EcoSentinel

D3.1 – Design of the EcoSentinel PoC (v1)

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Plant-e living plants generate electricity

European Innovation Council

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V0.1	13/01/2026	Table of Contents (preliminary) + Brainstorming
V0.2	25/02/2026	Task forces and PoC sections
V0.Draft	31/03/2026	Task forces + PoC integrated in the same document
vFinal	13/04/2026	Last modifications

Executive Summary

Deliverable D3.1 presents the **design of the EcoSentinel Proof-of-Concept (PoC)**, marking the transition from validated concepts and experimental results (WP1–WP2) to a **system-level integration framework**. Rather than demonstrating performance, this deliverable defines how previously developed components are **architecturally combined, interfaced, and prepared for integration** into a unified plant-based node.

The EcoSentinel PoC design is structured around **three complementary task forces**, each addressing a key functional subsystem:

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

  This task force focuses on the design of the interaction between plant traits and antenna boosters. It defines how plant morphological and physiological properties can be leveraged within antenna systems, and establishes the parameters, configurations, and experimental plans required to assess their influence on radiation performance.

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

  Task Force 2 defines the integration of Plant-Microbial Fuel Cells (P-MFCs) with ultra-low-power communication systems. It outlines the architecture required to couple bio-harvested energy with electronic components, specifying system constraints, communication strategies, and energy-aware design principles for autonomous plant-powered nodes.

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

  This task force establishes the design of a biosensing framework based on plant responses. It specifies how environmental and bioelectrical measurements can be structured into a dataset and used to develop a simplified digital-twin–like model, enabling the interpretation of plant physiological status.

These three task forces converge into the **PoC_v1 design**, which defines the integration of:

- plant-assisted antenna systems,
- bio-harvested energy modules (P-MFC),
- sensing and ultra-low-power communication electronics.

The PoC is therefore conceived as a **self-powered plant-based sensing node architecture**, where energy harvesting, sensing, and communication functionalities are coherently combined at design level. This deliverable specifies the overall system architecture, integration logic, interfaces, Key Performance Indicators (KPIs), and experimental planning required for subsequent phases.

It is important to note that **D3.1** focuses on the system-level design and integration strategy, while:

- **D3.2** provides the detailed description of the individual elements and components, and
- **D3.3** presents the implementation, validation, and results of the PoC.

1. Introduction

The goal of this document is to present the design of the first EcoSentinel Proof-of-Concept (PoC). The EcoSentinel PoC is going to be composed by the different components conceptualized, created, and tested during the *WP1 – Theoretical Foundations on Plants Digitalization* and the *WP2 – Experiments on Plants Digitalization*.

In this document, different prototyped components are combined gradually (Task Forces) to test its integration and validate its performance. Finally, all the components are integrated to compose the first alpha version of the Proof-of-Concept (PoC) of the EcoSentinel node.

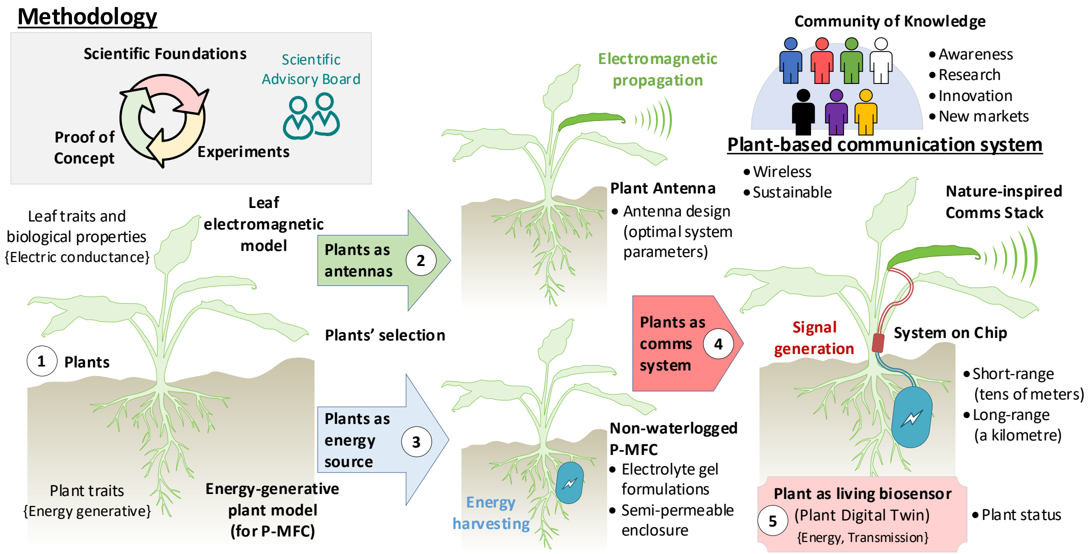

Figure 1. EcoSentinel Reference Components

The following **task forces [*TX*]** considered (considering the reference components from Figure 1):

***[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 the feasibility of a self-powered plant-based sensing node where energy harvested from a Plant-Microbial Fuel Cell (P-MFC) powers an EcoSentinel 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.

First, the three defined task forces [T1 – T2 – T3] are explained in detail. After explaining the integration of the different components, the [PoC_v1] is also explained.

2. Tasksforces

In this section, the **three task forces** [*TX*] are defined, depicting the **components** that integrates them, the **Objective/s** of the integration [*TX – OX*], the Key Performance Indicators (**KPIs**) [*TX – KPIX*] and the **Experiments plan** to be performed and the expected result.

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

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

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

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

- **Reason**: to assess the interaction between plant and antenna booster, and to identify plant species and associated functional traits that maximize radiation transmission potential.
- **Elements**:
  - **Element 1**: Antenna booster with specific matching for optimum radiation performance in free space and for placement on *Aloe Vera* plant.
  - **Element 2**: Set of plants with different morphological, physical, and physiological functional traits: *Lavandula angustifolia* (lavender), *Ficus benjamina* (ficus or Benjamin tree), *Calendula officinalis* (marigold), *Chlorophytum comosum* (spider plant), *Dracaena trifasciata* (sansevieria), *Monstera minima* (mini monstera), *Aloe vera* (true aloe).
- **Diagram**

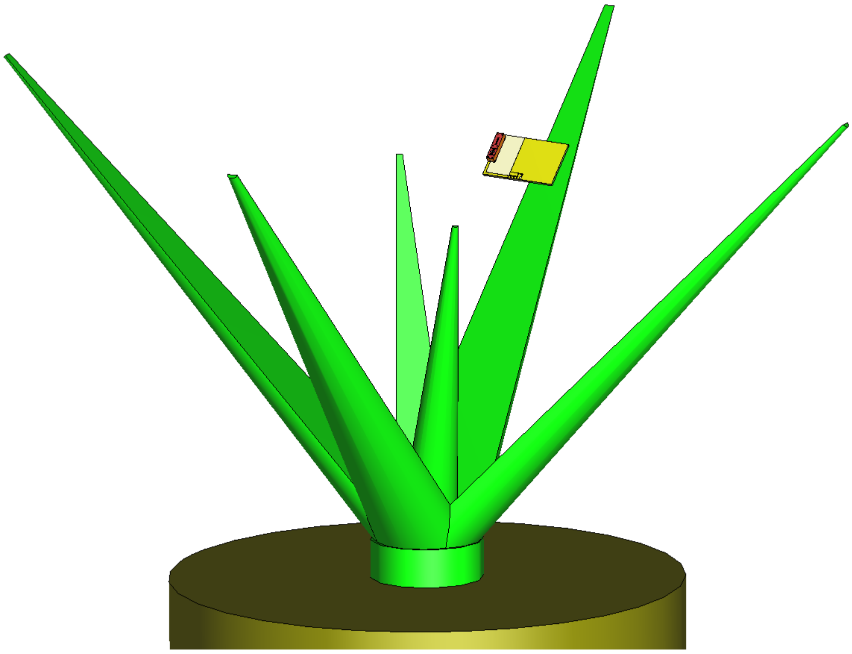

Figure 2. T1 - Schematic view of Antenna booster placed on Aloe vera leaf.

- **Objectives**:
    - ***T1 – O1***: Assess overall plant health through measurement of photosynthetic efficiency.
    - ***T1 – O2***: Measure the radiation efficiency of the antenna booster placed on various plant species with different physical, physiological, and morphological traits and evaluate the plants' effect on radiation efficiency of the antenna booster.
- **KPIs**:
    - ***T1 – KPI1***: Leaf EM model with +10 parameters related to traits and biological properties, considering +3 different frequencies, highlighting those parameters (at least 3) that improve the most EM antenna performance.
    - ***T1 – KPI2***: Identify a minimum of 10 viable plant species that enhance antenna bandwidth and efficiency under lab environment. Additionally, at least 1 plant species should demonstrate the capability to double the antenna bandwidth and improve efficiency by 3 dB.

2.1.1.1. T1 Experiments plan

<u>T1 - Experiment 1: Photosynthetic efficiency</u>

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.

Goal

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 α* fluorescence and OJIP kinetics. OJIP stands for Origin, J-step, I-step, and Peak, describing the successive stages of chlorophyll fluorescence increase that reflect the progressive closure of PSII reaction centers during the onset of photosynthesis. It reflects the functional state of the photosynthetic apparatus.

How

When plants experience stress—such as drought, waterlogging, nutrient deficiency, extreme temperature, or light imbalance—the first detectable alterations often occur in the electron transport chain of PSII. These changes are reflected in modifications of fluorescence parameters and in the shape of the

OJIP curve, making photosynthetic efficiency a reliable indicator of physiological performance and plant vitality.

The experiment will be conducted under homogeneous environmental conditions to minimize external stress factors. The fluorescent signal will subsequently be assessed. Plants under stress will be discarded prior to measurement, ensuring that differences in photosynthetic efficiency among the tested species mainly reflect intrinsic species response rather than environmental stress.

Chlorophyll α fluorescence will be analysed by recording OJIP fluorescence induction curves.

Where

Côte d'Azur University (Nice, France) – Indoor controlled environment.

Expected Result

All the tested plants should present a functional photosynthetic apparatus under the tested conditions which is represented by typical OJIP pattern and key parameters (e.g., Fv/Fm; PI, etc).

Needs / Risks

For this experiment, we will need plant species with different trait syndromes (i.e., a recurrent set of functionally related traits that co-vary within or across species, reflecting common ecological strategies or adaptations to specific environmental conditions) such as water content, size and thickness of leaves, number of leaves, presence of cuticle, waxes and trichomes, pigmentation, metabolic traits, *etc*.
The Photosynthetic Efficiency Analyzer HANDY-PEA will be used for evaluation of the overall plants' health. Measurement will be performed on 20 leaves for each species, randomly selected.

- **Tests under T1 - Experiment 1**

Table 1. T1 – *Experiment 1 – Test List*

Test #	Title	Description	KPI link	Expected results
1	Photosynthetic efficiency	All plants subjected to measurement for antenna radiation efficiency were evaluated for their photosynthetic efficiency.	**KPI2** Validation support of plant species that enhance antenna performance.	Control of plant health confirmed through photosynthetic efficiency.

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.

Goal

We will test different combinations of plant species and antenna boosters, selecting plants that vary in key physical, morphological, and physiological traits, such as leaf water content, ionic composition of aqueous tissues, leaf number, and size, to assess their influence on system performance.

The aim is to demonstrate that certain plants can enhance antenna efficiency by up to 3 dB and to identify plant species, as well as the associated morphological, physical, and physiological traits, responsible for this improvement.

How

Different plants are selected for the radiation efficiency evaluation where the antenna booster is placed on different selected positions of each plant and measured in UniCA's 3D scanning anechoic system.

The antenna measurement system at UniCA has a specificity of using an RF-optical transducer, avoiding the antenna elongation effect by the measurement coaxial cable that usually introduces a measurement error.

Where

Côte d'Azur University (Nice, France) – Indoor controlled environment.

Expected Result

This comparative experiment is expected to allow the identification of the morphological, physical, and physiological characteristics of plant species that enhance radiation efficiency, as well as the quantification of the extent to which efficiency can be improved for a given plant species.

Needs / Risks

For this experiment, we will need various plant species, with different traits such as water content, size and thickness of the leaves, number of leaves etc.

Measurement facility for radiation efficiency measurement at UniCA.

- **Tests under T1 - Experiment 2**

***Table 2. T1 –** Experiment 2 – Test List*

Test #	Title	Description	KPI link	Expected results
1	Antenna booster position along a leaf	Antenna booster is placed in different positions of *Aloe vera* leaf, and the radiation efficiency is measured.	**KPI1** Identifying key leaf EM parameters influencing antenna efficiency across frequencies.	Antenna placement in different positions along *Aloe vera* leaf presents different levels of radiation efficiency enhancement.
2	Antenna booster on plants	Radiation efficiency of antenna booster placed on different types of plants will be measured in a 3D scanning system.	**KPI2** Evaluating plant species that improve antenna bandwidth and efficiency	Identification of leaf traits that enhance the radiation efficiency of the antenna booster.

2.1.2. [T2] Task Force 2: Plant-Microbial Fuel Cell (3) – Comms system (4)

- **Reason**: 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.
- **Elements**:
  - **Element 1 – Plant system (energy host):** Plant pot with a spider plant (*Chlorophytum comosum*), used as the host environment for the P-MFC system.
  - **Element 2 – EcoSentinel PCB nodes (V0.4):** Two custom EcoSentinel PCBs integrating energy harvesting circuitry and communication software.
  - **Element 3 – 868 MHz SMA helical antenna:** Two 868 MHz helical antennas are connected to the EcoSentinel PCBs, providing wireless communication capability within the sub-GHz ISM band, and ensuring efficient RF signal transmission and reception.

  - **Element 4 – Data visualization system:** PC running Serial Studio (open-source software) to visualize received data (RSSI, packet reception, sensor metrics).

- **Diagram**

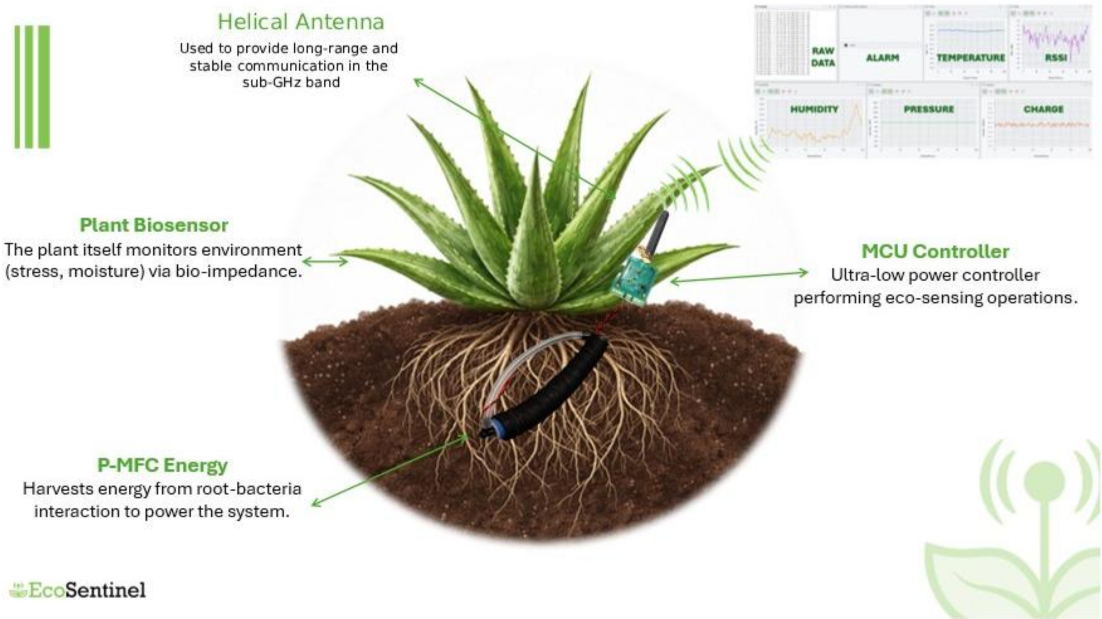

Figure 3. T2 - Schematic view of the P-MFC providing energy to the MCU and the signal transmission powered by the plant leaf.

- **Objectives**:
  - ***T2 – O1***: Demonstrate the feasibility of a P-MFC being capable of providing enough power to do relevant sensor measurements and transmit these wirelessly to a gateway.
- **KPIs**:
  - ***T2 – KPI1***: The storage element (10 F Hybrid supercapacitor) should be charged up within a controlled span of time (so it contains enough energy to do tens-hundreds of measurements and transmissions), showing that the P-MFC provides power and the energy-harvesting circuitry functions. Formally defined in D2.3 as “Targeting fully self-sustaining operation through bio-harvested energy at the microwatt scale and long-range communication.”
  - ***T2 – KPI2***: The quality of communication service must be evaluated based on the packet error rate (PER). Formally defined in D2.3 as “Communication quality of service will be evaluated with the Packet Error Rate (PER) versus distance, to assess the maximal communication distance with a PER lower than 0.1 %”.

2.1.2.1. T2 Experiments plan

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 should charge the supercapacitor in a few hours or even a few days.

Goal

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.

How

Two flowerpots containing soil, a plant and water-logged P-MFCs were connected to EcoSentinel PCBs equipped with an energy recovery circuit and a 10 F hybrid lithium supercapacitor with a leakage current of 0.001 mA (reference name: AHCR-S04R0S), initially lightly charged (voltage greater than or equal to 2.5 V).

The voltage of the supercapacitor was monitored with a voltmeter over time to determine how quickly the P-MFC could recharge the supercapacitor via the energy-harvesting circuit.

Where

Côte d'Azur University (Nice, France) – Indoor controlled environment.

Expected Result

If the P-MFC starts up properly (reaching a power above 300 uW), it should be able to charge the supercapacitor in a few hours to a few days.

Needs / Risks

The P-MFC is a (micro)biological system that depends on many external conditions such as temperature, but also microbial, organic, and chemical conditions in the soil, so there is always a risk that startup takes longer than expected or power output is lower than expected.

The energy-harvesting circuit should be well designed; it uses very high-ohmic resistors (up to 10 MΩ) to ensure ultra-low power consumption of the circuit, so there is a risk of malfunctioning when parasitic currents are too high.

Environmental dependency: P-MFC performance depends on temperature and microbial/chemical soil conditions.

Startup and power variability: The system may take longer to start or produce lower power than expected.

Circuit reliability risk: High-ohmic resistors (up to 10 MΩ) used for ultra-low power may be sensitive to parasitic currents, potentially causing malfunction.

- **Tests under T2 - Experiment 1**

Table 3. T2 – *Experiment 1 – Test List*

Test #	Title	Description	KPI link	Expected results
1	Monitoring supercap charging from P-MFC	A plant pot with a water-logged P-MFC was connected to a prototype PCB with a 10 F super-capacitor for energy harvesting.	**KPI2** "Targeting fully self-sustaining operation through bio-harvested energy at the microwatt scale and LoRa sub-GHz long-range communication."	The supercapacitor is expected to take more than 20 hours to charge, or even 1 to 2 days.

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

The custom 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.

Goal

Validation of a simple sustainable communication protocol (uplink-only) with data from the PCB sensors.

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, the wake-up radio is not used, as it will be leveraged in a future experiments. Instead, we focus on deep-stop operation and simple data transmissions.

How

Two flowerpots containing soil, a plant and water-logged P-MFCs were connected to EcoSentinel PCBs equipped with an energy-harvesting circuit and a 10 F supercapacitor already charged (minimum voltage above 2.5 V). The end node periodically transmits data (per example, the supercapacitor voltage and temperature) to a gateway, where it is monitored using Serial Studio, a data visualization software.

Where

Côte d'Azur University (Nice, France) – Indoor controlled environment.

Expected Result

The P-MFC should provide sufficient energy to ensure optimal operation of the PCB communication protocol.

Needs / Risks

The P-MFC is a (micro)biological system whose performance depends on several environmental factors, including temperature and the microbial, organic, and chemical conditions of the soil. Consequently, energy production may vary, and there is a risk that the energy harvested will not be sufficient to sustain the P-MFC's operation in the long term.

Furthermore, regarding the EcoSentinel custom board, it is a prototype, and improvements to reduce power consumption in the various sleep modes still need to be made.

<u>Environmental dependency</u>: Power generation depends on soil and temperature conditions.

<u>Energy availability risk</u>: The harvested energy may be insufficient for sustained PCB operation.

<u>PCB optimization limitation</u>: The PCB is not yet optimized for sleep modes, leading to higher power consumption during idle periods.

Tests under T2 - Experiment 2

Table 4. T2 – *Experiment 2 – Test List*

Test #	Title	Description	KPI link	Expected results
1	Monitoring data	The custom PCB periodically transmits data to a gateway and then enters deep-stop mode. It wakes up via the RTC to send data again, powered by energy harvested from the P-MFC.	**KPI1** "Targeting fully self-sustaining operation through bio-harvested energy at the microwatt scale and LoRa sub-GHz long-range communication." **KPI2** "Communication quality of service will be evaluated with the Packet Error Rate (PER) versus distance, to assess the maximal communication distance with a PER lower than 0.1 %."	Periodic data being seen on Serial Studio and the communication survives indefinitely.

2.1.3. [T3] Task Force 3: Plant-Microbial Fuel Cell (3) – Living Biosensor (5)

- **Reason**:

  The activity was motivated by the need to:

  - Validate electrochemical impedance as a measurable indicator of plant–soil physiological status.
  - Determine whether two-electrode electrochemical impedance spectroscopy (EIS) is sufficient for biosensing deployment.
  - Identify stable polarization conditions compatible with energy harvesting.
  - Enable integration of electrochemical features into a simplified plant-state estimation framework.

  Given the dual role of the P-MFC (energy source + living biosensor), it was necessary to verify that biosensing measurements can be executed without compromising harvesting operation.

- **Elements**:
  - **Element 1**: Plant-Microbial Fuel Cell (P-MFC). Soil-based electrochemical cells with anode and cathode operating under biological activity.
  - **Element 2**: PalmSens4 pontentiostat electrochemical front-end used for Cyclic Voltammetry (CV) and Electrochemical Impedance Spectroscopy
  - **Element 3**: Electrode Configurations:
    - Two-electrode configuration
    - Three-electrode configuration (Ag/AgCl reference electrode)

- **Diagram**

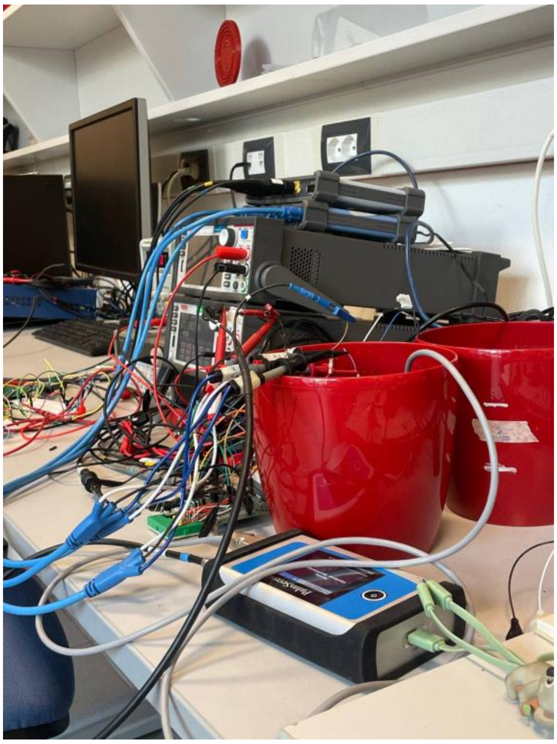

Figure 4. T3 - P-MFC and Palmsense 4 setup

- **Objectives:**
  - ***T3 – O1***: Characterize electrode behaviour under cyclic voltammetry and identify limiting electrode.
  - ***T3 – O2***: Evaluate the capability of EIS to resolve anode and cathode contributions.
  - ***T3 – O3***: Assess the impact of DC polarization point on impedance spectra and electrode stability.
  - ***T3 – O4***: Identify a stable operating point compatible with both energy harvesting and biosensing.
- **KPIs**:
  - ***T3 – KPI1***: Electrode Contribution Resolution. Clear distinction between anode and cathode impedance behaviour.
  - ***T3 – KPI2:*** Stable Polarization Point. Identification of operating points ensuring reproducible EIS.
  - ***T3 – KPI3***: Energy-Harvesting Compatibility. Demonstrate feasibility of performing EIS at a harvesting-compatible bias.
  - ***T3 – KPI4:*** Limiting Electrode Identification. Determine which electrode constrains performance.

2.1.3.1. T3 Experiments plan

<u>T3 - Experiment 1: Electrochemical Biosensing through EIS and P-MFC Analysis</u>

This experiment investigated the electrochemical behaviour of Plant–Microbial Fuel Cells (P-MFCs) as biosensing elements of plant and soil status. The activity focused on evaluating the suitability of Electrochemical Impedance Spectroscopy (EIS) and cyclic voltammetry (CV) for distinguishing anode and cathode contributions and identifying stable operating conditions compatible with simultaneous energy harvesting and biosensing.

Goal

- Feasibility of using P-MFC impedance as a biosensing indicator.
- Separation of anode and cathode contributions.
- Influence of DC polarization point on impedance spectra and electrode stability.
- Identification of a stable polarization point compatible with energy harvesting.

The experiment validates the "Plant impedance signal" hypothesis, confirming that impedance behaviour reflects electrochemical and biological processes in the soil–plant system.

How

The following experimental steps were performed:

- Construction and stabilization of P-MFC setup.
- Cyclic Voltammetry (CV) scans at 0.001 V/s using PalmSens4 to analyse polarization stability.
- Initial 5-minute discharge to eliminate capacitive reconnection current.
- Identification of 600 mV as a stable OCV reference value.
- Execution of two-electrode EIS at:
  - OCV, -0.1 V, -0.2 V, -0.3 V, -0.4 V
- Execution of three-electrode EIS:
  - Separate anode and cathode characterization.
  - Ag/AgCl reference electrode positioning near working electrode.
- Frequency sweep: 50 mHz → 1 MHz, 10 mV AC perturbation.

Where

UniTn laboratory (Trento, Italy) – Indoor controlled environment.

Expected Result

- The cathode is the limiting electrode in the tested configuration.
- Two-electrode EIS cannot resolve individual electrode contributions.
- Three-electrode EIS clearly distinguishes anode and cathode impedance behaviour.
- Polarization point significantly affects impedance spectra.
- Only OCV and OCV – 0.4 V provide stable and replicable EIS conditions.
- EIS at OCV – 0.4 V is compatible with simultaneous energy harvesting and biosensing, avoiding long OCV recovery delays.

These results confirm the feasibility of integrating energy harvesting and biosensing within the same P-MFC operating regime.

Needs / Risks

- DC polarization stability is critical for reproducible EIS.
- Capacitive currents after reconnection affect early measurements.
- Three-electrode configuration is required for accurate biosensing analysis.
- Temperature and moisture control are necessary for repeatability.

Tests under T3 - Experiment 1

Table 5. T3 – *Experiment 1 – Test List*

<table>
<tr><th>Test #</th><th>Title</th><th>Description</th><th>KPI link</th><th>Expected results</th></tr>
<tr><td>1</td><td>CV Stability Analysis</td><td>Evaluate polarization stabilization and identify limiting electrode.</td><td>KPI4
Limiting Electrode Identification. Determine which electrode constrains performance.</td><td>Cathode identified as limiting electrode.</td></tr>
<tr><td>2</td><td>Two-Electrode EIS</td><td>Assess impedance response under different polarization points.</td><td rowspan="2">KPI1
Electrode Contribution Resolution. Clear distinction between anode and cathode impedance behaviour.</td><td>Electrode contributions not distinguishable.</td></tr>
<tr><td>3</td><td>Three-Electrode EIS</td><td>Separate anode and cathode impedance contributions.</td><td>Clear distinction between anode and cathode behaviour.</td></tr>
<tr><td>4</td><td>Polarization Stability Assessment</td><td>Evaluate electrode drift and stability at different bias points.</td><td>KPI2
Stable Polarization Point. Identification of operating points ensuring reproducible EIS.
KPI3
Energy-Harvesting Compatibility. Demonstrate feasibility of performing EIS at a harvesting-compatible bias.</td><td>Stable operation only at OCV and OCV – 0.4 V; OCV – 0.4 V compatible with energy harvesting.</td></tr>
</table>

3. Proof-of-Concept

In this section, the **Proof-of-Concept** [*PoC_v1*] is defined, depicting the **components** that integrates them, the **Objective/s** of the integration [*PoC_v1 – OX*], the Key Performance Indicators (**KPIs**) [*PoC_v1 – KPIX*] and the **Experiments plan** to be performed and the expected result.

- **Reason**: The purpose of PoC_v1 is to demonstrate the interoperability of the elements developed in the EcoSentinel Task Forces (T1, T2 and T3) by assembling and testing the first EcoSentinel node prototype. The PoC_v1 focuses on:
    - validating point-to-point connectivity between two EcoSentinel nodes,
    - evaluating prototype performance in terms of reliability, communication distance, and energy efficiency,
    - establishing the basis for a future scalable multi-node EcoSentinel architecture.
- **Elements**:
    - **Element 1 – Plant system (energy host):** Plant pot with a spider plant (*Chlorophytum comosum*), used as the host environment for the P-MFC system.
    - **Element 2 – P-MFC (energy harvesting system):** Plant-Microbial Fuel Cell integrated into the plant pot (Element 1), providing bio-harvested energy for the EcoSentinel node.
    - **Element 3 – Plant-assisted antenna system:** Two plant pots, each containing an Aloe plant (*Aloe vera*).
        - **Element 3a:** Plant used for signal transmission enhancement
        - **Element 3b:** Plant used for signal reception enhancement
    - **Element 4 – EcoSentinel PCB nodes (V0.3):** Two custom EcoSentinel PCBs integrating energy harvesting circuitry and communication software.
        - **Element 4a:** End device node (sensor + transmitter)
        - **Element 4b:** Gateway node (receiver)
    - **Element 5 – Antenna Boosters:** Two antenna boosters coupled to the EcoSentinel PCBs and placed on the plant leaves.
        - **Element 5a:** Transmission booster (connected to Element 3a)
        - **Element 5b:** Reception booster (connected to Element 3b)
    - **Element 6 – Data visualization system:** PC running Serial Studio (an open-source software) to visualize received data (RSSI, packet reception, sensor metrics).
- **Diagram**

  The PoC_v1 deployment consists of two EcoSentinel nodes arranged in a point-to-point communication setup.
    - One node operates as end device, performing sensing and transmission
    - One node operates as gateway, receiving and visualizing data

The system integrates:

- plant-based energy harvesting (P-MFC),
- plant-assisted antenna radiation,
- ultra-low-power wireless communication.

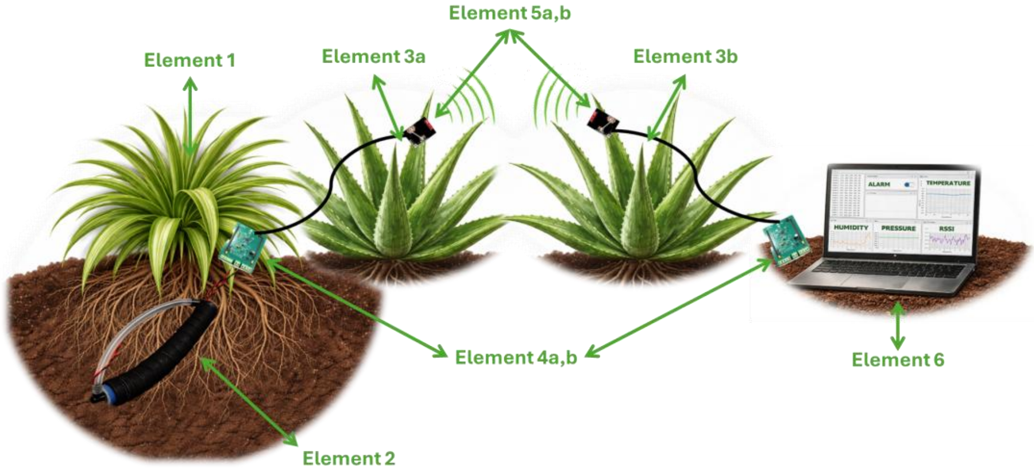

Figure 5. Poc_v1 - EcoSentinel PoC_v1 deployment diagram

- **Objective**:
  - ***PoC_v1 – O1***: To deploy and validate the first alpha EcoSentinel system composed of two interconnected EcoSentinel (PoC_v1) nodes, enabling self-powered sensing and wireless communication.
    The system comprises:
    - a self-powered sensing node, integrating a custom EcoSentinel PCB (V0.3), a Plant-Microbial Fuel Cell (P-MFC) as the energy source, and plant-assisted antenna boosting for transmission,
    - and a receiver/gateway node, based on the EcoSentinel PCB and plant-assisted antenna boosting for signal reception and data interfacing.
- **KPIs**:
  - ***PoC_v1 – KPI1***: **Functional validation of the EcoSentinel prototype node**

    The PoC_v1 experiment aims to demonstrate the successful integrated operation of the EcoSentinel system, including plant-based energy harvesting, PCB activation, point-to-point wireless communication between two prototype nodes, and gateway-side data reception and visualization.

    Additionally, the experiment will enable the extraction of relevant Figures of Merit (FoM), including:

    - RSSI (dBm),
    - transmission rate (packets per second),
    - operation time (seconds),
    - system response under parametric stress conditions.

3.1. PoC_v1 Experiments plan

<u>PoC_v1 - Experiment 1: Short-term validation of EcoSentinel node-to-node connectivity under controlled indoor conditions</u>

The experiment evaluates point-to-point communication between two EcoSentinel nodes at fixed distances (2 m and 4 m), within observation periods shorter than 2 days.

Controlled indoor conditions are assumed to exclude external factors such as environmental disturbances or long-term plant–RF interactions, which are considered out of scope for this experiment.

Goal

The goal of this experiment is to:

- Validate short-term transmission success between EcoSentinel nodes,
- Assess packet delivery and RSSI stability under known conditions (line-of-sight, same room),
- Confirm Aloe-assisted antenna functionality for communication,
- Demonstrate point-to-point connectivity under controlled conditions.

This experiment contributes to the validation of the WP1 Network hypothesis, assessing whether a nature-inspired communication architecture is feasible under channel constraints.

How

The experiment is conducted by deploying a self-powered EcoSentinel sensing node and a receiver/gateway unit, composed as follows:

EcoSentinel sensing node:

- P-MFC-based energy harvesting system,
- EcoSentinel PCB (V0.4) as the processing and communication core,
- Aloe leaves used as transmission radiators using Antenna Boosters.

Receiver/gateway unit:

- External power supply (computer-based),
- EcoSentinel PCB (V0.4) as the processing and communication core,
- Aloe leaves used as reception radiators using Antenna Boosters.

Where

Côte d'Azur University (Nice, France) – Indoor controlled environment.

Expected Result

- Reliable data transmission and visualization at 2 m and 4 m (line-of-sight),
- Stable RSSI behaviour with expected attenuation over distance,
- Successful extraction of Figures of Merit (FoM),
- Demonstration of short-term viability of Aloe-assisted communication,
- Confirmation of P-MFC capability to sustain 1 frame/s transmission rate.

Needs / Risks

- Energy availability: P-MFC must sustain continuous operation (risk of depletion of the storage element during testing),
- Controlled environment: excludes environmental variability (wind, humidity, long-term effects),
- Short observation window: limited to short-term validation only,
- Manual setup constraints: the coaxial cable connecting the antenna booster to the PCB may have influenced the results by unintentionally acting as an antenna or enhancing signal propagation, potentially masking the actual contribution of the plant-based radiator.

- **Tests under PoC_v1 - Experiment 1**

Table 6. PoC_v1 – *Experiment 1 – Test List*

Test #	Title	Description	KPI link	Expected results
1	2 m transmission	Receive/visualize data at 2 m (LoS)	**KPI1** Prototype node functionality	Reliable communication, stable RSSI, successful visualization. Expected RSSI decrease.
2	4 m transmission	Receive/visualize data at 4 m (LoS)		

4. Conclusions and next steps

Deliverable D3.1 has defined the **system-level design of the EcoSentinel Proof-of-Concept (PoC)**, establishing a coherent integration framework that brings together the core technological components developed in WP1 and WP2.

Through the definition of three complementary task forces—**Plants as Antennas (T1), Plants as Energy Sources and Communication Systems (T2), and Plants as Biosensors (T3)**—this deliverable structures the EcoSentinel architecture into modular yet interdependent subsystems. Each task force specifies its objectives, system elements, Key Performance Indicators (KPIs), and experimental planning, ensuring consistency across disciplines and alignment with project goals.

A key outcome of this work is the definition of the **PoC_v1 architecture**, which integrates:

- plant-assisted antenna systems,
- bio-harvested energy through Plant-Microbial Fuel Cells (P-MFCs),
- ultra-low-power sensing and communication modules.

This architecture formalizes the concept of a **plant-based, self-powered sensing node**, where biological processes are intrinsically linked to energy generation, communication, and environmental sensing functionalities.

Following the system design defined in this deliverable, the next steps focus on **detailing, implementation, and validation of the EcoSentinel PoC**:

- **Component definition**

  Provide detailed descriptions of the individual PoC elements, including their technical characteristics and interfaces.

- **PoC implementation**

  Integrate the different subsystems (antenna, P-MFC, sensing, and communication) into a unified prototype.

- **Validation and results**

  Test the integrated PoC and evaluate its performance against the defined KPIs.

- **System refinement**

  Use insights from testing to improve integration and prepare future iterations.

References

Nock, C. A., Vogt, R. J., & Beisner, B. E. (2016). Functional Traits. In *Encyclopedia of Life Sciences* (pp. 1–8). Wiley. https://doi.org/10.1002/9780470015902.a0026282

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Abbreviations

Acronym	Description
AC	Alternating Current (electrical current type)
Ag/AgCl	Silver / Silver Chloride (reference electrode used in measurements)
CV	Cyclic Voltammetry (electrochemical measurement technique)
D3.1 / D3.2 / D3.3	Deliverable 3.1 / 3.2 / 3.3 (official project reporting documents)
dB / dBm	Decibel / Decibel-milliwatt (units of signal strength and power)
DC	Direct Current (electrical current type)
EC	European Commission
EIS	Electrochemical Impedance Spectroscopy (biosensing measurement technique)
EM	Electromagnetic (related to radiation or fields)
EU	European Union
F	Farad (unit of electrical capacitance)
FoM	Figures of Merit (quantities used to characterise system performance)
Fv/Fm	Variable fluorescence / Maximum fluorescence (chlorophyll fluorescence ratio)
Hz	Hertz (unit of frequency)
ISM	Industrial, Scientific and Medical (unlicensed radio frequency bands)
KPI / KPIs	Key Performance Indicator(s) (performance measurement metrics)
LoRa	Long Range (low-power wide-area network communication protocol)
LoS	Line-of-Sight (unobstructed transmission path between nodes)
MCU	Microcontroller Unit (processing chip)
MHz / mHz	Megahertz / Millihertz (units of frequency)
mV / V	Millivolt / Volt (units of electrical potential)
MΩ	Megaohm (unit of electrical resistance)
OCV	Open-Circuit Voltage (voltage measured when disconnected from a circuit)
OJIP	Origin, J-step, I-step, Peak (chlorophyll fluorescence transient stages)
PaA	Plants as Antennas (EcoSentinel task force concept)

PaB	Plants as Biosensors (EcoSentinel task force concept)
PaCS	Plants as Communication Systems (EcoSentinel task force concept)
PaES	Plants as Energy Sources (EcoSentinel task force concept)
PC	Personal Computer (used as a data visualisation system)
PCB	Printed Circuit Board (electronic hardware component)
PEA	Plant Efficiency Analyser (equipment used to measure photosynthetic health)
PER	Packet Error Rate (metric for communication quality of service)
PI	Performance Index (photosynthetic performance metric)
P-MFC	Plant-Microbial Fuel Cell (bio-energy harvesting system)
PoC / PoC_v1	Proof of Concept / Proof of Concept, version 1 (prototype demonstration)
PSII	Photosystem II (protein complex in light-dependent reactions of photosynthesis)
RF	Radio Frequency (wireless transmission wave type)
RSSI	Received Signal Strength Indicator (measure of received radio signal power)
RTC	Real-Time Clock (electronic component for timekeeping and wake-up functions)
SMA	SubMiniature version A (coaxial RF connector type)
T1 / T2 / T3	Task Force 1 / 2 / 3 (project working groups)
UniCA	Université Côte d'Azur (partner institution)
UniTn	University of Trento (partner institution)
WP / WP1 / WP2	Work Package / Work Package 1 / 2 (project structural divisions)

EcoSentinel

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