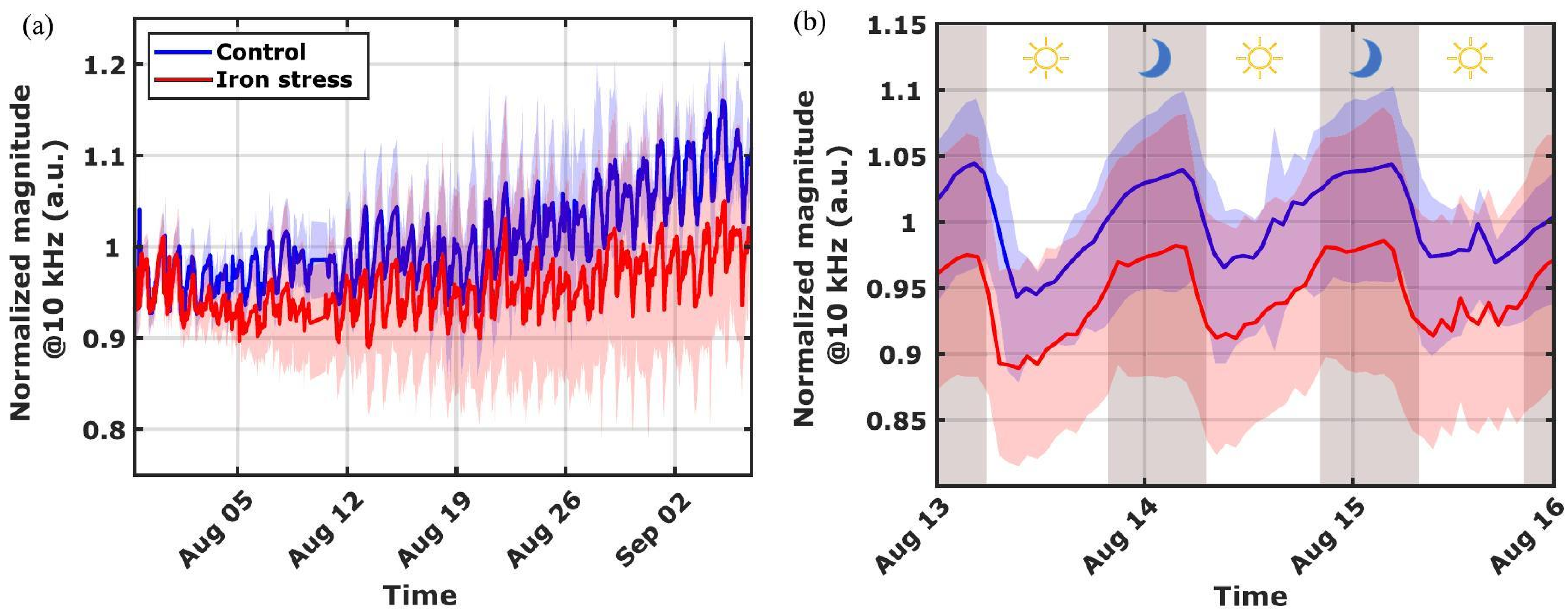

Fig. 2. Time-series plot of normalized impedance at 10 kHz over a 1-month period. The shaded colored zones represent the range of magnitude changes over time for both groups (blue shadow for control plants and red shadow for iron-stressed plants). (a) The median magnitude values of the control plants represented by a blue line while the iron-stressed plants depicted by a red line. (b) Zoomed-in time-series plot showing stem impedance seasonal patterns between night conditions (indicated by the moon symbol and dark shading) and light conditions (represented by the sun symbol and absence of shading).

iron-deficient nutrient solution, were exposed to the same environmental conditions, monitored by sensors inside the greenhouse. The first symptoms of iron deficiency observed in this work, characterized by a reduction in photosynthetic activity and a tendency of the leaves to present a yellow coloration [5], started toward the end of the experiment (i.e., on the 31st August) and were noted following a visual observation. Such timing and observation method is clearly not ideal, as it would not allow a prompt intervention to mitigate the stress-induced effects on the plant health and thus yield. For this reason, to experimentally prove such behavior, as well as to anticipate such diagnosis exploiting the potential use of the bioimpedance technique for early stress detection, the data were subjected to a comprehensive data analysis, comprising three subsequent steps. Here, the measurement has been analyzed to investigate the evolution overtime of first the raw impedance magnitude and second the extracted equivalent circuit parameters. Finally, based on the assumption of statistical difference among circuit parameters between the two main conditions (i.e., control and stress), different classification algorithms were used to identify the state of the plant, whether in control state, early or late stress, validating the potential employment of such technique within a decision support system.

A. Time-Series Analysis

A first step in the exploration of the acquired dataset consisted in the evaluation of the raw impedance data, investigating approaches found in literature to monitor the plant behavior. The evolution over time of the normalized bioimpedance magnitude response at 10 kHz is depicted in Fig. 2(a). Such a point was chosen based on the study of Garlando et al. [20], which successfully employed this approach to monitor the response to water stress of tobacco plants over a one-month time span. Analyzing the normalized impedance magnitudes over time sheds light on how iron stress affects the bioimpedance properties of tomato plant stems. The data reveals a noticeable difference in impedance trends shortly after iron is removed from the nutrient solution, distinguishing the iron-deficient plants from the control group. The control plants show a shift in impedance magnitude (about 0.1 a.u. from the experiment's start), likely due to ionic changes during different growth stages of the tomato plants [29]. In contrast, the impedance response in iron-deprived plants can be attributed to an adaptation to iron shortage, involving complex molecular signaling. This includes variations in proteome profiles [30], metabolic changes [31], transcriptomic adjustments [32], and alterations in ionic composition and structure [33]. While a clear correlation with such changes appears to be challenging, such results highlight the potential of utilizing impedance measurements for monitoring iron stress in plants. Nevertheless, a deeper observation of the trends observed in the acquired data offers food for thought for further applications. In Fig. 2(b), a magnified view of a three-day period is shown to clarify the discernible seasonal variations in magnitude between the diurnal condition, represented by the sun symbol, and the nocturnal condition, represented by the moon symbol. This seasonality is consistently observed throughout the whole experiment in both iron-stressed and control plants and can be connected to the extensively documented circadian rhythms in plants [20], [34], [35]. Such phenomenon can be explained by plant transpiration, which involves the release of water vapor through stomatal openings, subsequently driving the uptake of water and nutrients from the roots to the shoots. The rate of transpiration varies between day and night in tomato plants due to the closure or partial closure of stomata during dark conditions, wherein photosynthesis is absent. Here, the flow of water and nutrients is opposite, going from the shoots to the roots [36]. Such results effectively prove that bioimpedance could be exploited as a potential alternative and low-cost tool to monitor the plant sap flow trends, an important plant health status indicator, which is commonly monitored using bulky and expensive equipment. In order to summarize the information collected through the bioimpedance measurements, the equivalent circuit components were calculated by fitting the measured spectra on