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A Long-Range Low-Power Modular Platform for Plant Health Monitoring in Climate-Smart Agriculture Scenarios

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***Abstract*—This paper presents a modular, low-power IoT platform for in-vivo plant monitoring, designed to operate autonomously for years using a single AA lithium battery. The system features a custom dual-board architecture: the Core board, responsible for processing and communication, and the Sensing board, which integrates detection of plant stem electrical signals, soil matric potential, and environmental parameters. The stem sensing subsystem is based on a dual-frequency analog front-end that also employs a digitally programmable relaxation oscillator. This design allows the system to adapt to different plant species and hydration conditions while maintaining low complexity and minimal power consumption. Experimental evaluation demonstrates that a complete sensing and communication cycle is completed in less than 5 seconds, with an estimated lifetime between 5.04 and 10.72 years assuming one data sample every 15 minutes. Preliminary tests conducted in a climatic chamber show the platform's ability to detect plant bio-activity in response to changes in air temperature and light intensity, while also ensuring stable signal acquisition.**

***Index Terms*—Plant Health Monitoring, Precision Agriculture, Modular Architecture, Low-Power Design, Internet of Things**

I. INTRODUCTION

In recent years, agriculture has become a key sector in addressing climate change [1]. Highly vulnerable to extreme weather events, it is embracing AgriTech innovations to boost productivity and resilience through smart systems tackling drought, soil degradation, and climate instability. One of the pillars of AgriTech is precision agriculture [2], which entails site-specific crop management based on data-driven monitoring and control. This paradigm requires the development of sensing systems capable of capturing high-resolution information about the state of plants, soil, and ambient conditions with minimal human intervention. Among the many physiological indicators of plant health, stem electrical bio-impedance has emerged as a promising non-destructive metric to detect the early onset of both abiotic and biotic stress conditions, such as drought [3], [4], salinity, or pathogen-induced vascular disruption [5]. This technique suffers from several issues: it is electronically complex, power-hungry, and processing-intensive, as the impedance spectra must be sampled, processed, and transmitted. A more recent approach has simplified the detection of changes in stem electrical bio-impedance by incorporating the sensed plant stem segment into the feedback loop of a relaxation oscillator. The output is a square wave signal with a frequency that varies in response to the impedance. It has been demonstrated that this frequency is strongly inversely correlated with the stem electrical bio-impedance [6]. In this way, the information is shifted in the frequency of the square wave, which can be sampled by a digital timer, significantly reducing electronic complexity, energy consumption, and processing requirements. This technique has been successfully employed in several small-scale experiments [6]–[8]. However, it has shown limitations in robustness, particularly when dealing with single prototypes and under harsh environmental conditions such as those found in open fields, where temperature variations, rainfall, wind, sunlight, and pests are present. We faced connection issues due to unreliable multi-row headers, causing signal loss from vibrations—unsuitable for long-term field use. These connectors are also costly and increase board expenses. Additionally, sensor size is limited by the development board's dimensions. To overcome these barriers, we propose a novel small, long-range, low-power Internet of Things (IoT) [9] modular platform tailored for transmitting various electrical signals, soil moisture data, and environmental parameters over long distances. Moreover, it provides an integrated approach to plant health monitoring by addressing all three domains in which the plant exists (soil, environment, and the plant itself) enabling early detection of both abiotic and biotic stress conditions. The aim of this work is not to provide an extensive agronomic validation, but rather to demonstrate the integration and low-power operation of the proposed modular platform, paving the way for future experiments across multiple plant species and environmental conditions.

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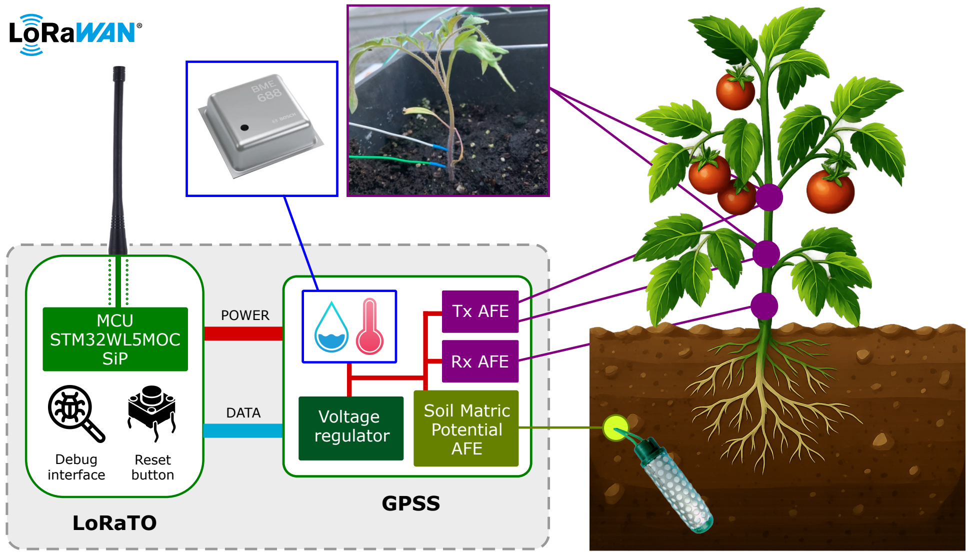

Fig. 1. A schematic illustration of the long-range, low-power modular platform within a typical climate-smart agriculture scenario.

II. System Architecture

The proposed system is designed as a compact (90 mm×44 mm×24 mm) and autonomous IoT sensing node capable of real-time, in-vivo monitoring of plant physiological status under field conditions. The modular platform, as shown in Fig. 1, consists of two tightly integrated Printed Circuit Boards (PCBs):

- *LoRaTO* board (or *Core* board), which handles data processing, and wireless transmission;
- *Global Plant Status Shield (GPSS)* (or *Sensing* board), which hosts power regulation and the analog and digital interfaces for the acquisition of plant, soil, and environmental signals.

An extensive description of the two boards is presented in Section II-A and Section II-B.

A. Core Board – LoRaTO board

The *LoRaTO* board constitutes the processing and communication core of the system. At its heart lies, as shown in Fig. 1, the STM32WL5MOC microcontroller, a System-in-Package (SiP) (STMicroelectronics, Switzerland) that integrates a dual-core, one 32-bit ARM Cortex-M4 and one M0+ core with a sub-GHz RF transceiver supporting LoRa modulation [10]. Designed as a generic and modular platform, the *LoRaTO* board is intentionally decoupled from specific sensor configurations. The flexibility is achieved through a standardized interface and the exposure of key microcontroller peripherals via castellated pads, including GPIOs, ADCs, timers, and I²C lines. Power is supplied externally. This is done to make the board agnostic from different power sources. A more traditional way is to use a primary battery to supply the board but more innovative ways can include battery-less systems [11] that harvests energy from the sun [12] or plant microbial fuel cells [13]. Actual firmware supports the LoRaWAN Class-A protocol [14], enabling asynchronous uplink communication with minimal airtime and energy consumption. A gateway in the area ensure data connectivity over internet. The board includes a debug connector and a reset button for MCU programming and reset.

B. Sensing Board – Global Plant Status Shield

GPSS, as shown in Fig. 1, is a board developed to demonstrate and validate the capabilities of the *LoRaTO* board in a real-world agronomic scenario. The *Sensing* board integrates a battery shell for AA-size batteries, a voltage regulation (Fig. 1) with a programmable buck converter to step down the input voltage and generate a regulated 2 V rail for the microcontroller and its internal subsystems. *GPSS* is engineered to enable the simultaneous acquisition of biophysical and environmental parameters across three key sensing domains: plant stem frequencies, soil matric potential [15], and ambient environmental conditions. All analog and digital conditioning circuits reside locally on the shield, which interfaces mechanically and electrically via pads with the castellated pads of the *Core* board, ensuring compact integration and signal integrity. The *GPSS* organizes its sensing capabilities into three functional blocks:

1) Stem Frequencies: This measurement strategy has been originally detailed in [8]. The architecture implements a three point measurement scheme, consisting of a two-electrodes signal transmitter and a downstream receiver (one electrode), placed at different heights along the plant axis. In *GPSS*, a square-wave signal is generated by Tx AFE (Analog Front End), as shown in Fig. 1, having a stem portion in feedback loop with a relaxation oscillator, and the attenuated waveform is also collected by a receiver circuit, the Rx AFE (Fig. 1), incorporating a high-pass filter, peak detector, buffer, and voltage-controlled oscillator. Regarding Tx AFE, as relaxation oscillators implemented in [6], [8], a capacitor (C) and two resistors are added: one in series (R_s) with the stem track

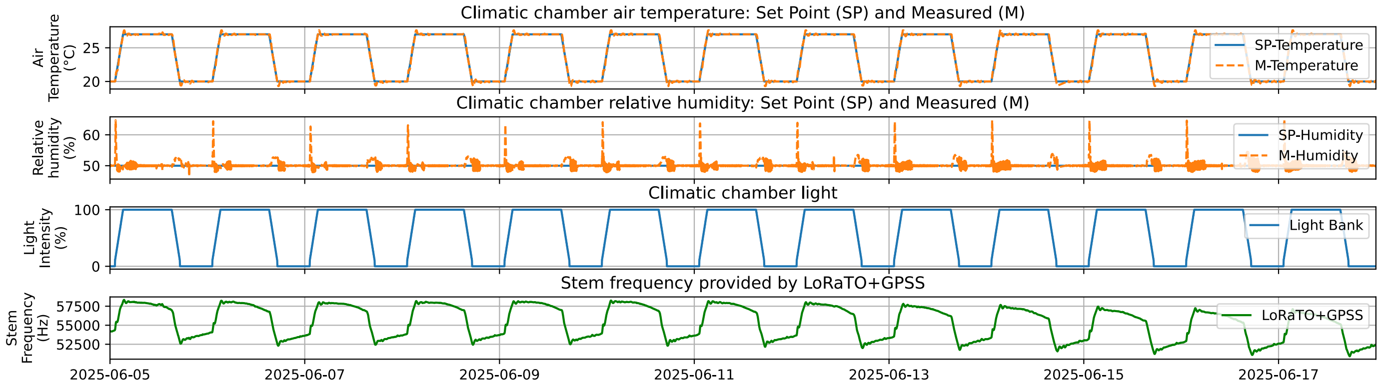

Fig. 2. Functional test plots. The first three plots above show the environmental conditions (air temperature, relative humidity, light intensity) set in the climatic chamber for testing on *Nicotiana tabacum*. The graph below shows the stem frequency of the plant measured using the Tx AFE of *LoRaTO+GPSS*.

path and the other in parallel (R_p) with the stem track and the series resistance. This resistor network allows setting the generable frequency boundaries. However, different plants (or even different growth stages of the same species) have different impedance ranges, making it difficult to have a reliable system for every plant. Moreover, in this iteration, we introduce a digitally programmable relaxation oscillator, in which both the resistive and capacitive elements of the R_p, R_s, C are configurable at runtime. This is done using a quad digital potentiometer (MCP4452-104E/ST, Microchip, USA) for the resistors and an analog multiplexer (TMUX1204DGSR, Texas Instruments, USA) for a 4-element array of discrete capacitors. A fixed Rx AFE configuration, as in [8], was chosen.

2) Soil Matric Potential: *GPSS* integrates the soil matric potential AFE for a commercial soil matric potential sensor, the WATERMARK 200SS, which offers a cost-effective and robust method for measuring soil matric potential. The WATERMARK 200SS sensor behaves as a variable resistor, decreasing in resistance with increasing soil moisture. A custom circuit forms an RC network with a capacitor, creating a relaxation oscillator. A microcontroller measures the oscillation period, converts it to frequency, and transmits the data via LoRa.

3) Environmental Parameters: To contextualize plant and soil measurements within the surrounding atmospheric conditions, the *GPSS* integrates a BME688 environmental sensor (Bosch, Germany). This device provides multi-modal environmental data, including temperature, relative humidity, barometric pressure, and volatile organic compounds (VOCs), which can offer indirect insights into plant stress and microclimatic variations at the canopy level. The sensor communicates with the *LoRaTO* board via the I^2C protocol.

III. Results and System Evaluation

A. Functional Test

To validate our modular platform in a real climate-smart agriculture scenario, we need to test it with a real plant. Moreover, given the challenge of testing all three domains, we started with the Tx AFE, leaving the Rx AFE, soil, and environmental sensors as future work. To do this, we tested

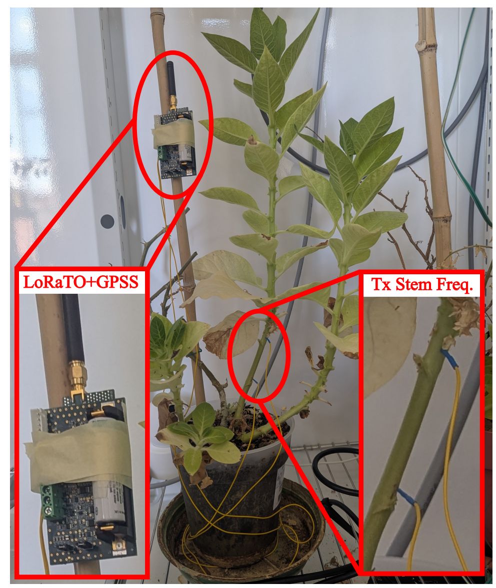

Fig. 3. Photo of the functional test in climatic chamber Fitoclima 1200.

the modular platform (*LoRaTO+GPSS*), as shown in Fig. 3, on a *Nicotiana tabacum* plant, using two surgical stainless steel needles 1 cm long and 0.4 mm in diameter, placed 5 cm apart. The Tx AFE elements C, R_s, and R_p were set to 1 nF, 1 kΩ, and 33 kΩ, respectively. To induce changes in plant activity, a Fitoclima 1200 climatic chamber (Aralab, Portugal) was employed, which allows temperature, relative humidity, and light intensity to be configured as desired. A first naive approach was to set a constant relative humidity of 50% and a daily cycle composed of 12 h of 100% light intensity using 26 000 lx visible light fluorescent lamps, followed by 8 h during which the lights are switched off. The remaining hours were used to emulate a ramp-up (2 h) of air temperature and light intensity and a ramp-down (2 h) of the same quantities. The climatic chamber also allows measurement of the actual air temperature and humidity against the configured set points. The results of the trial tests on the Tx AFE conducted between June 5th, 2025 and June 18th, 2025 are shown in Fig. 2. The plant was

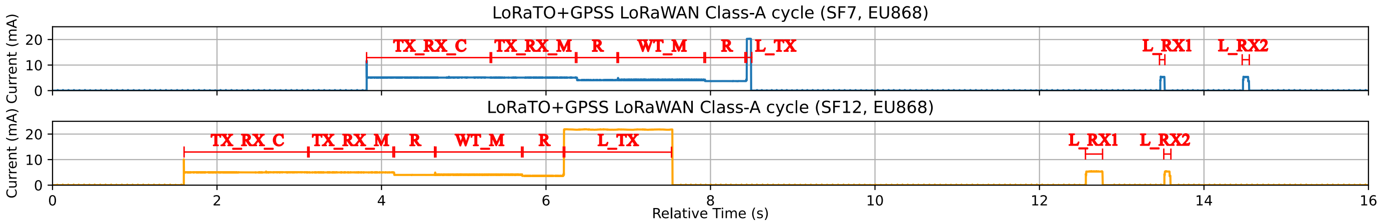

Fig. 4. Measured current consumption of the modular platform in a typical LoRaWAN Class-A cycle in the best coverage case (Spreading Factor 7 – SF7) and in the worst coverage case (Spreading Factor 12 – SF12). The system wakes up when an alarm in the Real Time Clock (RTC) is triggered, switching on and configuring the passive elements and Tx and Rx AFE (`TX_RX_C`), the measurement of relaxation oscillators (`TX_RX_M`), a resting phase to discharge elements and switching off Tx and Rx AFE (`R`), the measurement of WATERMARK (`WT_M`), a resting phase to discharge elements (`R`), a LoRaWAN Class-A transmission (`L_TX`), the opening of receive window 1 (`L_RX1`), and the opening of receive window 2 (`L_RX2`). Measurements done with Keithley DMM7510.

regularly hydrated. A clear daily variation in stem frequency can be observed, corresponding to changes in air temperature and light intensity, suggesting the effectiveness of the system in detecting plant bio-activity. During light-on and higher temperature phases, the stem frequency increases (indicating lower stem bio-impedance), whereas during light-off and lower temperature phases, the stem frequency decreases (indicating higher stem bio-impedance). During the ramp stages, the stem frequency changes abruptly as a response to variations in plant bio-activity. The more trapezoidal shape of the frequency trend, compared to other experiments [6], [16], is due to the forcing action of the climatic chamber, which allows fine control of both temperature and light intensity. Such experiment, performed on a single plant specimen, should be interpreted mainly as a proof-of-concept to verify the correct operation of the Tx AFE module, rather than as an agronomic conclusion on physiological responses.

B. Power Consumption and Lifetime Estimation

One of the primary objectives of the proposed system is to enable low-power operation suitable for multi-year deployments powered by a single AA 3.6 V $LiSOCl_2$ battery. During standby, the system enters the Stop2 low-power mode of the microcontroller, a power-saving mode provided by the STM32WL5MOC. In this state, the measured current draw (measurement with Agilent 34401A) is limited to 1.7 µA, which includes leakage currents from all components of the modular platform. The wake-up events are triggered by a low-frequency internal Real Time Clock (RTC). In the functional test, it was configured with a LoRaWAN Class-A cycle every 5 min. When active, the node performs a sequence of operations consisting of the configuration and measurement of the Tx AFE and Rx AFE modules, configuration and measurement of the WATERMARK sensor, transmission of a LoRaWAN packet, and the opening of two receive windows for downlink packets, as required by the LoRaWAN Class-A cycle. Figure 4 shows the measured current profile in two noteworthy coverage scenarios. Spreading Factor 7 (SF7) is typically used when the end node (i.e., the modular platform) is close to the gateway, whereas Spreading Factor 12 (SF12) is used to cover longer distances. Additionally, the caption of Fig. 4 illustrates the steps that compose a complete measurement and communication cycle of the modular platform. In the test firmware, the configuration and measurement operations for Tx AFE, Rx AFE, and WATERMARK last approximately 4.5 s. Knowing that the entire platform is powered at 3.6 V, it is possible to compute the energy consumption per measurement and communication cycle. The results show 23.13 µW h for the SF7 case and 51.18 µW h for the SF12 case. The majority of the energy consumption within one hour is attributed to the few seconds spent in active mode, compared to the much lower consumption during standby mode. Assuming one sample every 15 min and a 3.6 V $LiSOCl_2$ battery with a nominal capacity of 2600 mA h, the estimated lifetime is 10.72 years (around 128 months) for the SF7 case and 5.04 years (around 60 months) for the SF12 case. A longer periodicity could still capture meaningful plant bio-activity, extending platform lifetime in greenhouse or field use.

IV. CONCLUSIONS

This work presented a modular, low-power IoT platform for in-vivo plant monitoring, integrating physiological, soil, and environmental sensing into a compact, autonomous node. The system combines a dual-frequency stem electrical bio-signal measurement architecture with LoRaWAN connectivity and subsystem-level power gating, achieving full-cycle operation in less than 5 s and an estimated lifetime between 5.04 and 10.72 years, assuming one sample every 15 min. Preliminary data from tests in a climatic chamber also suggest that the system is capable of capturing the physiological activity of the plant. A representative time series shows a clear variation in stem frequency from the Tx AFE, correlated with light exposure and temperature. These trends align with known physiological behavior, although further validation is required to evaluate the individual environmental contributions to the stem frequency data. Future work will focus on testing the remaining *GPSS* modules (Rx AFE, WATERMARK, and the BME688 sensor), cross-species calibration, extensive robustness testing in harsh environments (greenhouse and open field), and integration with decision-support tools enables data-driven irrigation and early stress detection from stem frequency data [17].

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References

[1] Food and Agriculture Organization of the United Nations, *The State of the World's Land and Water Resources for Food and Agriculture 2021 – Systems at breaking point*. FAO, May 2022. [Online]. Available: http://dx.doi.org/10.4060/cb9910en

[2] A. Monteiro, S. Santos, and P. Gonçalves, "Precision agriculture for crop and livestock farming—brief review," *Animals*, vol. 11, no. 8, 2021. [Online]. Available: https://www.mdpi.com/2076-2615/11/8/2345

[3] U. Garlando, L. Bar-On, P. M. Ros, A. Sanginario, S. Calvo, M. Martina, A. Avni, Y. Shacham-Diamand, and D. Demarchi, "Analysis of in vivo plant stem impedance variations in relation with external conditions daily cycle," in *2021 IEEE international symposium on circuits and systems (ISCAS)*. IEEE, 2021, pp. 1–5.

[4] U. Garlando, S. Calvo, M. Barezzi, A. Sanginario, P. M. Ros, and D. Demarchi, "Ask the plants directly: Understanding plant needs using electrical impedance measurements," *Computers and Electronics in Agriculture*, vol. 193, p. 106707, 2022.

[5] I. Jócsák, G. Végvári, and E. Vozáry, "Electrical impedance measurement on plants: a review with some insights to other fields," *Theoretical and Experimental Plant Physiology*, vol. 31, no. 3, pp. 359–375, 2019. [Online]. Available: https://doi.org/10.1007/s40626-019-00152-y

[6] U. Garlando, S. Calvo, M. Barezzi, A. Sanginario, P. M. Ros, and D. Demarchi, "A "plant-wearable system" for its health monitoring by intra-and interplant communication," *IEEE Transactions on AgriFood Electronics*, vol. 1, no. 2, pp. 60–70, 2023.

[7] S. Calvo, M. Barezzi, D. Demarchi, and U. Garlando, "In-vivo proximal monitoring system for plant water stress and biological activity based on stem electrical impedance," in *2023 9th International Workshop on Advances in Sensors and Interfaces (IWASI)*. IEEE, 2023, pp. 80–85.

[8] M. Barezzi, L. Rolle, D. Demarchi, and U. Garlando, "Sensor system for water stress detection using in-plant transmitted signal amplitude evaluation," in *2024 IEEE SENSORS*. IEEE, 2024, pp. 1–4.

[9] O. Elijah, T. A. Rahman, I. Orikumhi, C. Y. Leow, and M. N. Hindia, "An overview of internet of things (iot) and data analytics in agriculture: Benefits and challenges," *IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 3758–3773, 2018.

[10] "Lora features description." 2025, https://lora.readthedocs.io/ [Accessed: 23-06-2025].

[11] S. Calvo, M. Barezzi, U. Garlando, R. La Rosa, and D. Demarchi, "An energy autonomous and battery-free plant's electrical impedance measurement system," in *2024 IEEE International Symposium on Circuits and Systems (ISCAS)*, 2024, pp. 1–4.

[12] A. Albanese, M. Nardello, and D. Brunelli, "Automated pest detection with dnn on the edge for precision agriculture," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 11, no. 3, pp. 458–467, 2021.

[13] E. Osorio de la Rosa, J. Vázquez Castillo, M. Carmona Campos, G. R. Barbosa Pool, G. Becerra Nuñez, A. Castillo Atoche, and J. Ortegón Aguilar, "Plant microbial fuel cells–based energy harvester system for self-powered iot applications," *Sensors*, vol. 19, no. 6, 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/6/1378

[14] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "Overview of cellular lpwan technologies for iot deployment: Sigfox, lorawan, and nb-iot," in *2018 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, 2018, pp. 197–202.

[15] A. Bianchi, D. Masseroni, M. Thalheimer, L. Olivera de Medici, and A. Facchi, "Field irrigation management through soil water potential measurements: a review," *Field irrigation management through soil water potential measurements: a review*, vol. 1119, no. 2, p. 25–038, 2017. [Online]. Available: https://doi.org/10.19199/2017.2.2038-5625.025

[16] U. Garlando, L. Bar-On, P. M. Ros, A. Sanginario, S. Calvo, M. Martina, A. Avni, Y. Shacham-Diamand, and D. Demarchi, "Analysis of in vivo plant stem impedance variations in relation with external conditions daily cycle," in *2021 IEEE International Symposium on Circuits and Systems (ISCAS)*, 2021, pp. 1–5.

[17] F. Cum, S. Calvo, A. Sanginario, and U. Garlando, "Evaluation of machine learning models for water stress detection using stem impedance," *IEEE Transactions on AgriFood Electronics*, 2024.