EcoSentinel

D3.3 – Results on the EcoSentinel PoC (v1)

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Plant-e living plants generate electricity

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Executive Summary

Deliverable D3.3 – Results on the EcoSentinel Proof-of-Concept (PoC) presents the implementation, experimental validation, and performance assessment of the first integrated EcoSentinel system, building upon the design defined in D3.1 and the component-level specification detailed in D3.2.

This deliverable marks the culmination of the first development cycle of the project, where the concepts, models, and experimental results developed in WP1 and WP2 are consolidated into a fully operational PoC_v1. The objective is to validate the feasibility of a plant-based, self-powered sensing node capable of combining energy harvesting, communication, and biosensing functionalities within a unified system.

The work is structured around the three EcoSentinel Task Forces, each corresponding to a core functionality:

- **Task Force 1 (T1): Plants as Antennas (PaA)**

  Experimental validation confirms that plant species and their functional traits influence antenna radiation performance. Measurements of photosynthetic efficiency and antenna behaviour across multiple species provide insight into the relationship between plant physiology and electromagnetic performance, supporting the feasibility of plant-assisted antenna systems.

- **Task Force 2 (T2): Plants as Energy Sources (PaES) + Communication Systems (PaCS)**

  The results demonstrate that energy harvested from Plant-Microbial Fuel Cells (P-MFCs) can effectively power ultra-low-power electronics and enable wireless data transmission. Experimental tests validate energy extraction, system operation under constrained power budgets, and the capability to sustain sensing and communication tasks.

- **Task Force 3 (T3): Plants as Biosensors (PaB)**

  Electrochemical and system-level measurements confirm that plant–soil–microbe interactions can be monitored through electrical signals, supporting the concept of plants as living biosensors. The results provide the basis for correlating system behaviour with plant physiological status and for developing simplified digital-twin–like models.

These subsystems are integrated and validated within the **PoC_v1 configuration**, where a plant-powered node performs sensing and wireless communication using bio-harvested energy. The experimental evaluation demonstrates continuous operation, successful data transmission, and system-level coherence between energy generation, sensing, and communication.

Overall, the results confirm the **technical feasibility of EcoSentinel's core vision**: plants can function as multimodal digital nodes, simultaneously acting as energy sources, communication enablers, and biosensors within a sustainable technological ecosystem.

At the same time, the validation process highlights key challenges related to system stability, energy variability, and integration complexity, which define the priorities for the next development cycle.

This deliverable therefore represents a critical milestone, transitioning EcoSentinel from component-level validation to **fully integrated system demonstration**, and laying the foundation for further optimisation, scaling, and real-world deployment.

1. Introduction

The goal of this document is to present and analyse the **results obtained from the first EcoSentinel Proof-of-Concept (PoC)**.

The deliverable reports the experiments and validation tests conducted on the three task forces and the integrated PoC configuration.

The document includes:

- description of the experimental setups
- measurements and performance evaluation
- discussion of integration challenges and system limitations
- identification of key findings and directions for future improvements

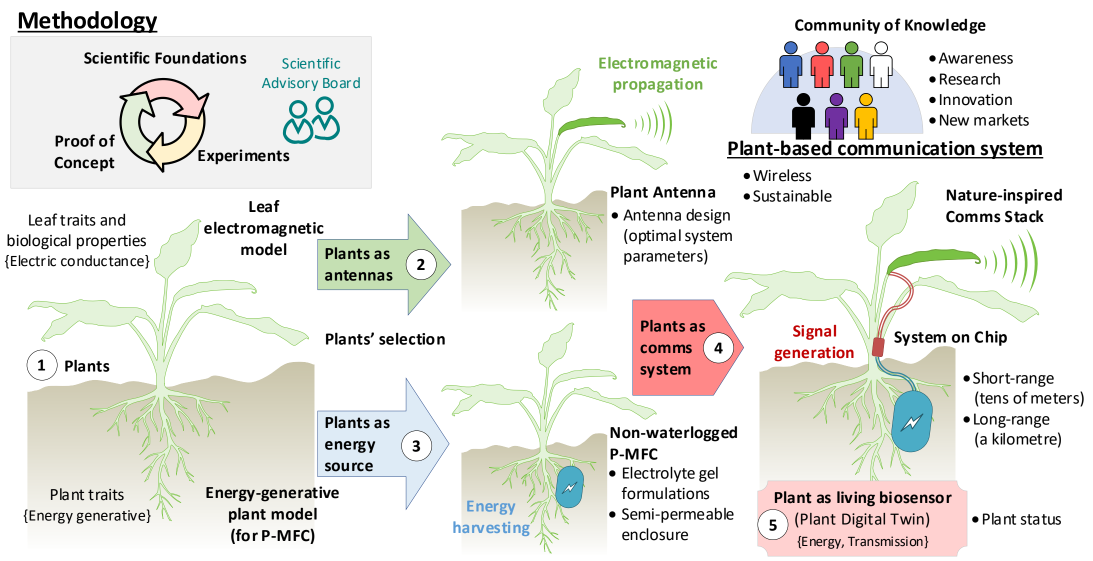


Figure 1. EcoSentinel Reference Components

The following **task forces [*TX*]** and the associated experiments have been considered and presented in the D3.1 Design of EcoSentinel PoC (v1):

***[T1]* Plant (1) – Antenna Booster (2)**

The objective of this task force is to assess the radiation efficiency of antenna boosters installed on various plant species with differing functional traits (i.e. the set of morphological, physiological, structural or phenological characteristics of an organism) (Nock et al., 2016), and to evaluate how these plant characteristics influence the radiation performance of the antenna boosters.

***[T2]* Plant-Microbial Fuel Cell (3) – Comms system (4)**

This task force aims to demonstrate that it is possible to harvest energy from plants through a Plant-Microbial Fuel Cell (P-MFC) and power low-power electronics and enable wireless communication. The goal is to validate the feasibility of a self-sustaining plant-powered sensing and communication system.

***[T3]* Plant-Microbial Fuel Cell (3) – Living Biosensor (5)**

This task force aims to develop a simplified digital-twin–like model to estimate the plant state based on experimental data. The objective is to build a structured dataset combining measurements collected from the P-MFC setup (environmental and bioelectrical parameters) with complementary data provided by project partners. This integrated dataset will be used to explore correlations and identify a reliable match between measured variables and the physiological state of the plant.

***[PoC_v1]* Plant (1) – Antenna Booster (2) – P-MFC (3) – Comms System (4)**

This PoC aims to demonstrate a self-powered plant-based sensing node where energy harvested from a Plant-Microbial Fuel Cell (P-MFC) powers a custom PCB for sensor measurements and wireless communication. The system integrates plant-based energy harvesting, ultra-low-power electronics, and a plant-assisted antenna booster to validate sustainable wireless data transmission. The objective is to show that bio-harvested energy can support periodic sensing and communication to a gateway.

Each task force [T1 – T2 – T3] is explained in detail. After explaining the integration of the different components, the [PoC_v1] is also explained.

2. [T1] Task Force 1: Plant – Antenna Booster

T1 has the objective of assessing the interaction between plant and antenna booster, and to identify plant species and associated functional traits that maximize radiation transmission potential.

Diagram

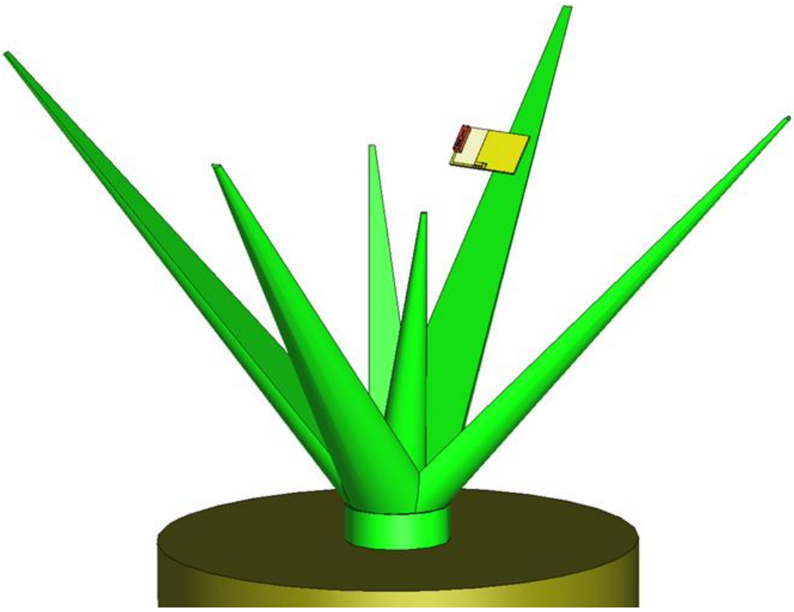


Figure 2. T1 - Schematic view of Antenna booster placed on Aloe vera leaf

2.1. T1 - Experiments

List of experiments

- **T1 - Experiment 1 - Photosynthetic efficiency**
  - In this experiment, we will assess the overall plant health via photosynthetic efficiency of the plant species that are selected for the Experiment 2.
    The aim is to characterize specie-specific photosynthetic signature, since plant stress can be related with alterations of photosynthetic efficiency and plant performance.
- **T1 - Experiment 2 - Plant - Antenna booster radiation efficiency**
  - In this experiment, we will assess the radiation efficiency of the antenna booster when placed on different plant species.

2.1.1. T1 - Experiment 1 – Photosynthetic efficiency

All plants subjected to measurement for their antenna properties will be evaluated for their photosynthetic efficiency.

Photosynthetic efficiency is widely used as a proxy for plant health because photosynthesis is one of the most sensitive physiological processes in plants. In particular, the efficiency of photosystem II (PSII), measured through chlorophyll a fluorescence and OJIP kinetics, reflects the functional state of the photosynthetic apparatus.

Table 1. T1 – Exp 1 - Tests

Tests	Description
T1 – Exp 1 – Test 1 Photosynthetic efficiency	All plants subjected to measurement for antenna radiation efficiency were evaluated for their photosynthetic efficiency.

2.1.1.1. T1 – Experiment 1 – Test 1 - Photosynthetic efficiency

Setup

Figure 3. Experimental setup for measuring the fluorescence transient and photosynthetic efficiency. Leaves are dark-adapted using leaf clips (10 clips per leaf, in repeated measurements) for 30 minutes and then exposed to a 1-second pulse of photosynthetically active radiation. The signal is recorded by the Handy PEA and converted into a fluorescence induction curve, with simultaneous recording of photosynthetic efficiency parameters

Results

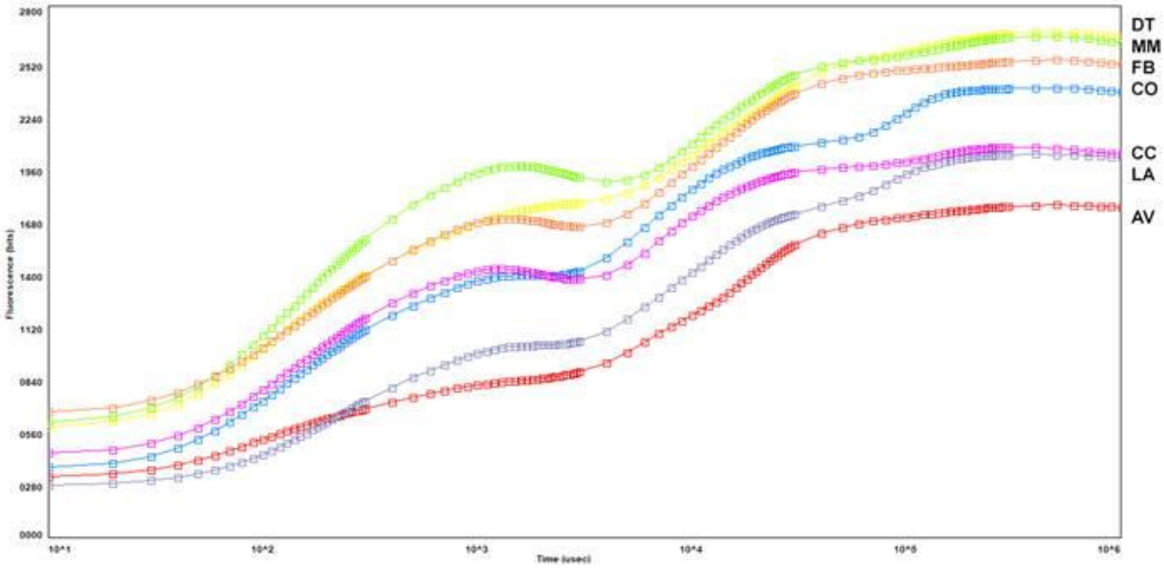


Figure 4. The OJIP chlorophyll fluorescence induction curves (fluorescence vs. time on a logarithmic scale) obtained with the Handy PEA Photosynthetic Efficiency Analyzer for different plant species: DT – Dracaena trifasciata; MM – Monstera minima; FB – Ficus benjamina; CO – Calendula officinalis; CC – Chlorophytum comosum; LA – Lavandula angustifolia; AV – Aloe vera. Data are average of 30 leaves per plant

Analysis

The OJIP fluorescence induction curves showed the typical OJIP pattern in all analysed species, indicating a functional photosynthetic apparatus under the tested conditions. However, differences in fluorescence amplitudes and kinetics were observed among species, reflecting variability in PSII photochemical efficiency and electron transport capacity. In particular, *D. trifasciata* and *M. minima* exhibited the highest fluorescence intensities, while *A. vera* showed consistently lower values, suggesting comparatively reduced photosynthetic performance.

These differences are likely related to species-specific physiological and structural traits, such as leaf anatomy, chlorophyll content, and the organization of the photosynthetic apparatus, all of which influence light absorption and electron transport efficiency.

Although both *D. trifasciata* and *A. vera* are CAM (Crassulacean Acid Metabolism) species, CAM plants can show substantial variability in PSII activity depending on factors such as leaf thickness, chloroplast distribution, and the species-specific level of Crassulacean Acid Metabolism. For example, the highly succulent leaves of *A. vera* may lead to greater internal light attenuation and different energy dissipation dynamics, which could result in lower fluorescence signals compared with *D. trifasciata*.

Therefore, the observed differences in the OJIP curves likely reflect intrinsic anatomical and physiological differences among species, rather than stress effects.

2.1.2. T1 - Experiment 2 – Plant - Antenna booster radiation efficiency

The goal of this experiment was testing different combinations of plant species and antenna boosters, selecting plants that vary in key physical, morphological and physiological traits such as leaf water content and structure.

The aim is to demonstrate that certain plant species can enhance antenna efficiency by up to 3 dB, and to identify the associated functional traits driving this improvement.

Table 2. T1 – Exp 2 - Tests

Tests	Description
T1 – Exp 2 – Test 1 Antenna booster position along a leaf	Antenna booster is placed in different positions of *Aloe vera* leaf, and the radiation efficiency is measured.
T1 – Exp 2 – Test 2 Antenna booster on plants	Radiation efficiency of antenna booster placed on different types of plants will be measured in a 3D scanning system.

2.1.2.1. T1 – Experiment 2 – Test 1 - Antenna booster position along a leaf

Setup

The antenna booster is placed in different positions along *Aloe vera* leaf and for each position the radiation efficiency is measured.

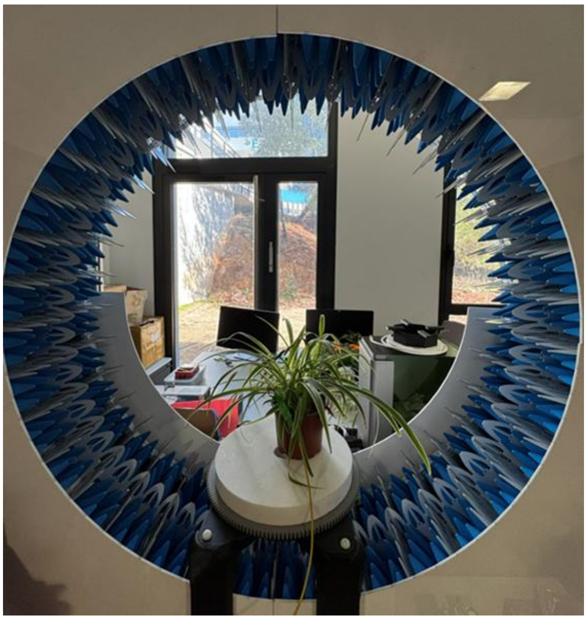


Figure 5. Measurement setup for measurement of radiation efficiency of plant-antenna booster on Chlorophytum comosum.

Figure 6. Antenna booster placement along the Aloe vera leaf: left, middle section of the leaf; right, lower section of the leaf.

Results

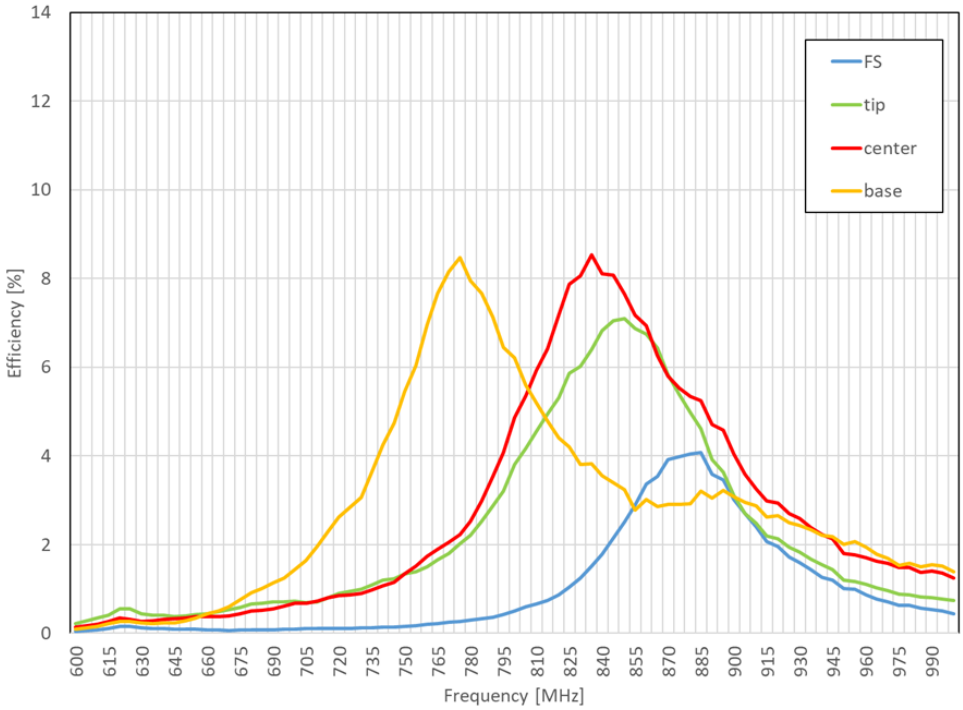


Figure 7. Measured antenna booster radiation efficiency at three positions on an A. vera leaf (FS is in free space).

Analysis

Figure 7 presents the measured radiation efficiency for the three antenna positions along the leaf. The results clearly show that all placements improve overall radiation efficiency compared to the free-space case (4%), with an increase of approximately 8% (that is 3 dB improvement).

Among the tested positions, the centre of the leaf provides the best performance, yielding about a 1.5% improvement over placement at the tip. Although positioning the antenna at the bottom of the leaf still results in relatively high efficiency (around 8.5%), it introduces a notable frequency shift from 840 MHz to 770 MHz.

These findings indicate that while the leaf enhances antenna performance in general, the central position offers the most balanced improvement without significant frequency detuning.

2.1.2.2. T1 – Experiment 2 – Test 2 - Antenna booster on plants

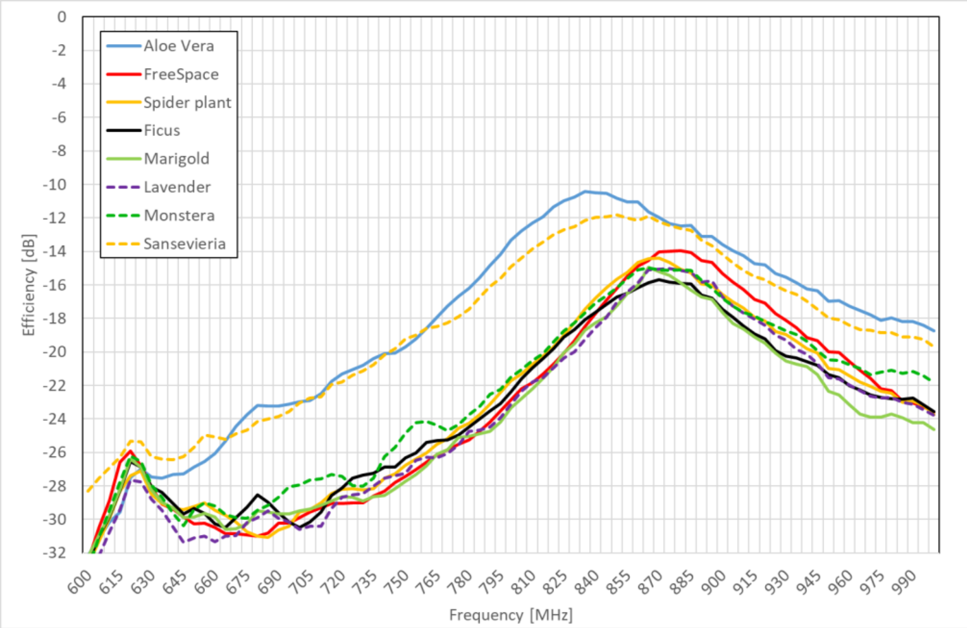
Setup

The antenna booster is placed on the selected plant, as shown in Figure 8 and the radiation efficiency is measured for each of the 8 previously selected plants.

The measurement system is the same as described in the previous test, shown on Figure 5.

Figure 8. Set of various plants used in the experiment with an antenna booster placed on each plant.

Results



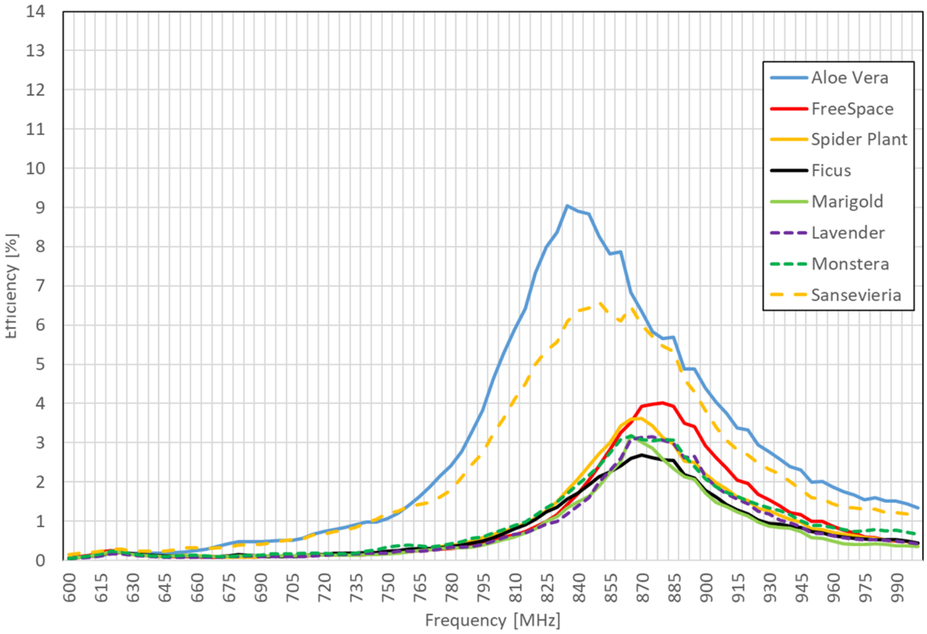


Figure 9. Measured radiation efficiency of the antenna booster placed on different plant species selected (above in dB, below in percentage).

Analysis

Figure 9 illustrates the measured radiation efficiency of the antenna booster when placed on various plant types with differing physical and physiological characteristics.

For clarity, both representations in dB and in percentage are shown.

The results show that the *Aloe vera* plant provides the highest improvement compared to the free-space scenario, reaching nearly 9% radiation efficiency and an improvement of almost 4 dB compared to the free space. Similarly, the sansevieria plant (*Dracaena trifasciata*) achieves up to 6.5% efficiency, representing a significant enhancement.

In contrast, other plants that differ in size and leaf density exhibit lower efficiencies than in free space, with the *ficus* showing the poorest performance at approximately 1.5% below the free-space case.

Although these plants are botanically distinct, *Aloe vera* and *Dracaena trifasciata* belong to different families. They share similar functional traits, such as high tissue water content, increased leaf thickness, the presence of a well-developed cuticle and waxes, reduced water loss, and CAM-type metabolism.

Interestingly, both species exhibit a more pronounced impact on radiation efficiency. We will further investigate which of these traits strongly influence radiation efficiency.

The important fact to notice is that the antenna has been tuned for optimum performance in free space. When placed on plants such as *Aloe vera* or *Dracaena trifasciata*, there is a detuning of the efficiency peak of approximately 25 MHz. This is due to the dielectric nature of the plants material and needs to be considered for the PoC design.

2.2. T1 - Discussion and Key findings

The results show that placing the antenna in the central position of the leaf provides the most balanced enhancement while minimizing frequency detuning.

Among the tested plants, *Aloe vera* and *Dracaena trifasciata* deliver the most significant gains—approximately 4 dB and 2.5 dB respectively—likely due to shared traits such as high-water content, thicker leaves, and waxy surfaces. However, these benefits come with limitations: plants inherent dielectric properties can shift the resonant frequency (e.g., up to 25 MHz detuning), and not all plants are beneficial—some, like lavender, can even reduce efficiency below the free-space case.

Overall, the hypothesis is confirmed: certain plants can enhance radiation efficiency by more than 3 dB, though performance depends strongly on plant properties and antenna tuning.

Key findings

- Central leaf placement on *Aloe vera* offers best performance with minimal detuning
- *Aloe vera* increases efficiency by approximately 4 dB (highest improvement) compared to free space and *Dracaena trifasciata* improves efficiency by approximately 2.5 dB
- Frequency detuning occurs (up to 25 MHz shift) due to plant dielectric properties and thus antenna tuning optimized for free space must be adjusted for plant-based use cases
- Some plants (e.g., ficus, lavender) reduce efficiency below the free-space antenna performance over certain frequency ranges, probably due to small leaf size and thickness, lower water content and higher leaf density.

3. [T2] Task Force 2: Plant-Microbial Fuel Cell – Comms system

Task Force 2 has the objective of obtaining power from plants via the P-MFC, to power all electric components (sensors, MCU processing, antenna) via the energy-harvesting circuit on a PCB.

Diagram

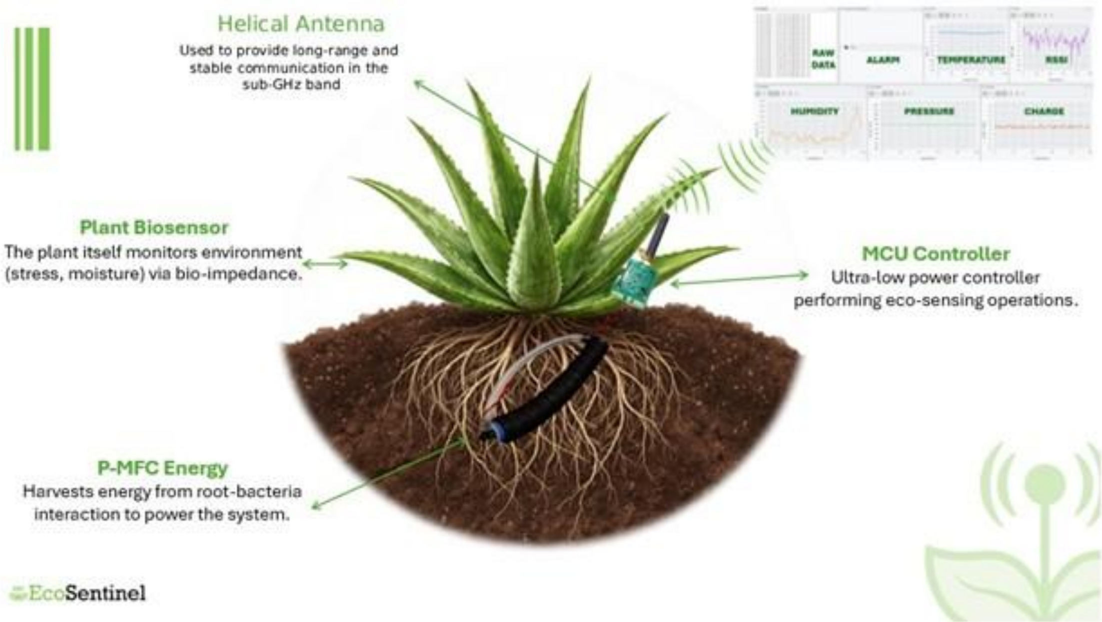


Figure 10. T2 - Schematic view of the P-MFC providing energy to the MCU and the signal transmission powered by the plant leaf.

3.1. T2 - Experiments

List of experiments

- **T2 - Experiment 1 - Testing the energy extraction from a P-MFC**
  - A plant pot with a water-logged P-MFC was connected to the EcoSentinel PCB for energy-harvesting extraction, containing a 10 F supercapacitor as the energy storage element. The P-MFC and the energy recovery circuit should charge the supercapacitor in a few hours or even a few days.
- **T2 - Experiment 2 - Collecting sensor data from the EcoSentinel PCB powered by energy harvesting from a P-MFC**
  - The EcoSentinel PCB periodically (every 5 minutes) sends data to a gateway and then enters deep-stop mode (lowest power consumption state), waking up via the RTC to transmit again, powered by energy harvested from the P-MFC.

3.1.1. T2 - Experiment 1 - Testing the energy extraction from a P-MFC

A plant pot with a water-logged P-MFC was connected to the EcoSentinel PCB for energy-harvesting extraction, containing a 10 F hybrid supercapacitor as the energy storage element.

The P-MFC and the energy recovery circuit are expected to charge the supercapacitor in a few hours or even a few days.

Validation of P-MFC power production and energy-harvesting. Directly related to the WP1 D1.1 Hypotheses: "Communication hypotheses. A plant-based system can sustain wake-up radio communication with minimal power draw, using optimized RF frequencies and environmental steering. Signal frequency from 400 to 900 MHz, environment, specifically soil humidity and compactness, and antenna polarization (vertical or horizontal) significantly affect communication range."

For this experiment, however, no radio communication is used, as it focuses on validating the prerequisite conditions required for the hypothesis to be tested.

Table 3. T2 – Exp 1 - Tests

Tests	Description
T2 – Exp 1 – Test 1 Monitoring supercapacitor charging from a P-MFC	A plant pot with a water-logged P-MFC was connected to a prototype PCB with a 10 F supercapacitor for energy harvesting.

3.1.1.1. T2 – Exp 1 – Test 1 - Charging a 10 F supercapacitor

Setup

Connection of the Microbial-Full Cell device to the EcoSentinel development board and a 10 F supercapacitor with a maximum voltage of 3.8 V, and measurement of the supercapacitor's voltage at regular intervals.

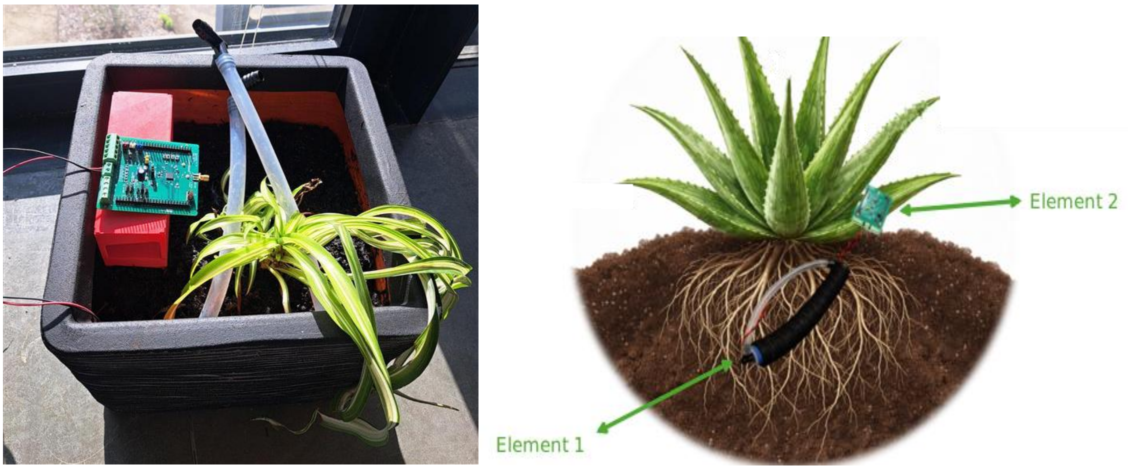


Figure 11. Setup Experiment 1 Test 1 (P-MFC and EcoSentinel Board)

Results

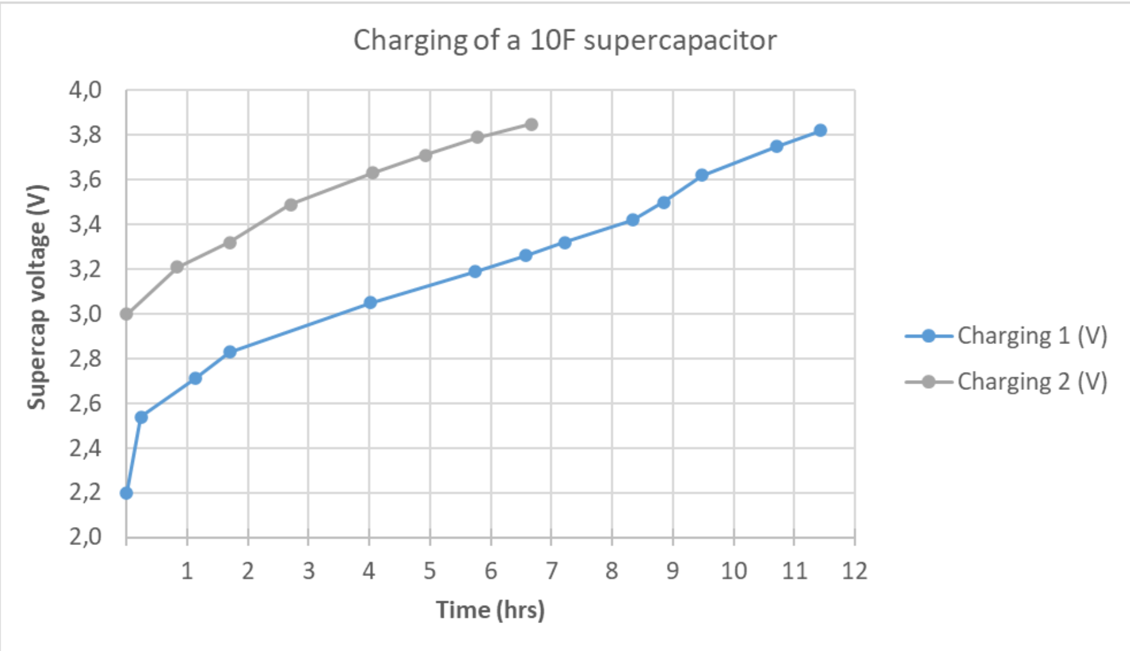


Figure 12. Results of the P-MFC charging up two pre-charged 10 F supercapacitor via the energy-harvesting circuitry on the EcoSentinel PoC PCB.

Figure 12 shows the evolution of the voltage of a 10 F supercapacitor while it is being charged uniquely by a P-MFC. The supercapacitor is placed on an EcoSentinel board equipped with an energy harvesting module.

During the **first test**, the initial voltage is approximately 2.2 V and increases progressively to reach 3.8 V after 11 hours. The increase is slow but continuous throughout the experiment.

During the **second test**, the initial voltage is higher (≈ 3.0 V). The voltage reaches 3.5 V in about 3 hours and then stabilizes around 3.85 V after 6 to 7 hours. The voltage rise is faster compared to the first test.

Analysis

The results show that the P-MFC, combined with the energy harvesting module, can charge a 10 F lithium hybrid supercapacitor, with a slow dynamic typical of low-power sources.

The difference between the two tests is mainly due to the higher initial voltage in the second test, which reduces the required charging time.

The charging curve is nonlinear, which is typical: charging is faster at the beginning due to a large voltage difference, then gradually slows down as the supercapacitor voltage approaches the system voltage, reducing the charging current. In the case of a lithium hybrid supercapacitor, this behaviour is also influenced by its internal structure combining capacitive and electrochemical mechanisms, which can accentuate the stabilization phase at the end of the charge.

The results also show that the system can recharge a 10 F lithium hybrid supercapacitor using a P-MFC source, with a charging time of a few hours, compatible with the application. This validates the system's ability to store energy autonomously (KPI1 validated).

The device is therefore suitable for intermittent low-power applications, with further optimizations still possible.

3.1.2. T2 - Experiment 2 - Collecting sensor data from a PCB powered by energy harvesting from a P-MFC

In this experiment, we will examine the data transmission bandwidth to the gateway as well as the voltage behaviour of the supercapacitor over time.

Table 4. T2 – Exp 2 - Tests

Tests	Description
T2 – Exp 2 – Test 1 Send sensor readings to the gateway and monitor power consumption	Sends sensor readings to the gateway and monitors consumption at various points in time.
T2 – Exp 2 – Test 2 Add sleep mode and measure the power consumption of a frame	Same as in T1, just use sleep mode to reduce power consumption.
T2 – Exp 2 – Test 3 Regularly transmit the sensor values to the gateway	Sending sensor readings to the gateway using the 10 F capacitor with the board connected to the P-MFC.

3.1.2.1. T2 – Exp 2 – Test 1 - Send sensor readings to the gateway and monitor power consumption

Setup

The board is equipped with temperature, humidity, and pressure sensors. During transmission and waiting periods, a power profiler is used as the sole power source, supplying the board at 3.3 V. This setup allows accurate measurement of the current consumption during data transmission and waiting phases.

Figure 13. Setup Experiment 2, Test 1 (EcoSentinel Dev Kit and power profiler).

Results

In this section, the transmitted data consist of temperature, humidity, and pressure sensor readings sent to the gateway using sub-GHz long-range communication.

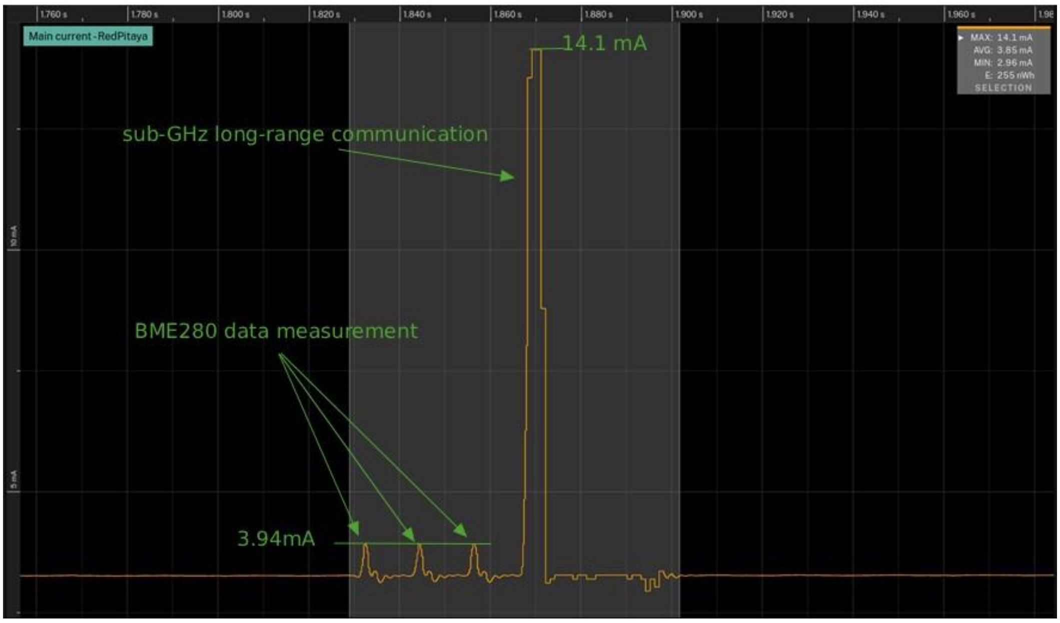


Figure 14. Power consumption when reading sensors and sending data.

Figure 14 shows the evolution of the current consumed by the board over time.
A low and stable current is observed during the idle state, corresponding to the standby mode. Slight increases in current occur when the sensors are activated.
A current peak of approximately **14 mA** is measured, corresponding to the data transmission phase. This phase is short in duration.
The overall measured values are:

- Maximum current: **14.1 mA**
- Average current: **3.85 mA**
- Minimum current: **2.96 mA**

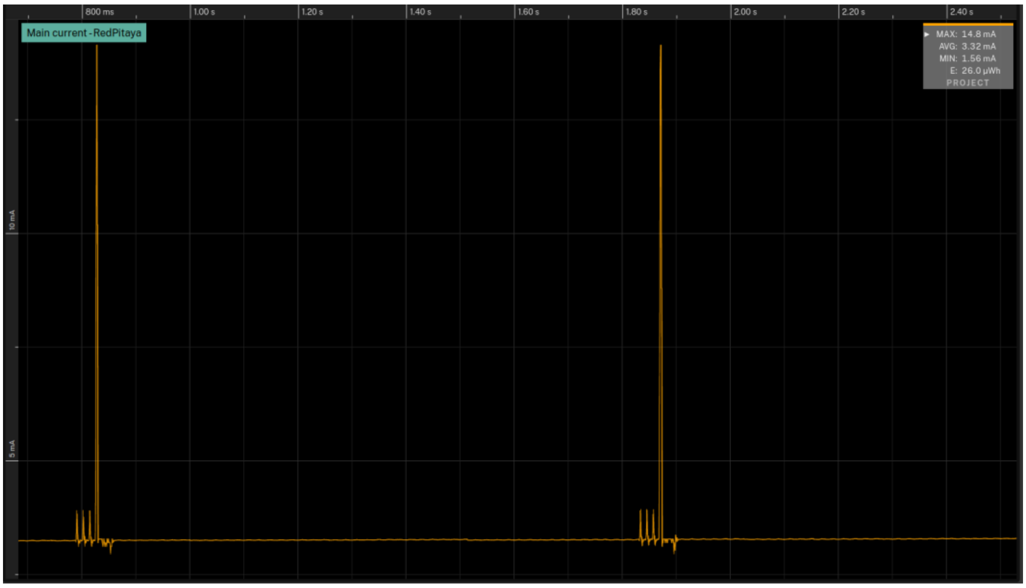


Figure 15. Energy consumption: reads sensors and sends data - overview.

The system sends data every 5 minutes, as shown in Figure 14. Power consumption when reading sensors and sending data. Between transmissions, the microcontroller remains in wait mode, which results in a current consumption of **3.22 mA.** Considering both the transmission and wait phases, the average current consumption of the system is **3.27 mA**. This profile shows that the MCU spends most of its time in wait mode.

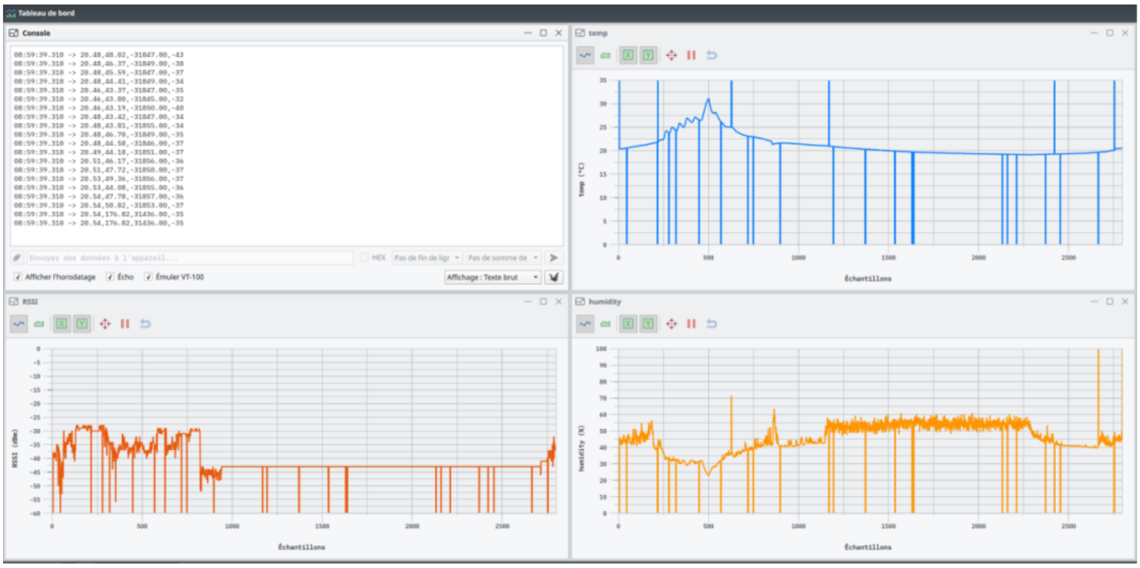


Figure 16. Display of collected data: temperature, humidity, RSSI, and pressure.

Analysis

This initial test demonstrates that communication between the board and the gateway is feasible, albeit with high power consumption when powered by a P-MFC.

Most of the energy is consumed during wait mode, where the MCU draws **3.22 mA**.

During data transmission, the current peaks at **14.1 mA**, while the average consumption, considering both transmission and wait phases, is **3.27 mA**.

Temperature, humidity, pressure, and RSSI data are correctly received and displayed on the gateway, confirming the reliability of the transmission.

These results highlight the importance of reducing power usage during inactive periods, which motivates the implementation of a sleep mode in Test 2 to optimize energy efficiency.

3.1.2.2. T2 – Exp 2 – Test 2 - Add a sleep mode and measure a consumption

Setup

The setup is like the previous test, except that the microcontroller and sensors are now in deep stop mode (equivalent to wait mode). The system regularly sends sensor readings to the gateway and uses a power consumption analysis tool to measure the board's power usage during transmission and during the waiting periods before transmission, when the MCU is in deep stop mode.

Figure 17. Setup Experiment 2 test 2 (power profiler and EcoSentinel Dev Kit).

Results

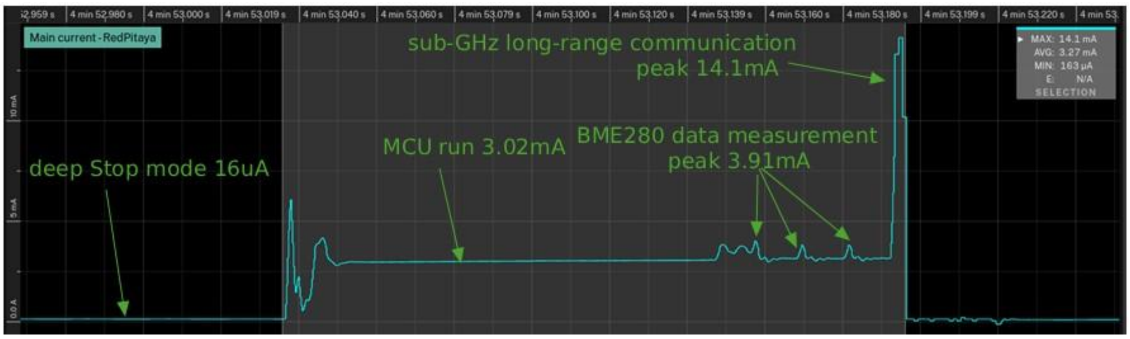


Figure 18. Power consumption optimized by using sleep/stop mode during sensor reading and data transmission.

Figure 18 shows the evolution of the board's current consumption over time. A very low current is observed during the idle state, corresponding to the deep stop mode, around 16 µA, highlighting the effectiveness of the low-power strategy.

When the system wakes up, the current rises to approximately 3.02 mA, corresponding to the MCU running phase. Additional small peaks, up to 3.91 mA, occur during BME280 sensor data acquisition.

A significant current peak of about 14.1 mA occurs during the sub-GHz long-range communication phase, which is short in duration, indicating efficient data transmission.

Overall measured values are:

- Maximum current: 14.1 mA
- Average current: 3.85 mA during 161 ms active mode (excluding deep stop mode)
- Minimum current: 16 µA

These results demonstrate that using deep stop mode significantly reduces power consumption during idle periods, making the system suitable for low-power, energy-constrained applications.

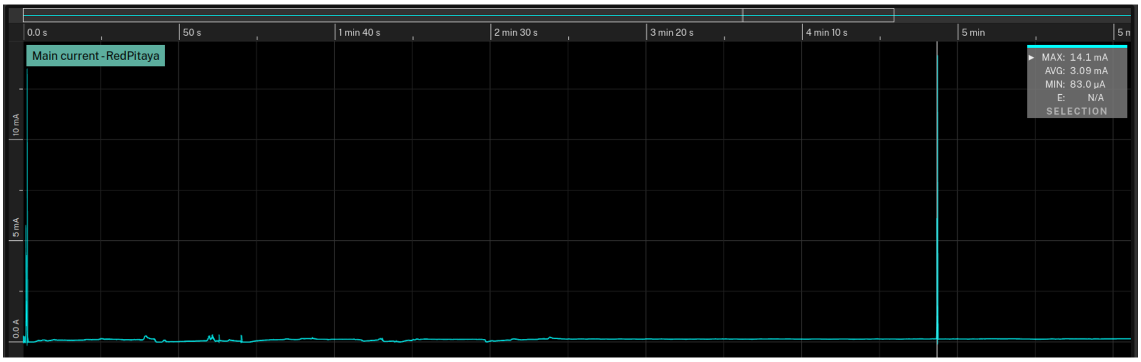


Figure 19. Power consumption when reading sensors and sending data use a deep stop mode - overview

The system sends data every 5 minutes, as shown in *Figure 19*. Between transmissions, the microcontroller remains in deep stop mode, resulting in a current consumption of 16 µA. Considering both transmission and waiting phases, the average current consumption over 5 minutes is 18.2 µA. This profile shows that the MCU spends most of its time in deep stop mode, significantly reducing overall power consumption.

Analysis

This test demonstrates that using deep stop mode significantly reduces the system's overall power consumption, making it suitable for energy-constrained applications powered by P-MFCs. Most of the energy is now consumed during short wake-up phases for sensor reading and data transmission, while the MCU remains in deep stop mode for most of the time, drawing only 16 µA.

During data acquisition, small current peaks up to 3.91 mA occur, and a significant peak of 14.1 mA is observed during sub-GHz communication. Considering both waiting and transmission phases, the average current consumption over 5 minutes is 18.2 µA. Sensor readings for temperature, humidity, and pressure, as well as RSSI, are correctly received by the gateway, confirming reliable communication. These results highlight the effectiveness of deep stop mode in optimizing energy efficiency.

3.1.2.3. T2 – Exp 2 – Test 3 - Regularly transmit the sensor values to the gateway

Setup

In this test, we monitor the data being transmitted as well as the supercapacitor voltage (the board is connected to the P-MFC to charge the capacitor at the same time.)

Figure 20. Setup Experiment 2, Test 3 (an EcoSentinel board sending sensor data to its gateway).

Results

Figure 21. Dashboard showing sensor data and supercapacitor voltage in real time

The deployment was monitored in real-time using Serial Studio on the data collection PC, as shown in *Figure 21*. This tool provides an instantaneous visualization of temperature, humidity, and pressure readings, while tracking wireless link quality (RSSI) and the energy balance (supercapacitor voltage in mV and P-MFC power in uW). Using Serial Studio also facilitates data sharing with Plant-E.

The experiment demonstrated that while the Packet Error Rate (PER) without integrity control was approximately 1%, implementing a CRC successfully reduced this rate to less than 0.1%, ensuring near-perfect data reception.

Analysis

Although transmission is generally stable, Serial Studio highlights unexpected additional transmissions occurring between the standard 5-minute intervals.

The source of these irregular occurrences remains under investigation. Furthermore, the supercapacitor voltage curve indicates a progressive discharge despite the P-MFC energy input, suggesting that dynamic adaptation of the transmission interval is necessary to maintain system autonomy based on its energy state.

KPI2 is considered validated, though further characterization of packet loss as a function of distance is required.

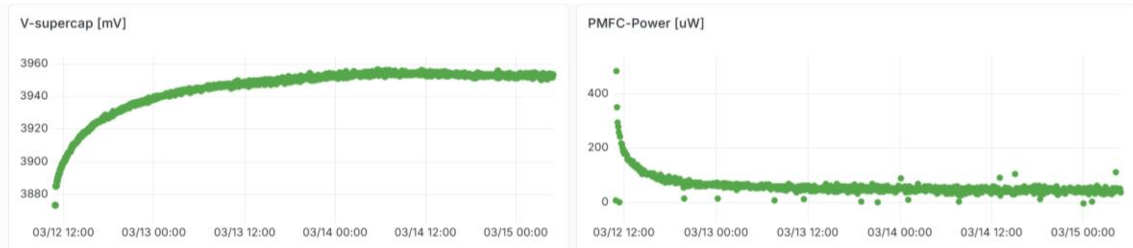


Figure 22. Screenshot of the dashboard, showing that the P-MFC charged-up the supercapacitor while the board was transmitting measurements every 5 minutes.

Figure 22 confirms that the P-MFC provides sufficient energy to offset the power consumed during transmissions, achieving a stable state of charge.

This energy stability validates the long-term viability of the autonomous sensor node. However, to maintain this balance even during potential drops in microbial fuel cell performance, implementing an algorithm that adapts the transmission interval to the measured voltage of the supercapacitor (input/output energy balance) remains a priority for optimizing resource management.

3.2. T2 - Discussion and Key findings

The results obtained during this task force indicate that data transmission is generally reliable under default conditions. However, some unexpected additional transmissions were observed.

Compared to the assumptions defined in WP1 and the initial results of WP2, the system generally meets expectations in terms of communication capacity. Nevertheless, the observed anomalies highlight a discrepancy between theoretical assumptions—particularly regarding energy management—and the system's actual behaviour.

Several limitations must be highlighted. On the one hand, the source of the unexpected transmissions has not yet been identified. On the other hand, the experimental setup does not yet allow for a precise evaluation of performance as a function of distance. These factors limit the full validation of the system's robustness.

Key findings

- The communication system operates correctly under standard conditions, confirming the basic functionality of the PoC.

KPIs 1 and 2 have been validated, confirming that the system meets the expected performance requirements. However, packet loss over long distances has yet to be precisely characterized.

4. [T3] Task Force 3: Plant-Microbial Fuel Cell – Living Biosensor

The objective of Task Force 3 is to investigate the use of Plant-Microbial Fuel Cells (P-MFCs) as living biosensors, exploiting their electrochemical behaviour to extract information related to plant–soil conditions and biological activity.

Diagram

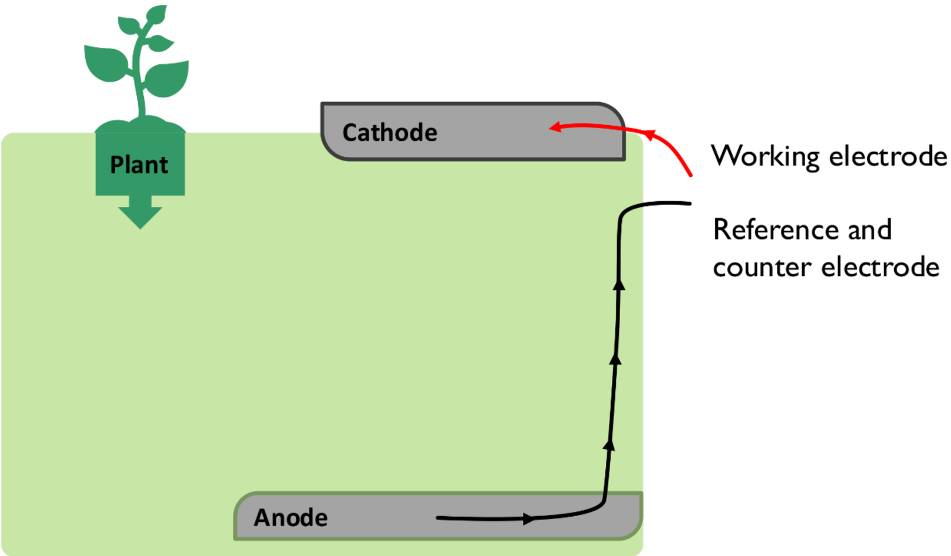


Figure 23. T3 - Schematic view of Electrodes placement for P-MFC test

4.1. T3 - Experiments

List of experiments

- **T3 – Exp 1 – Electrochemical Biosensing through EIS and P-MFC Analysis**
  - The focus is on identifying measurable electrochemical indicators, such as impedance response and polarization behaviour, that can be used for plant-state estimation while maintaining compatibility with energy harvesting operation.

4.1.1. T3 – Experiment 1 - Electrochemical Biosensing through EIS and P-MFC Analysis

The focus is on identifying measurable electrochemical indicators, such as impedance response and polarization behaviour, that can be used for plant-state estimation while maintaining compatibility with energy harvesting operation.

Table 5. T3 – Exp 1 - Tests

Tests	Description
T3 – Exp 1 – Test 1 CV Stability and Polarization Analysis	Evaluation of system stabilization after reconnection and identification of limiting electrode through cyclic voltammetry.
T3 – Exp 1 – Test 2 Two-Electrode EIS Characterization	Analysis of global impedance response under different polarization points.
T3 – Exp 1 – Test 3 Three-Electrode EIS Characterization	Separation of anode and cathode contributions using a three-electrode configuration.
T3 – Exp 1 – Test 4 Polarization Stability Assessment	Identification of stable operating points for reproducible measurements and compatibility with energy harvesting.

4.1.1.1. T3 – Exp 1 – Test 1 - CV Stability and Polarization Analysis

The objective of this experiment is to evaluate the stabilization behaviour of the P-MFC after reconnection and to identify the limiting electrode affecting system performance. The experiment aims to:

- analyse capacitive effects and transient behaviour,
- assess voltage recovery after load conditions,
- identify which electrode limits the electrochemical performance of the system.

Table 6. T3 – Exp 1 – Test 1 -Subtests

Tests	Description
T3 – Exp 1 – T1 – Subtest 1 CV Scan Analysis	Perform cyclic voltammetry to analyse current response and stabilization behaviour.
T3 – Exp 1 – T1 – Subtest 2 Voltage Stabilization	Monitor electrode voltage over time after reconnection.
T3 – Exp 1 – T1 – Subtest 3 Limiting Electrode Identification	Analyse electrode overpotential behaviour.

a. T3 – Exp 1 – Test 1 – Subtest 1 - CV Scan Analysis

Setup

Cyclic Voltammetry performed using PalmSens4 at 0.001 V/s on the P-MFC system after stabilization.

Results

Progressive reduction of peak current across successive scans until stabilization is reached.

Analysis

The system exhibits capacitive effects after reconnection, associated with the charging and discharging of the electrode–electrolyte interface (double-layer capacitance). This results in transient currents that affect the initial measurements. Multiple scans are required to reach a stable electrochemical state, indicating transient behaviour driven by charge redistribution.

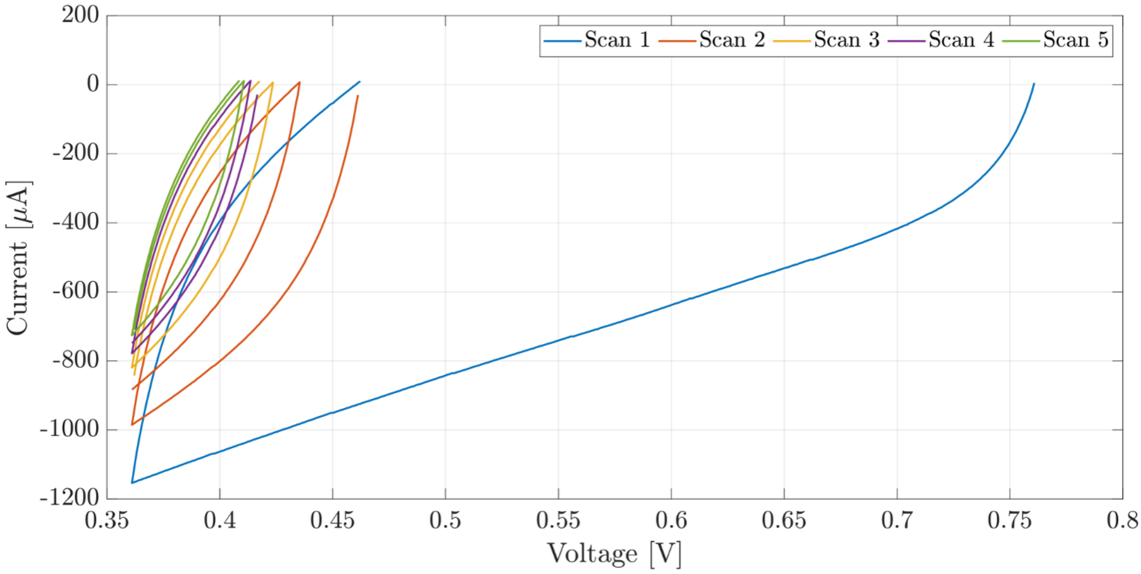


Figure 24. Voltage - Current relation - Capacitive effects

b. T3 – Exp 1 – Test 1 – Subtest 2 - Voltage Stabilization

Setup

Monitoring of electrode potentials over time after reconnection of the P-MFC.

Results

Several minutes are required for voltage stabilization due to capacitive discharge effects.

Analysis

The presence of capacitive currents significantly affects early measurements.

A stabilization phase is necessary to ensure repeatable and reliable electrochemical measurements.

c. T3 – Exp 1 – Test 1 – Subtest 3 - Limiting Electrode Identification

Setup

Cyclic Voltammetry (CV) measurements performed on the P-MFC using the PalmSens4 interface at a scan rate of 0.001 V/s. Electrode potentials (anode and cathode) are monitored during the voltage sweep to evaluate their behaviour under load conditions.

Results

The cathode exhibits higher overpotential compared to the anode.

Analysis

The cathode is identified as the limiting electrode, constraining system performance. This highlights the need to analyse electrode contributions separately.

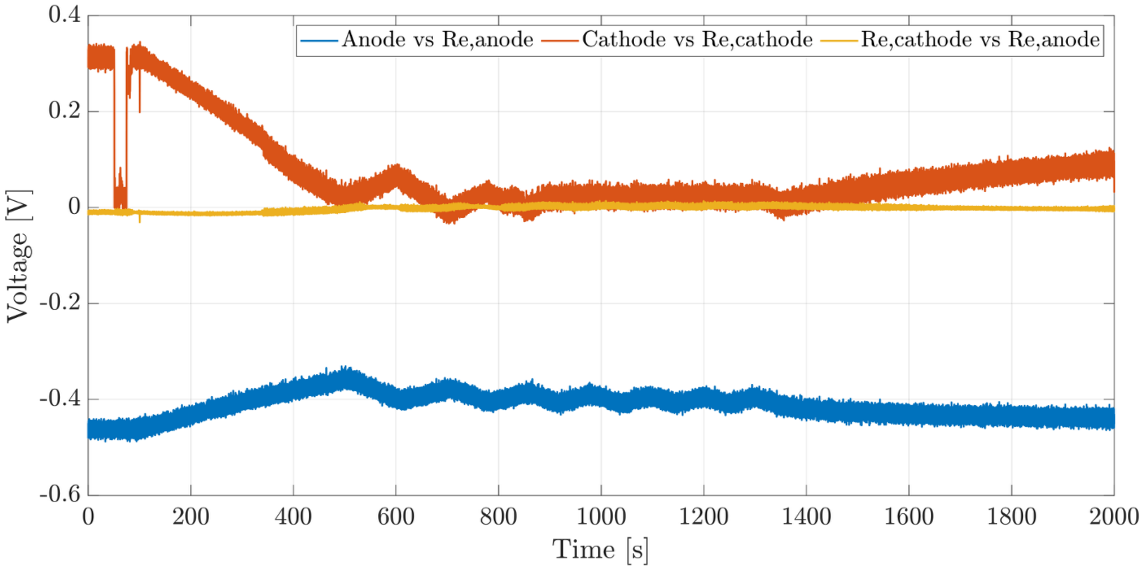


Figure 25. Relationship among the configurations.

4.1.1.2. T3 – Exp 1 – Test 2 - Two-Electrode EIS Characterization

The objective of this experiment is to evaluate the impedance response of the P-MFC using a two-electrode configuration and assess its suitability for biosensing applications. The experiment aims to:

- analyse how impedance spectra vary with polarization,
- evaluate the sensitivity of the system to operating conditions,
- identify limitations in distinguishing electrode contributions.

Table 7. T3 – Exp 1 – Test 2 -Subtests

Tests	Description
T3 – Exp 1 – T2 – Subtest 1 Polarization Sweep	Perform EIS at different polarization points (OCV to OCV – 0.4 V).
T3 – Exp 1 – T2 – Subtest 2 Global Impedance Analysis	Analyse overall cell impedance behaviour.
T3 – Exp 1 – T3 – Subtest 3 Electrode Contribution Assessment	Evaluate ability to distinguish anode and cathode contributions.

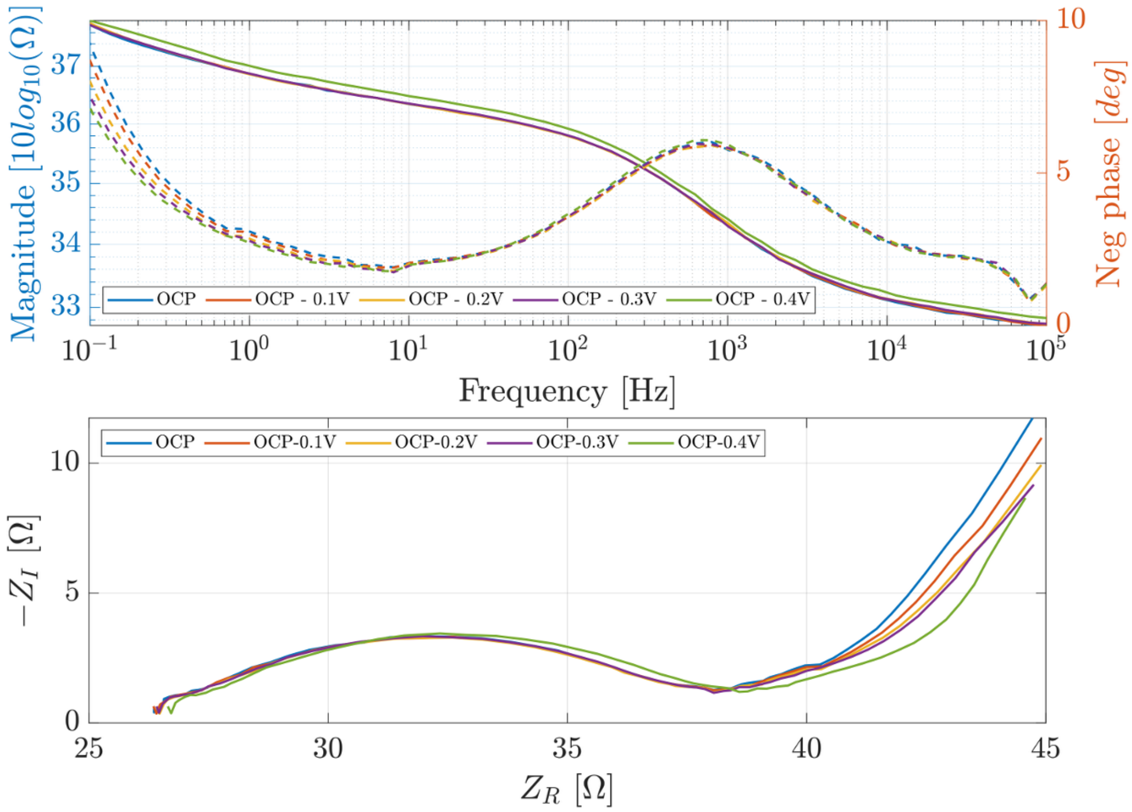


Figure 26. Two-electrode EIS under varying DC polarization points. Although polarization point effect is visible, it is impossible to discriminate anode and cathode impedance contributions.

a. *T3 – Exp 1 – Test 2 – Subtest 1 - Polarization Sweep*

Setup

Electrochemical Impedance Spectroscopy (EIS) measurements performed on the P-MFC using the PalmSens4 interface in a two-electrode configuration (anode–cathode), applying different DC polarization points (OCV to OCV – 0.4 V) with a superimposed AC perturbation (5–10 mV) over a frequency range of 100 kHz to 10 mHz.

Results

Nyquist plots show clear variation in impedance spectra with polarization.

Analysis

The impedance response is strongly dependent on operating conditions, confirming sensitivity to electrochemical state and biological activity.

b. T3 – Exp 1 – Test 2 – Subtest 2 - Global Impedance Analysis

Setup

Electrochemical Impedance Spectroscopy (EIS) measurements performed on the P-MFC using the PalmSens4 interface in a two-electrode configuration, acquiring the full impedance spectrum over a frequency range of 100 kHz to 10 mHz with an AC perturbation of 5–10 mV.

Results

Typical two-arc Nyquist behaviour observed, with high-frequency noise at higher frequencies.

Analysis

The observed spectrum reflects combined contributions of anode and cathode processes, as well as diffusion effects within the system.

a. T3 – Exp 1 – Test 3 – Subtest 3 - Electrode Contribution Assessment

Setup

Comparison of impedance spectra across polarization points in two-electrode configuration.

Results

Changes in impedance are visible, but electrode contributions cannot be separated.

Analysis

Two-electrode EIS is insufficient for biosensing purposes, as it does not allow discrimination between anode and cathode behaviour.

4.1.1.3. T3 – Exp 1 – Test 3 - Three-Electrode EIS Characterization

The objective of this experiment is to perform electrode-level impedance analysis using a three-electrode configuration, enabling separation of anode and cathode contributions.

The experiment aims to:

- isolate electrode-specific behaviour,
- analyse the impact of polarization on each electrode,
- improve the interpretability of impedance data for biosensing.

Table 8. T3 – Exp 1 – Test 3 -Subtests

Tests	Description
T3 – Exp 1 – T3 – Subtest 1 Anode EIS Analysis	Perform EIS on anode using reference electrode.
T3 – Exp 1 – T3 – Subtest 2 Cathode EIS Analysis	Perform EIS on cathode using reference electrode.
T3 – Exp 1 – T3 – Subtest 3 Electrode Comparison	Compare anode and cathode responses.

a. *T3 – Exp 1 – Test 3 – Subtest 1 - Anode EIS Analysis*

Setup

Electrochemical Impedance Spectroscopy (EIS) measurements performed using a three-electrode configuration, with the anode as working electrode (WE), the cathode as counter electrode (CE), and an Ag/AgCl reference electrode positioned near the anode.

Results

Lower impedance values and clear polarization-dependent shift in the low-frequency region.

Analysis

The anode shows distinct electrochemical behaviour, influenced by microbial activity and diffusion processes.

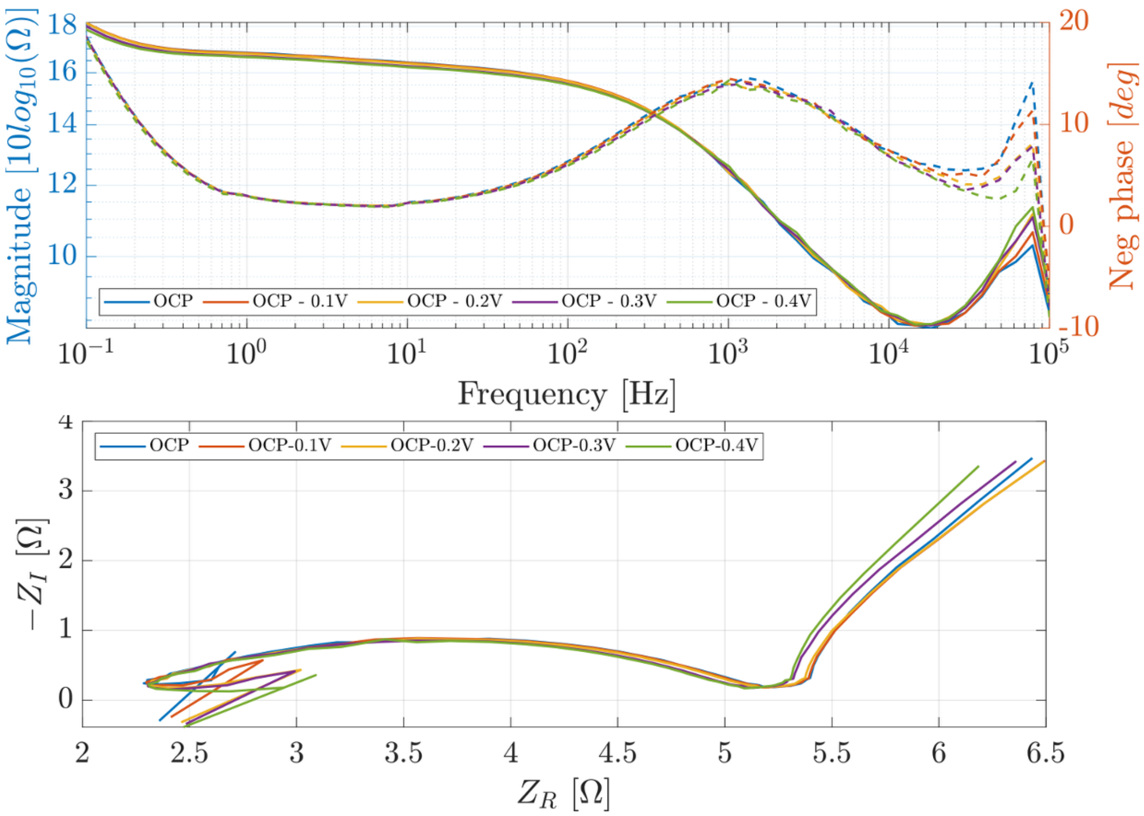


Figure 27. Three-electrode EIS under varying DC polarization points. The working electrode is the anode.

b. T3 – Exp 1 – Test 3 – Subtest 2 - Cathode EIS Analysis

Setup

Electrochemical Impedance Spectroscopy (EIS) measurements performed using a three-electrode configuration, with the cathode as working electrode (WE), the anode as counter electrode (CE), and an Ag/AgCl reference electrode positioned near the cathode.

Results

Higher impedance values and significant changes in the high-frequency arc and diffusion branch.

Analysis

The cathode exhibits stronger limitations and higher resistance, confirming its dominant role in limiting system performance.

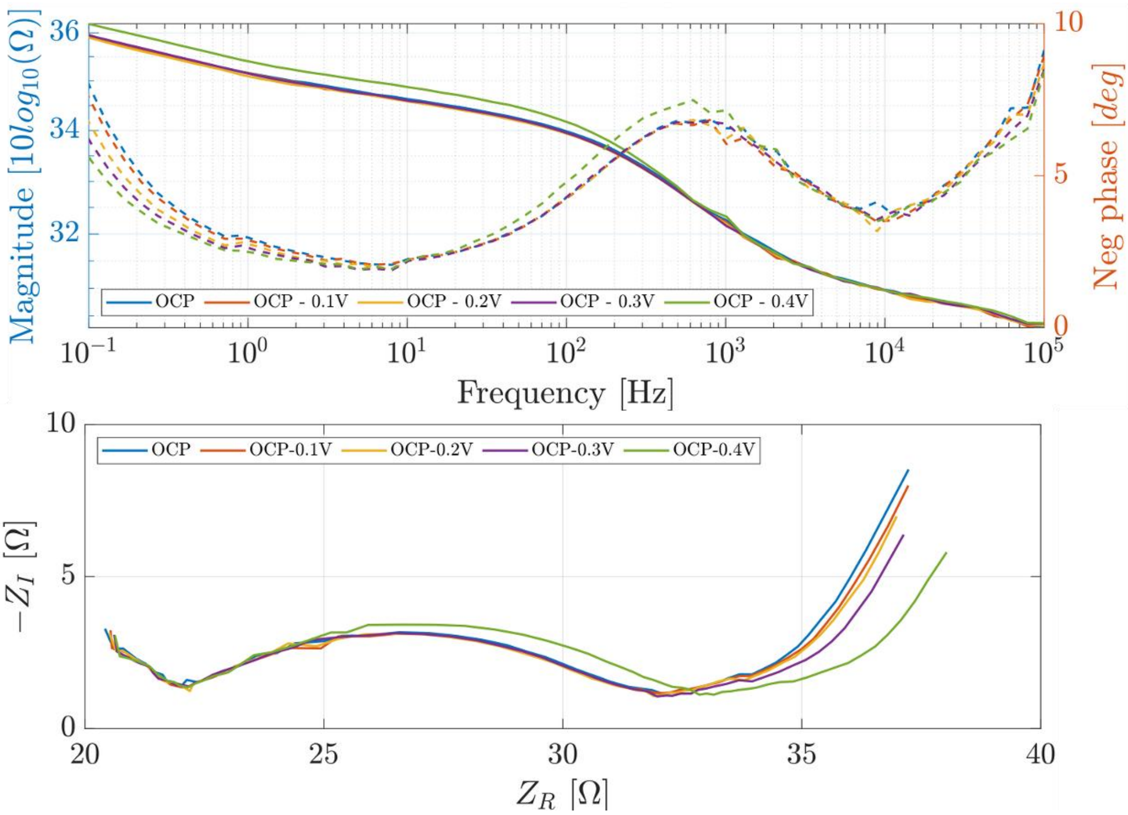


Figure 28. Three-electrode EIS under varying DC polarization points. The working electrode is the cathode.

c. T3 – Exp 1 – Test 3 – Subtest 3 - Electrode Comparison

Setup

Electrochemical Impedance Spectroscopy (EIS) measurements performed in three-electrode configuration for both anode and cathode, enabling direct comparison of electrode-specific impedance spectra under the same operating conditions.

Results

Different shapes and magnitudes observed between the two electrodes.

Analysis

Three-electrode configuration enables clear separation of electrode contributions, which is essential for accurate biosensing interpretation.

4.1.1.4. T3 – Exp 1 – Test 4 - Polarization Stability Assessment

The objective of this experiment is to identify stable operating conditions for EIS measurements and evaluate compatibility with energy harvesting operation.

The experiment aims to:

- analyse electrode stability over time,
- evaluate drift under different polarization points,
- determine optimal operating conditions for combined sensing and energy harvesting.

Table 9. T3 – Exp 1 – Test 4 -Subtests

Tests	Description
T3 – Exp 1 – T4 – Subtest 1 Time Stability Analysis	Monitor electrode behaviour over time under different polarization points.
T3 – Exp 1 – T4 – Subtest 2 Stable Operating Point Identification	Identify polarization points ensuring stable measurements.
T3 – Exp 1 – T4 – Subtest 3 Energy Compatibility Assessment	Evaluate compatibility between sensing and energy harvesting.

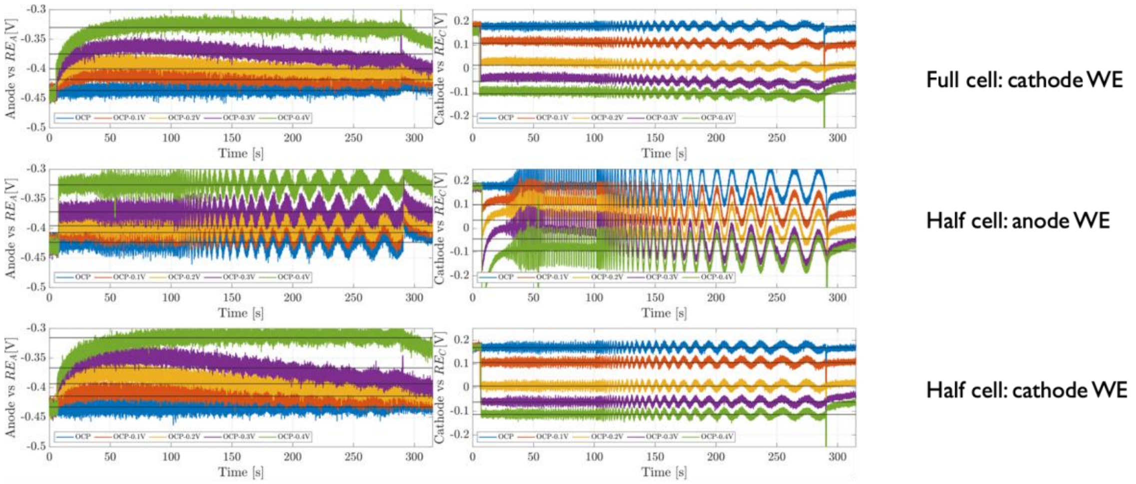


Figure 29. Time development of anode (left) and cathode (right) during two-electrode tests (top), three-electrode tests on anode (middle) and cathode (bottom). The counter electrodes drift less at OCV and at OCV – 0.4 V.

a. *T3 – Exp 1 – Test 4 – Subtest 1 - Time Stability Analysis*

Setup

Electrochemical Impedance Spectroscopy (EIS) measurements performed using the PalmSens4 interface under different DC polarization points, monitoring electrode potentials over time to evaluate stability and drift.

Results

Drift observed in most polarization conditions.

Analysis

Unstable polarization points lead to DC polarization variations across time, reducing measurement reliability. As it can be seen from Figure 29, while the working electrode is effectively controlled by the potentiostatic setpoint, the counter electrode (anode for the top/bottom image, cathode for the middle image) drifts in all cases except for OCV and OCV-0.4 polarization points.

b. T3 – Exp 1 – Test 4 – Subtest 2 - Stable Operating Point Identification

Setup

Electrochemical Impedance Spectroscopy (EIS) measurements performed at multiple polarization levels (OCV to OCV – 0.4 V) to evaluate impedance stability and identify reproducible operating conditions.

Results

Stable conditions observed only at OCV and OCV – 0.4 V.

Analysis

Only specific operating points, namely OCV and OCV – 0.4 V, ensure reproducible measurements, highlighting the importance of correct bias selection.

4.2. T3 - Discussion and Key findings

Discussion

The results obtained in Task Force 3 confirm that the electrochemical behaviour of the Plant-Microbial Fuel Cell (P-MFC) can be effectively used as a source of biosensing information related to plant–soil conditions.

In alignment with the WP1 hypothesis on plant impedance signals, the experiments demonstrate that impedance spectra are strongly influenced by electrochemical processes occurring at the electrode–soil–microbe interface. Variations in impedance response with polarization confirm that the system is sensitive to internal biological and environmental conditions, supporting the feasibility of electrochemical biosensing.

Compared to WP2 results, the experimental campaign provides a deeper understanding of how these signals can be reliably measured and interpreted. In particular, the use of three-electrode EIS enables the separation of anode and cathode contributions, which was not achievable with simpler configurations. This represents a key step toward extracting meaningful and interpretable features from the system.

However, several limitations have been identified. First, the system exhibits significant transient behaviour after reconnection due to capacitive effects, requiring a stabilization phase before measurements. Second, two-electrode configurations are insufficient for detailed biosensing analysis, limiting their applicability in simplified or embedded systems. Third, the stability of impedance measurements strongly depends on the selected polarization point, with only specific operating conditions (OCV and OCV – 0.4 V) ensuring reproducibility.

Despite these limitations, the results have important implications for the PoC design. The identification of a stable operating point compatible with both sensing and energy harvesting demonstrates the feasibility of integrating dual-function operation within a single P-MFC system. This is a critical requirement for low-power, autonomous deployments. Furthermore, the ability to isolate electrode-specific behaviour opens the possibility of defining electrochemical features that can be used in a data-driven plant-state estimation framework.

Overall, Task Force 3 establishes a validated experimental basis for using P-MFCs as living biosensors within EcoSentinel, while also highlighting the constraints that must be addressed for system integration and scalability.

Key findings

- **Finding 1:** Electrochemical impedance of P-MFCs is strongly influenced by biological and soil-related processes, confirming its suitability as a biosensing signal.
- **Finding 2:** Two-electrode EIS is insufficient to distinguish anode and cathode contributions, limiting its effectiveness for accurate biosensing.
- **Finding 3:** Three-electrode EIS enables clear separation of electrode behaviours, allowing more reliable interpretation of electrochemical signals.
- **Finding 4:** The cathode is identified as the limiting electrode in the current configuration, significantly influencing overall system performance.
- **Finding 5:** Stable and reproducible measurements are achievable only at specific polarization points (OCV and OCV – 0.4 V).
- **Finding 6:** The operating point at OCV – 0.4 V allows simultaneous energy harvesting and biosensing, enabling practical implementation in the PoC.

5. [PoC_v1] Proof-of-Concept (v1)

This section presents the results obtained from the first EcoSentinel Proof-of-Concept (PoC_v1), which integrates the components developed across the EcoSentinel task forces (T1, T2 and T3).

The experiments described in this section correspond to the initial integration of these subsystems into a functional EcoSentinel node and their validation in a point-to-point communication scenario.

The results presented here reflect the **first joint experimental effort across all partners**, consolidating previous individual experiments into a unified system-level validation.

Diagram

Figure 30. EcoSentinel PoC_v1 deployment diagram

5.1. PoC_v1 - Experiments

List of experiments

- **PoC_v1 – Exp 1 – End Device Connectivity Validation**
    - Short-term (below 12 hours) validation of EcoSentinel node-to-node connectivity under controlled indoor conditions.

5.1.1. PoC_v1 - Experiment 1 - End Device Connectivity Validation

This experiment assesses the performance of the EcoSentinel prototype in a point-to-point configuration at distances of 2 m and 4 m, using Aloe plant leaves as transmission and reception elements.

The objective is to verify the correct operation of the integrated system, including energy harvesting, wireless communication, and data visualization, under controlled indoor conditions.

The experiment also evaluates the behaviour of the communication link with increasing distance, considering the constraints imposed by the plant-based propagation medium.

This activity supports the validation of the EcoSentinel communication approach and contributes to the assessment of PoC_v1 – KPI1 (functional system operation).

Table 10. PoC_v1 – Exp 1 - Tests

Tests	Description
PoC_v1 – Exp1 – Test 1 **2 meters transmission**	The end device transmits data to the gateway at 2 m and 4 m (line-of-sight). Reception and data visualization are verified, demonstrating functional system operation under short-range conditions.
PoC_v1 – Exp1 – Test 1 **4 meters transmission**	

5.1.1.1. *PoC_v1 – Exp 1 – Test 1& 2 2- and 4-meters transmission*

Setup

Figure 31. EcoSentinel node deployed for PoC_v1

Figure 32. EcoSentinel gateway deployed for PoC_v1

Figure 33. Extended view of the whole setup for EcoSentinel's PoC_v1 at UniCA. The dashboard with data reception can be seen in the smart screens.

Table 11 summarizes the performance of the first EcoSentinel PoC against the established objectives (PoC_v1 – O1).

Table 11. PoC_v1 KPI information

KPI	Objective Description	Experimental Result Obtained	Status
KPI1	Functional validation of the EcoSentinel prototype node, including self-sustained operation, communication, and data visualization	Under the condition of the supercapacitor fully charged, the system successfully demonstrated a self-sustained node capable of continuous data exchange at 1 frame/sec over a 2-hour period. The P-MFC continuously delivered energy to the node, although during the test with high-frequency messaging, most energy came from the storage of the supercapacitor throughout the tests, and successful data reception and visualization were achieved at the gateway.	**Achieved**

The results in Table 6 confirm the successful functional validation of the EcoSentinel PoC_v1. The system demonstrated stable operation, enabling continuous data transmission and reception under controlled conditions, and supporting further analysis through the extraction of relevant Figures of Merit (FoM).

System Operation and Transmission Performance

Starting with a supercapacitor of 10 Farads fully charged, the EcoSentinel node (end device side) successfully executed transmissions at a frequency of 1 frame of 10 bytes per second using a transmission power of 14 dBm, demonstrating successful operation (correct data readings and no frames missed) over a continuous 2-hour period.

These results confirm that the feasibility of the proposed plant-to-plant communication systems approach.

Further experiments are required in order to (1) confirm the sustainability of the system in extended periods of time, (2) assessing the balance of the energy spent vs the energy harvested from the P-MFC, and (3) define the operation of the microcontroller according to the energy available in the supercapacitor considering the non-lineal voltage curve that hybrid supercapacitors exhibit.

This behaviour represents a key milestone, as it validates the stability of the EcoSentinel prototype and enables further analysis through the extraction of Figures of Merit (FoM), such as transmission performance under varying energy constraints.

Figures of Merit:

- Duration of the communication: 2 hours
- Packets per second: 1 packet per second
- Packets sent during the communication: 7.200 packets
- Base RSSI: -40 dBm
- Deep sleep consumption: 150 uA
- Consumption per packet sent: 3 mA
- Hybrid supercapacitor voltage rating: 2.5 V – 3.8 V

Dashboard Data Interpretation

The real-time data captured in Serial Studio provides insight into both the node's sensor readings and the system's operational behaviour.

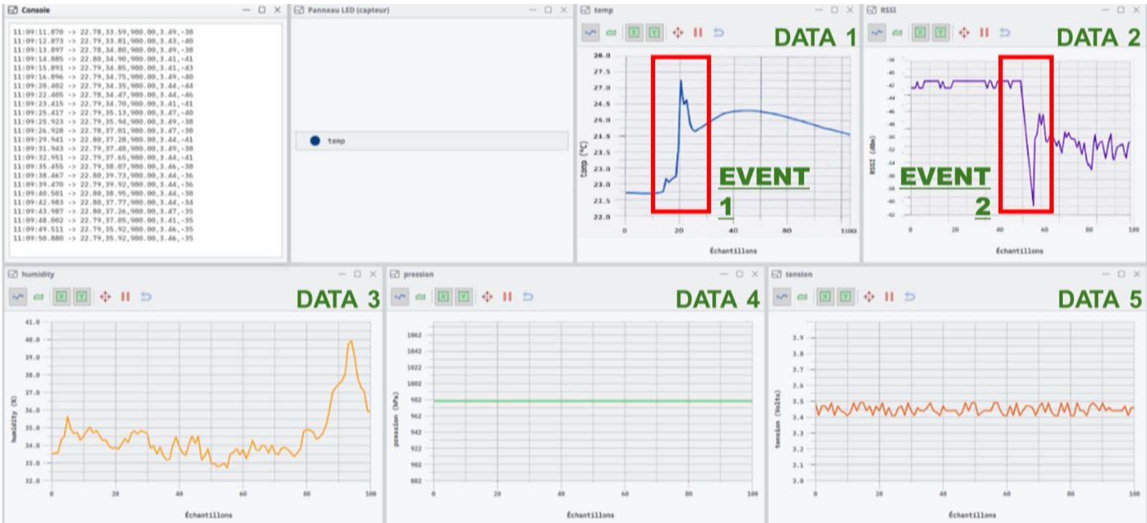


Figure 34. Real-time data visualization (Serial Studio) for the EcoSentinel PoC_v1 validation

Two controlled events were introduced to evaluate system responsiveness to environmental and operational changes:

- **Event 1:** Exposure of the temperature sensor to a localized heat source (flame)
- **Event 2:** Increase of the distance between the two nodes

Environmental data collected:

- **Temperature** (temp): The temperature readings remained stable around 22.5°C. A brief exposure of the sensor to a localized heat source (flame) was then introduced to test system responsiveness, resulting in an increase to approximately 27°C. The system successfully detected and visualized this variation in real time.
- **Humidity**: Humidity levels were observed between 33% and 40%, with visible variations reflecting sensitivity to local environmental changes around the plant.
- **Pressure** (pression): This metric remained constant at 980 hPa, serving as a control variable during the indoor tests.

System data:

- **RSSI** (Received Signal Strength Indicator): The signal quality exhibited two distinct phases. At 2 m distance, RSSI remained stable at approximately -40 dBm. When the distance increased to 4 m, RSSI decreased to approximately -52 dBm. This behaviour is consistent with expected indoor line-of-sight propagation and remained within a reliable communication range.
- **Voltage** (of the hybrid supercapacitor, indicating how much energy is available in storage): Voltage remained stable between 3.4 V and 3.5 V. The observed subtle sawtooth pattern reflects the periodic charging and discharging of the supercapacitor during transmission cycles, confirming that the P-MFC energy harvesting system continuously meets the power demand.
-

Significance of Results

The results obtained demonstrate the feasibility of integrating plant-based energy harvesting, communication, and sensing into a single functional EcoSentinel node. The system showed stable operation under controlled conditions, confirming that bio-harvested energy can sustain continuous data transmission and real-time monitoring.

5.2. PoC_v1 - Discussion and Key findings

The results obtained from PoC_v1 demonstrate the successful functional integration of the EcoSentinel system under controlled conditions. The combination of plant-based energy harvesting, plant-assisted antenna propagation, and ultra-low-power communication enabled stable operation and continuous data exchange between nodes.

The system maintained reliable communication over short distances (2 m and 4 m), with signal behaviour consistent with expected indoor propagation trends. The observed RSSI degradation remained within acceptable limits, confirming the viability of Aloe-assisted transmission and reception in a point-to-point configuration. These results provide a baseline for future experimentation at longer distances and under more complex channel conditions, including outdoor environments and varying environmental factors.

From an energy perspective, the P-MFC provided sufficient power to sustain continuous operation at 1 frame per second, with stable voltage levels and predictable charge–discharge cycles. This confirms the feasibility of bio-harvested energy as a power source for low-duty-cycle communication systems.

The system also demonstrated the capability to capture and visualize environmental variations in real time, validating the integration of sensing and communication functionalities within the same platform.

Key findings include:

- Successful functional validation of the EcoSentinel PoC_v1 prototype
- Stable energy supply from the P-MFC enabling continuous operation
- Reliable short-range communication using plant-assisted antenna systems
- Consistent RSSI behaviour with increasing distance
- Effective real-time data acquisition and visualization

These findings confirm the viability of the EcoSentinel concept at the prototype level and provide a solid basis for further experimentation, system optimization, and progression to the next development cycle.

6. Conclusions and next steps

Deliverable D3.3 presents the successful implementation and validation of the first EcoSentinel Proof-of-Concept (PoC_v1), marking the completion of the project's first development cycle. By integrating the outcomes of WP1 (theoretical foundations) and WP2 (experimental validation), this work demonstrates the feasibility of a plant-based, self-powered sensing node capable of combining energy harvesting, communication, and biosensing functionalities within a unified system.

The results obtained across the three Task Forces confirm the core hypotheses of the EcoSentinel concept:

- **Plants as Antennas (T1):**

  The experimental evaluation shows that plant species and their functional traits have a measurable impact on antenna performance. This validates the concept of using plants as active components in RF systems and highlights the importance of plant selection and trait characterization for optimizing electromagnetic behaviour.

- **Plants as Energy Sources + Communication Systems (T2):**

  The integration of P-MFCs with ultra-low-power electronics demonstrates that bio-harvested energy can sustain sensing and wireless communication tasks. The system successfully operates under strict energy constraints, confirming the viability of plant-powered IoT nodes.

- **Plants as Biosensors (T3):**

  The results confirm that electrical and electrochemical signals derived from plant–soil systems can be used to infer plant and environmental status. This supports the development of plant-based biosensing and lays the groundwork for digital-twin–like modelling.

At system level, the PoC_v1 demonstrates **end-to-end functionality**, including energy harvesting, sensing, data transmission, and real-time monitoring. The achieved continuous operation and stable communication validate the integration strategy defined in D3.1 and implemented in D3.2.

6.1. Key Limitations and Challenges

Despite the successful validation, several limitations were identified:

- **Energy variability:**

  The power output of P-MFCs remains low and strongly dependent on environmental conditions, affecting system stability and duty cycles.

- **System robustness:**

  Variability in plant physiology and environmental factors introduces fluctuations in performance, particularly in antenna behaviour and biosensing signals.

- **Integration complexity:**

  Coupling biological systems with electronic components requires careful calibration and introduces constraints in reproducibility and scalability.

- **Limited optimisation stage:**

  The current PoC represents a first integration (alpha version), where trade-offs between energy, communication, and sensing have not yet been fully optimised.

These challenges define the main areas for improvement in the next phase of the project.

6.2. Next Steps (Cycle 2)

Building on the insights gained from PoC_v1, the next development cycle will focus on **system optimisation, robustness, and scalability**:

- **Energy subsystem optimisation (PaES):**
  - Improve P-MFC design for higher and more stable power output
  - Optimize water retention, substrate composition, and electrode configuration
  - Protection from roots
  - Enhance energy storage and power management strategies
- **Communication system enhancement (PaCS):**
  - Refine ultra-low-power communication protocols (wake-up radio, duty cycling, modulations)
  - Improve reliability, range, and packet efficiency under real conditions
  - Explore multi-hop and more resilient network topologies
- **Antenna–plant co-design (PaA):**
  - Identify optimal plant species and traits for RF performance
  - Improve antenna integration and placement strategies
  - Develop predictive models linking plant traits to EM behaviour
- **Biosensing and data modelling (PaB):**
  - Strengthen correlations between electrical signals and plant physiological states
  - Develop data-driven models and digital-twin approaches

   - Integrate multi-modal sensing (RF + electrochemical + environmental data)

- **System-level improvements:**
   - Increase robustness and repeatability of the PoC
   - Focus on the Figures of Merit
   - Move towards semi-field deployment conditions

6.3. Transition to Future Work

The results presented in D3.3 establish a solid foundation for the evolution of EcoSentinel from a proof-of-concept to a more mature and deployable system.

The next phase will focus on transforming the validated concepts into **scalable, reliable, and field-ready solutions**, enabling broader applications in environmental monitoring, precision agriculture, and sustainable IoT infrastructures.

Ultimately, the project advances toward its long-term vision of **integrating living plants into digital ecosystems**, where biological and technological systems coexist and interact to enable sustainable sensing, communication, and energy generation.

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Abbreviations

Acronym	Description
AC	Alternating Current
Ag/AgCl	Silver/Silver Chloride electrode
AV	Aloe vera
CAM	Crassulacean Acid Metabolism
CC	Chlorophytum comosum
CE	Counter Electrode
CO	Calendula officinalis
CRC	Cyclic Redundancy Check
CV	Cyclic Voltammetry
D1.1	Deliverable 1.1
D3.1	Deliverable 3.1
D3.2	Deliverable 3.2
D3.3	Deliverable 3.3
DC	Direct Current
dB	Decibel
dBm	Decibel-milliwatts
DT	Dracaena trifasciata
EC	European Commission
EIS	Electrochemical Impedance Spectroscopy
EU	European Union
FB	Ficus benjamina
FoM	Figures of Merit
GHz	Gigahertz
IoT	Internet of Things
kHz	Kilohertz
KPI1	Key Performance Indicator 1
KPI2	Key Performance Indicator 2
LA	Lavandula angustifolia
mA	milliampere
MCU	Microcontroller Unit
MHz	Megahertz

mHz	Millihertz
MM	Monstera minima
mV	millivolt
µA	microampere
µW	microwatt
OCV	Open Circuit Voltage
OJIP	Chlorophyll fluorescence transient phases (O-J-I-P)
P-MFC	Plant-Microbial Fuel Cell
PaA	Plants as Antenna
PaB	Plants as Biosensor
PaCS	Plants as Communication System
PaES	Plants as Energy Source
PCB	Printed Circuit Board
PC	Personal Computer
PER	Packet Error Rate
PoC	Proof-of-Concept
PoC_v1	Proof-of-Concept version 1
PSII	Photosystem II
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
RTC	Real-Time Clock
T1	Task Force 1
T2	Task Force 2
T3	Task Force 3
TX	Task Force (generic reference)
UniCA	University of Cote d'Azur
WE	Working Electrode
WP1	Work Package 1

EcoSentinel

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Plant-e living plants generate electricity

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