Preliminary Analysis of Trunk Electrical Bio-Impedance in Professional Apple Orchards

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***Abstract*—Accurate, low-power and reliable plant monitoring systems in smart agriculture are crucial to better resource management, such as water usage. Direct plant monitoring, particularly trunk electrical bio-impedance monitoring, is a promising solution to precisely monitor plants' health conditions without relying only on environmental measurements. This paper showcases data acquisition and a preliminary observation campaign on apple trees from a professional orchard using a previously developed trunk bio-impedance sensor. The system operated in the field for one year, continuously sampling data every 10 minutes. The implanted electrodes exhibited good biocompatibility after an initial wound recovery period from the plants. The preliminary results revealed trunk bio-impedance trends generally consistent with existing literature regarding vegetative states and astronomical seasonal variations in apple trees; moreover, the strength of daily components ranged from high values of seasonality intensity index (4.94, 6.37) during spring (vegetative growth) to low values during summer (0.29, 0.41), likely due to high temperatures and limited water availability.**

***Index Terms*—Bio-impedance Monitoring, Plant Health Monitoring, In-vivo Monitoring, Climate-Smart Agriculture, Internet of Things**

I. Introduction

Feeding the global population has consistently been a significant challenge, and this issue has intensified in recent decades due to climate change and the rapid increase in population. Current projections estimate that the global population will reach 10 billion by the end of this century [1]. Simultaneously, anthropogenic climate change is significantly diminishing the availability of arable land worldwide. Agriculture plays a dual role in this context: it is vital for food production but also contributes heavily to environmental degradation. It accounts for 26% of global greenhouse gas (GHG) emissions and for 70% of total freshwater withdrawals [2].

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Climate-smart, or precision, agriculture aims to address these concerns by enhancing crop yield while minimizing environmental impact. Nowadays, this is typically achieved by monitoring the environment around crops [3], [4]. While this approach can provide valuable data, studies have indicated that plant health can decline even without observable environmental changes [5]. This is because it is tough to assess plant health without examining the internal physiological status of the plant throughout its natural lifecycle. As a result, research has increasingly focused on sensors placed directly on plants to gather more relevant and precise information [6]–[9].

An interesting area of interest is measuring electrical impedance in plant stems or trunks [10]. This method is promising for assessing water stress in plants, as it is closely related to Soil Water Potential (SWP) [11] and biotic stresses [12]. However, current in-vivo stem/trunk impedance analysis techniques rely on complex, power-hungry, and expensive procedures usually involving laboratory-grade equipment. A promising alternative involves using a portion of the plant stem or trunk in the feedback loop of a relaxation oscillator [13]. The output of the relaxation oscillator is a square wave signal having a variable frequency. A strong inverse correlation has been demonstrated between stem electrical impedance and the frequency produced using this method [14], making continuous monitoring of stem electrical conductance and, consequently, evaluating the plant health status more accessible.

Nonetheless, this method has mainly been tested on plants in laboratory conditions [11] or during short-term experiments in research centers, such as with young apple crops [13], which do not provide a comprehensive view of real-world agricultural scenarios. These real conditions involve mature crops, field treatments (e.g., pesticide applications or soil tillage), pruning, and harvesting, where plants experience various types of stress (e.g., chemical, physical, environmental).

In particular, apple orchards follow a periodic cycle composed of vegetative growth, flowering, fruit development and maturation, harvest, and dormancy [15], during which trunk electrical conductance varies not only daily but also seasonally depending on the phenological stages of the crop.

This study aims to fill this knowledge gap by presenting a preliminary analysis of trunk frequency data, an indirect measure of trunk electrical bio-impedance, from two adult plants in a professional apple orchard in Italy, as introduced in a previous contribution [16]. In addition, soil data are collected through the setup described in [16], enabling the extraction of potential correlations with parameters such as soil matric potential. The proposed solution has been deployed in the field for over a year, demonstrating its suitability for harsh agricultural environments and long-term continuous monitoring operations.

II. Setup

The electronic system presented in [13] was installed within a professional apple orchard at two locations. Briefly, the electronic system (hereinafter referred to as WAPPIMP) can indirectly monitor the bio-impedance of a plant trunk section, providing as output the so-called *trunk frequency*. This is the frequency of the square wave signal generated by a relaxation oscillator in which the plant's trunk section is inserted in the feedback loop of the circuit [13] through two nails as electrodes.

The two stainless steel nails into the trunk are placed approximately 15 cm apart. Each nail was inserted 2.0 cm into the trunk to reach the internal vascular tissue while minimizing potential damage from electrode placement. Stainless steel was chosen as the electrode material due to its resistance to oxidation and its biocompatibility.

In addition, WAPPIMP can sense air temperature and relative humidity, as it is equipped with an HDC2080 [17] sensor, an integrated circuit by Texas Instruments, which measures these two environmental parameters. Data are transmitted via the LoRa protocol, enabling continuous monitoring of the trunk frequency in the plant, directly in the field. The measurement interval of WAPPIMP is set to 10 min.

One WAPPIMP unit was installed in F2_CV2 and the other in F2_EX2.

Additional data are provided by the WAPPSEN electronic system [18]. One such system is installed at the same location as each WAPPIMP unit (one in F2_CV2 and one in F2_EX2), providing soil matric potential data at depths suitable for adult apple root layer (−20 cm and −40 cm). The WAPPSEN system also records data at 10 min intervals.

III. Methodology

This study aims to evaluate the effectiveness of the previously described setup for continuous, year-long measurements on two apple trees in a professional orchard and to study its relationship with environmental parameters, including air temperature, humidity, and soil matric potential. Electrical bio-impedance measurements of a plant's trunk can be associated with soil matric potential, allowing for an estimation of the overall health status of the plants, as documented in previous studies [13], [14].

This approach uses a relaxation oscillator in feedback with the plant itself: the generated square-wave frequency is inversely correlated to the modulus of the trunk's impedance, as demonstrated in [14].

It is documented in the literature that plants respond differently to environmental conditions and seasonal changes [19], [20]. For example, deciduous species such as apple trees undergo dormancy during the cold season. In this study, the overall behavior of the trunk frequency is evaluated in terms of long-term variations (weeks or months) and short-term variations (daily). Trunk frequency and environmental data were collected from April 16th, 2024, to May 15th, 2025; samples from April 16th, 2024, to June 1st, 2024, were discarded from the analysis due to wound healing of the plant. This aspect will be discussed more in depth in section Section IV-A.

Trunk frequency data was decomposed into seasonal component and long-term trend using Seasonal-Trend decomposition based on LOESS (STL) [21], and a preliminary observation campaign was carried out. Hereinafter, the term seasonal will indicate periodic behavior (primarily daily). We will explicitly use the term astronomical seasonality when referring to behavior associated with astronomical seasons.

Given the variability across astronomical seasons in environmental conditions as well as plant physiology, the analysis was split into the following loose astronomical season periods:

- **Winter**: December 1st 2024 to February 28th 2025;
- **Spring**: March 1st 2025 to May 31st 2025;
- **Summer**: June 1st 2024 to August 31st 2024;
- **Autumn**: September 1st 2024 to November 30th 2024.

STL can capture varying trends and seasonal components; however, a key assumption of the algorithm is the consistent presence of seasonality in the data, an assumption that may not always hold.

For this reason, a strategy similar to that proposed by the authors in [22] was adopted to assess the presence of a significant seasonal component. For each astronomical season, the seasonality strength was assessed by evaluating the magnitude of the daily component on a periodogram, compared to the others: a seasonality index was calculated as the ratio between the amplitude of the dominant seasonal component (daily) and the sum of all the others. A higher seasonality index indicates a greater daily variation in trunk frequency measurements.

IV. Results and Discussion

A. Healing Time

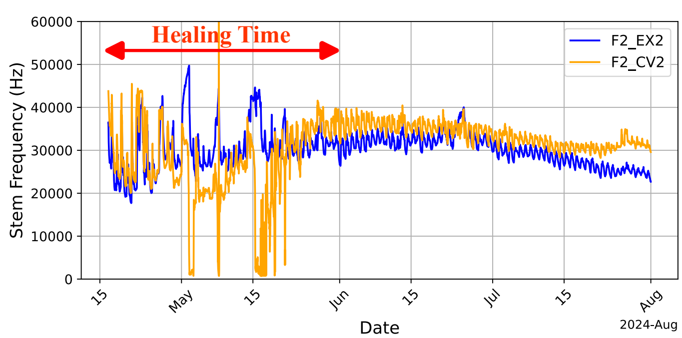

Fig. 1. Trunk frequency raw values recorded from April 16th 2024, the installation day. During the healing period, a significant amount of signal noise from the WAPPIMP sensors can be observed.

Inserting two needles into a mature apple plant causes physical damage to its tissue. As stated earlier, each needle was inserted for around 2 cm, with the electrodes placed 15 cm apart. Thinner needles increase the likelihood of breakage when in contact with the plant's woody structure. Unlike soft-stemmed species, where finer needles can be employed, a thicker needle was chosen for this application, as described in [13].

The two WAPPIMP trunk frequency sensors were installed on April 16th 2024.

Fig. 1 shows the data collected during the initial months from the two monitored plants, one at the experimental site and the other at the conventional site. A significant amount of signal noise is evident for approximately the first one to one and a half months. This is likely due to the time needed for the mature apple trees to establish a stable interface with the stainless steel electrodes. Consequently, the analysis begins on June 1st 2024.

The insertion was done without wound sealants. Wound sealants, such as grafting mastic or pruning paste, are applied to plant injuries to promote healing, prevent infections, and protect the exposed tissue from pests and environmental stress. Their usage in the insertion operation could reduce the required recovery time.

B. Observation Campaign

The results of the data collection, along with the seasonal-trend decomposition segmented by loose astronomical seasons, are presented in Fig. 2, in relation to the environmental conditions surrounding plants, specifically air temperature, relative humidity, soil water potential [23], and day–night cycles.

Moreover, Table I reports the calculated seasonality index for each astronomical season. As expected, the behavior of the plants under analysis differs from one astronomical season to another.

TABLE I
SEASONALITY INDEX BY SEASON AND PLANT

Pseudo Astronomical Season	**Plant 1**	**Plant 2**
Summer	0.29	0.41
Spring	4.94	6.37
Autumn	2.70	2.04
Winter	2.16	2.14

1) Winter: The bottom subplot pair in Fig. 2 presents the measurements collected during the winter period. Air temperature generally decreased steadily until the second week of January, with average values remaining below 5 °C. Relative humidity generally ranged between 70% and 90%, partly influenced by rainfall events. These rain events positively affected soil hydration, as indicated by soil water potential values consistently close to 0 kPa (values of soil water potential close to 0 indicate wet soil, while drier conditions result in more negative values). In summary, the climate during this period was characterized by cold and humid conditions. The plot in the left-most winter section also shows the trend extracted through the decomposition procedure: trunk frequency, reflecting the conductivity of the plant's trunk section, steadily decreased until the second week of January, following a pattern similar to that of air temperature. The moderate-high overall winter seasonality index for both plants reported in Table I indicates that overall during this season, daily behavior is present; however, the magnitude of it varies, as can be observed in Fig. 2. The intensity of the seasonal component during winter exhibits higher values till the third week of January, followed by an overall reduction.

The dormancy of apple trees during winter is a well-known mechanism; during this period, apple trees gradually enter a dormant phase in which photosynthetic activity and nutrient flow are significantly reduced. This behavior is consistent with the trends observed in both apple trees analyzed: a generally decreasing trend is evident up to the third week of January, followed by a reversal in the trend thereafter.

In the seasonal component plot (right-most plot in the winter section), a higher daily activity is noticeable in both plants during the initial part of the period (as indicated by the amplitude of the seasonal component), which then transitions into a phase of reduced activity.

2) Spring: Spring measurements are shown in the top subplot pair in Fig. 2. Overall, air temperature increased steadily throughout spring, leading into summer. During this time, temperatures remained above 6–7 °C. Specifically, early spring was characterized by temperatures ranging between 6 and 8 °C; in late spring, temperatures rose to settle on average between 16 and 18 °C. Air humidity measurements were constantly above 60%, with periods near 90% due to rainfall events. During spring, apples accumulate chill hours (hours with the temperature above 7 °C), and when a certain quantity is reached, the dormancy period ends. During this period, it is expected an increase of photosynthetic activity, nutrients and water flow through the trunk.

During the analyzed spring period, the trunk frequency sensor recorded a constant and stable upward trend, indicating a gradual increase in trunk conductivity, suggesting a higher presence of nutrients, consistent with the hypothesis of dormancy break and the onset of vegetative growth. Furthermore, the seasonal component plot for the spring period shows generally higher activity compared to the preceding winter dormancy phase, confirmed also by high values of seasonality index in Table I for both plants (4.94 and 6.37).

3) Summer: Summer showed higher temperatures, relative humidity around 70–80%, and strongly negative soil water potential values, indicating limited water availability in the field. The trend of trunk frequency decreases and no longer follows the temperature trend as it did in previous seasons. Interestingly, the seasonal plot revealed a reduced daily component compared to other astronomical seasons, further confirmed by the magnitude of the seasonality index in Table I (0,24 and 0.41), indicating, likely due to prolonged hot weather conditions combined with limited water availability.

4) Autumn: During autumn, temperature measurements show a gradual decrease, and relative humidity exhibits an increase associated with rainfall events. These precipitation events also contribute to an overall increase in soil water

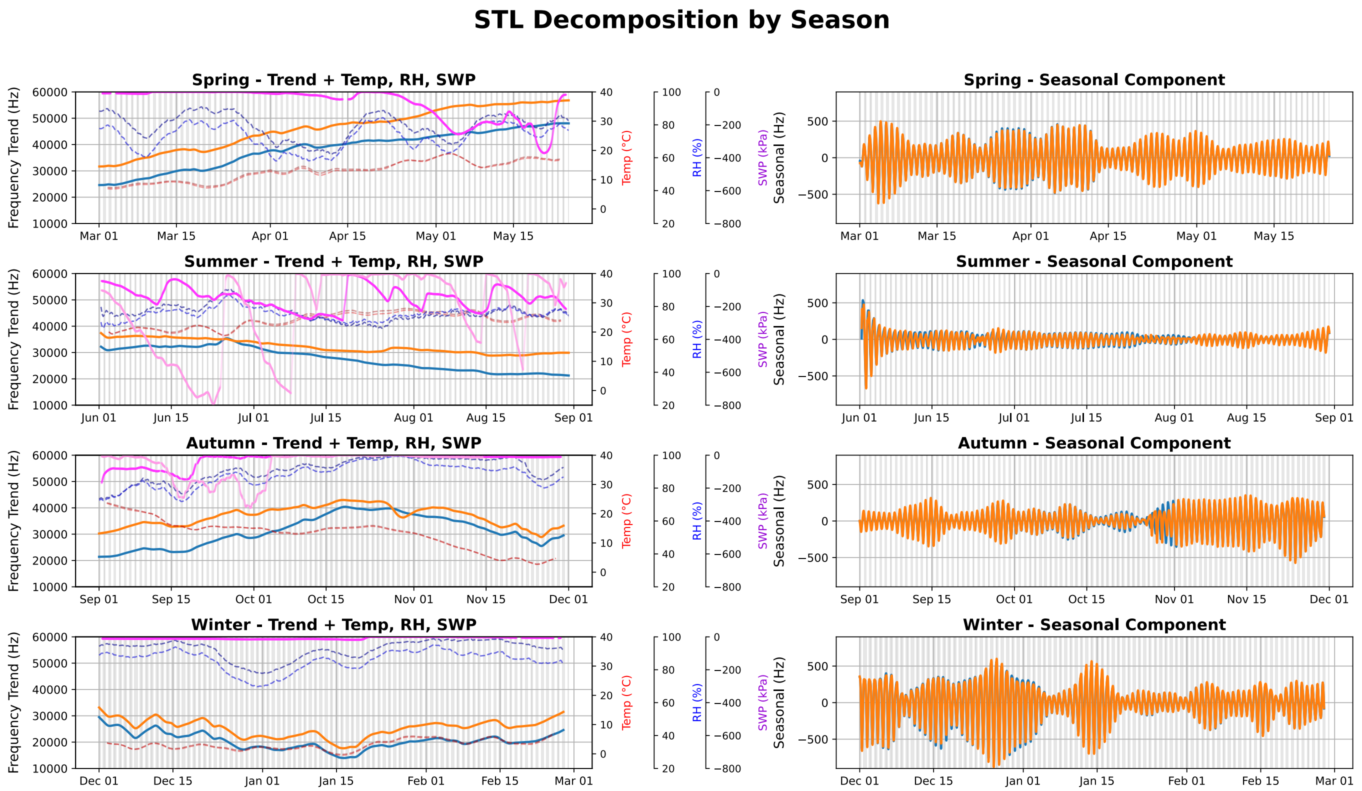

Fig. 2. Seasonal STL decomposition of trunk frequency measurements over one year. The four plots on the left display the extracted trend components from the STL decomposition of trunk frequency data (orange and blue solid curves) and corresponding environmental variables—temperature (dashed red), relative humidity (dashed blue), and soil water potential (solid purple)—for both installed devices, segmented by season. The plots on the right show the seasonal components of trunk frequency for each device, segmented by season.

potential, indicating improved water availability in the field. In response to these changing climatic conditions, a general upward trend in trunk frequency is observed, suggesting increased conductivity up to the first days of November. This behavior can be attributed to reduced water stress following the dry summer period, resulting in greater nutrient flow within plant tissues. As environmental stress decreases, the plant likely restores its internal water balance, improving physiological function and increasing trunk conductivity. Looking at the seasonal component graph, we noticed a general activity increase compared to the summer period and, within autumn itself, a generally higher activity starting from November till the beginning of winter.

V. Conclusions

This study monitored two apple trees from a professional orchard using a low-cost, low-power bio-impedance sensor with a long battery life [13], [16]. After an initial healing phase following electrode insertion, the trees tolerated the sensor installation well, demonstrating the non-invasive nature of the measurement approach.

A preliminary observation campaign was conducted over an uninterrupted monitoring period of approximately one year, representing one of the few in-vivo, long-term, continuous monitoring campaigns on fruit trees.

The preliminary results revealed trunk bio-impedance trends generally consistent with existing literature regarding vegetative states and astronomical seasonal variations in apple trees; moreover, the strength of daily components ranged from high values of seasonality intensity index (4.94, 6.37) during spring (vegetative growth) to low values during summer (0.29, 0.41), likely due to high temperatures and limited water availability. This work highlights how this bio-impedance sensor is sensitive to the detection of physiological mechanisms in fruit trees, making it a promising candidate for continuous plant monitoring based on direct observation of plant status, beyond solely relying on environmental conditions; however, much work has to be carried out to understand which physiological phenomena influence plants' bio-impedance measurements accurately.

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