Biohybrid systems for environmental intelligence on living plants: WatchPlant project

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ABSTRACT

New challenges such as climate change and sustainability arise in society influencing not only environmental issues but human's health directly. To face these new challenges IT technologies and their application to environmental intelligent monitoring become into a powerful tool to set new policies and blueprints to contribute to social good. In the new H2020 project, WatchPlant will provide new tools for environmental intelligence monitoring by the use of plants as "well-being" sensors of the environment they inhabit. This will be possible by equipping plants with a net of communicated wireless self-powered sensors, coupled with artificial intelligence (AI) to become plants into "biohybrid organisms" to test exposure-effects links between plant and the environment. It will become plants into a new tool to be aware of the environment status in a very early stage towards in-situ monitoring. Additionally, the system is devoted to be sustainable and energy-efficient thanks to the use of clean energy sources such as solar cells and a enzymatic biofuel cell (BFC) together with its self-deployment, self-awareness, adaptation, artificial evolution and the AI capabilities. In this concept paper, WatchPlant will envision how to face this challenge by joining interdisciplinary efforts to access the plant sap for energy harvesting and sensing purposes and become plants into "biohybrid organisms" to benefit social good in terms of environmental monitoring in urban scenarios.

KEYWORDS

Environmental intelligent monitoring, biohybrid systems, sap, AI, energy management.

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1 Introduction

The percent of people living in urban areas has risen in the last years and agreeing with this trend, 68% of the world population will live in cities by 2050, according to UN's estimates (Dye, 2008). Population exposure to hazards associated with high-density populated cities will rise as well, constituting a problem for both, human health directly, and for the environment contributing to climate change. (Dye, 2008; Harlan, 2011; West et al., 2016). Currently, air pollution methods are resource consuming (energy, space, etc.), hazardous themselves (e.g., poisonous materials) and expensive, so they cannot be easily scaled up to create a dense net of measurement stations distributed in large urban areas in a decentralized way (Snyder et al., 2013). WatchPlant aims to address this challenge by the use of plants as new "well-being" sensors of pollution in urban areas by the equipment of the plants with different sensors to monitor plants parameters in an early stage by plant's response detection, creating biohybrid systems capable of energy-efficient sensing of pollutants thanks to its self-deployment, self-awareness, adaptation, artificial evolution and their AI capabilities. To achieve this goal, WatchPlant aims to access phloem sap of the plant by the use of microtechnologies and fluid modelling since this fluid represents the most interesting fluid in vegetal organism because it has a valuable info hardly explored related with plant long distance signaling. These microtechnologies will be integrated in the system to use sap for sensing purposes, but also for energy harvesting, using sap as a radically new energy source for self-powered sensors development. WatchPlant devices will be distributed in urban scenarios in a decentralized way, they will interact locally between them and in a further step, this system is envisioned to be connected to the cloud to make it accessible to global models and citizens (Figure 1). In this sense, several energy consuming features as the communication between sensors nodes in the network should be address for energy efficiency purposes. To this aim, WatchPlant will apply multiple modalities of communication (BLE, GSM, WiFi) depending on the network topology and the system status. Furthermore, in-situ data processing will be applied, so that the minimum amount of information should be exchanged within the network nodes which constituted a challenged for IT technologies together with data processing and application of AI for social good (Figure 1). In WatchPlant, these major challenges will be addressed with novel concepts focused on energy-efficiency systems and new phytosensing implementation, including chemical sensors for sap, but also sensors for relevant plant features such as photosynthesis activity, sap flow and electrophysiology (Volkov, 2012; de Toledo et al., 2019; Oyarce et al., 2010). Additionally, these plant features will be combined with environmental sensors for temperature, humidity, a number of relevant gases (e.g., NO_2, O_3, SO_2), and particulates (e.g., PM2.5, black carbon, ultra-fine particles) to obtain a complex data matrix of plant and environment features that should be processed later on. Thus, this net of sensors will be integrated into the WatchPlant device including as well communication capabilities to create a distributed and decentralized system based on AI and machine learning for self-awareness capabilities (Mazarei et al., 2008; Chattoraj et al., 2001).

In this way, and by the use of microtechnologies to address under-sampled parameters and then, new strategies for data collection, distributed information, AI and machine learning, WatchPlant aim to create a resilient, reliable and environmentally responsible in-situ monitoring biohybrid system. It is envisioned to impact social good in terms of urban environment pollution surveillance, providing complete and real-time data collection for evidence-based policies and timely interventions to protect the health of citizens and environment. In this concept paper, the strategy to create biohybrid systems is proposed thanks to the use of networks, gather data over space and time, self-organizing sensor networks, machine learning, and evolutionary computation to interpret and maximize an energy-efficient exploitation of the available data (Pereira et al., 2018) to use plants as a new source of under-sampled information about the environment.

2 Plants as new source of information for IT

2.1 Alive sensors: plants as well-being sensors

The system for plant monitoring is based on CYBRES EIS spectrometer and intended for the sensing of electric, ionic and physiological responses of plants to external stimuli. The system measures biopotentials, tissue conductivity at different frequencies, analyses spectral responses to specific ionic groups (e.g. in plant sap) and allows to investigate the effects of frequency shift in tissue response. In addition to it, these phytosensors can also perform an electrical or light stimulation of plants (blue/red light stimulation) to measure plant reaction to this external stimulus. Signals are received by needles - or surface- electrodes and the gathered real-time data (with time stamps) is recorded into the internal flash memory, transmitted to a computer, or written as html-pages for the online data plot in Internet. To improve the accuracy of measurements, the system is thermally stabilized at the PCB level. In addition to electrophysiological sensors, the system is equipped with 3D accelerometer/magnetometer, real time clock, EM power meter, temperature/humidity/pressure/light and air quality (CO_2, O_3, PM1-2.5-10, NO_2) and voltage sensors for monitoring at the same time both, plants and environmental conditions during long-term experiments. USB interface is used for data transmission and for powering the device. In this context, although electrophysiological signals have been related to several plant responses to the environment (Galle et al., 2015; Sukhov et al., 2019) it is still difficult to interpret it to implement a decision support system able to take actions. For this reason, the application of AI in WatchPlant will be used to search for hidden relationships between the whole gathered data to provide an hypothesis to apply process-based models based on plant physiology.

Additionally, one of the most innovative concepts of this project is related to the phloem sap sensing, where a wide number of compounds obtained in the photosynthesis are present. Xylem has been extensively addressed and studied for different applications. However, there are only one approach to access specifically the phloem sap (Ono et al., 2018) but it will no address long terms exposure for real time measurements. This new concept can become into a big step ahead for the use of plants as well-being sensors since it would be possible to obtain new information about the plant long distance signaling for specific responses. In this sense, WatchPlant will provide a strategy to address the phloem sap and take that valuable information content by biomarkers sensing and ionic dynamics to provide information of the very early stage of plant responses thought biomarkers electrochemical detection in phloem sap.

The phloem sap is found in the plant's phloem tissue, located close to the surface of the plant stem. The tissue consists of columnar structures, called sieve tubes, running along the stem. The sieve tubes, with diameters in the order of tens of micrometers, serve as conduits for transporting the sap. To access the phloem sap, the phloem tissue must be penetrated while eluting minimal defense response from the plant. The defense response naturally occurring upon puncturing a sieve tube element is coagulation, leading to a blockage, which prevents the plant from loss of the nutrient-rich sap and pressure of the sieves. To successfully perform continuous sampling in such setting, we will design a minimally-invasive microneedle device to precisely access the phloem tissue, while simultaneously delivering an anticoagulating agent to the affected area. The phloem sap will then be aspirated by capillary pumping into a collection chamber and further downstream, to the sensing components and the enzymaic BFC. One example of a device capable of collecting phloem sap has been previously demonstrated (Ono *et al*., 2018). This device allows for phloem sap collection, but does not address the plant's defense mechanisms, which is crucial for continuous sampling. Moreover, it relies on active sensing for locating the phloem sap, which would ideally be avoided to allow easy, large-scale deployment. Additionally, fluid simulation will be addressed

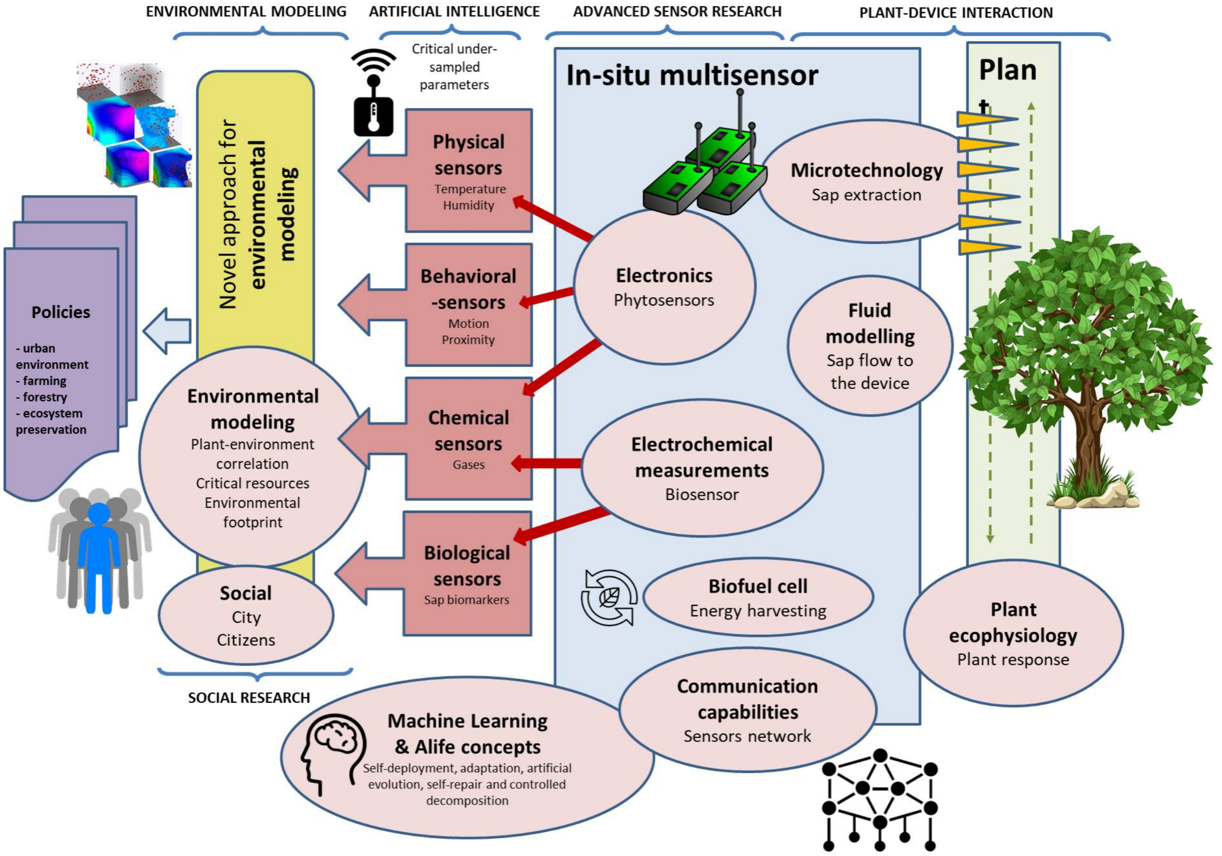

Figure 1. Schematic overview of WatchPlant project for biohybrid development including plant-device interaction, advanced sensor research, AI methods, and environmental modeling for social good (Hamman, H. et al. 2021).

in WatchPlant to maximize success in sap extraction by simulating the interaction between plant and WatchPlant device to create the biohybrid systems. Additionally, this system, due to the presence of the BFC, would be able to use sap, not only for sensing but for energy harvesting, using sap as a radically new energy source. BFC together with additional clean energy sources as solar cells, and AI for energy management will become the WatchPlant device into an efficient self-powered device operating in an eco-friendly scenario by the use of clean energy harvesting.

2.2. New source of information for environment understanding

As mention before, sap could constitute a powerful fluid to address under-sampled parameters about plant status by the measure of new biomarkers and ionic dynamics. However, it presents several limitations such as the continuous access to the plant for a long-term use as well as the interpretation of the signals according to the physiological state of the plant. In this sense, it has been already proved that simple changes in the environment such as turning on a light source or temperature fluctuations changes the dynamic of the plant's physiology. Consequently, the reaction can be observed in the measured data. Similar to this effect many other physiological and environmental stimuli could be monitored to determine the environmental circumstances, by measuring specific biomarkers or the correlation between different types of data output all correlate with each other. In this sense, WatchPlant will make an innovative use of the sensor outputs inferring physiological variables which can be used to fully understand the response of the plant to the environment. As an example, it has been reported the use of sap flow and leaf turgor sensors to infer stomatal conductance and photosynthesis in continuous and autonomous mode in the field (Hernandez-Santana et al., 2016; Rodriguez-Dominguez et al., 2018). Then, why is important to translate sensor outputs into physiological variables? Because it is known that stomata and photosynthesis respond to urban pollutants (Takahashi et al., 2020; Szkop, 2020; Xu et al. 2021) so, if WatchPlant is able to infer stomatal conductance and photosynthesis, and we know there is a mechanistic link between them and any abiotic stress, it would be possible to correlate our measurements with urban environment changes. In this sense, many studies support this approach: ozone causes a mean yield loss of 11.3% in six major food crops across the world, and this negative effect has been related to the negative effect of this pollutant on stomatal conductance and photosynthesis (Wu et al., 2021). Similarly, the particulate matter provokes a physical barrier for leaf gas exchange and in urban trees in Malaysia photosynthesis and stomatal conductance were reduced by 20-50% affecting tree growth severely (Philip, 2001). Thus, the challenge in Watchplant regarding advance sensor research is related to in situ measurements and post processing that data. In this sense, this pull of collected data open a space for new sources of information for environment understanding since information is gathered directly from living organisms (which keeps alive during the whole process) in contrast to isolated measurements of one sensor.

In this sense, on one hand, process-based models will be used in WatchPlant, when possible, to determine the relation between the plant and the environment. Examples of such models are the hydromechanical model of stomatal conductance (Buckley et al., 2003) and the biochemical model of photosynthesis (Farquhar et al, 1982). Both have been used successfully in agriculture to apply deficit irrigation strategies in fruit tree orchards in semi-arid regions (Diaz-Espejo et al., 2012; Hernandez-Santana et al., 2018). The strong point in the use of process-based models is that we can filter out the effect of a changing environment (light, temperature, air humidity, etc) in a mechanistic way and remove their confounding effects on the overall response to obtain a closer output related to the pollutant we are interested in. On the other hand, due to the difficulties of cause-and-effect models to describe with an analytical model-based approach the plant response in a due environment change, a data-based machine learning strategy will be also address in WatchPlant.

3 Plants as bio-hybrid organisms

3.1 Distributed sensor network

To achieve the goal of develop a dense net of measurement stations distributed in large urban areas in a decentralized way several advances in distributed sensors network should be carried out. The specific contribution of Watchplant in distributed AI aims to extend the overall system with 'add-on' features of distributed sensor network that increase the system's resilience and data quality. In particular, malfunctioning sensors and lost connections should be identified and self-repaired, and similarly, under-sampled regions and low data quality should be detected so that the sensor network reacts as a whole via self-organizing duty cycles, sensor replacement requests, and model-aided data processing. Networking and topology control methods have emerged in an attempt to answer such conditions that are more likely to happen in real applications that encompass various disturbances. It has been shown that information exchange between nodes has a direct impact on the system performance, including convergence speed and effectiveness of cooperation and distributed data gathering. However, a broad information exchange requires increasing the number of communication links (i.e. energy), which can lead to deteriorated control, for example in case of delays due to token exchange. In other cases, increasing the number of communication links is not even possible, with a given communication network, usually due to energy constraints. Additionally, the effects that outside and inside disturbances and shocks have on the system performance should be considered if particular method strives to be implemented in a real world scenario.

The communication topology of the sensor network can, in many cases, be described by an undirected graph, where each link in the network represents a communication channel between two nodes. In that case, graph theory mathematical formalism can be used to provide insights into the global properties of the underlying network topology. Furthermore, this enables adaptation of the system communication topology to retain the desired functionality even under disturbances caused by either intrinsic source (e.g. malfunction of a communication link), or outside source (e.g. adversarial attack on a communication link), a property commonly known as resilience. In general, two questions arise: i) *how to determine*, and ii) *how to maintain* the structure/connectivity of the network. Answers to these questions should provide techniques applicable for real-time deployment of sensors in a distributed manner which is the core of WatchPlant in terms of network of the distributed biohybrid. The used methods should consider not only keeping the underlying communication graph connected, but also taking into account the cost of maintaining such connectivity. In case of wireless networks, the cost comes in the form of energy required to communicate, and the computation time for an algorithm execution. Clearly, the notions of cost and connectivity level introduce contradictory objectives in the network connectivity control. In order to increase the network resilience (decrease the time required to return to the connectivity level prior to disruption), the number of links should be increased. On the other hand, increased number of links would in general increase the cost. Hence, the topology design, conciliating the algebraic connectivity maximization, and network cost minimization, will be considered as a convex optimization problem.

On the other hand, WatchPlant aims to design energy efficient biohybrid systems based on full clean energy harvesting by the use of solar cells and BFCs. Thus, from the energy efficiency point of view, the most appropriate network topology would be the one that achieves the desired algebraic connectivity with the minimal number of links. This argument holds for attacks as well, since the lower number of communication links enables less opportunity of the attack. However, minimal number of links makes the system sensitive to communication failures, since the loss of a single link might cause the loss of the connectivity property of the underlying graph. Hence, WatchPlant will research in new communication strategies to achieve the appropriate value of the connectivity, which is a trade-off between a robust, secure, and energy effective underlying communication graph, which depends on the number of nodes, the number of links, the network topology, and finally, on the intended application.

3.2 AI for energy management and data proccessing

According to our knowledge, the approach proposed in this project will constitute the first approach using phloem sap from living organism for energy harvesting. However, BFCs to develop self-powered sensors have been used in advance sensor research, especially in the clinical field, where the maximum expected energy harvested is in the range of 0.4 and 1.5 mW/cm^2 (Rasmussen et al., 2016; Hijaz et al., 2014) which hinder their real applicability to power high demanding energetic devices such as the proposed biohybrid systems. For this reason, WatchPlant propose new strategies in advance sensor research to design more efficient BFCs using very conductive materials but also the combination of BFCs with solar cells to ensure the independency of this biohybrid system from potentially external energy sources for its long-term operation, neither qualified user, being an in situ, autonomous and portable self-powered device using sap as radically new energy source.

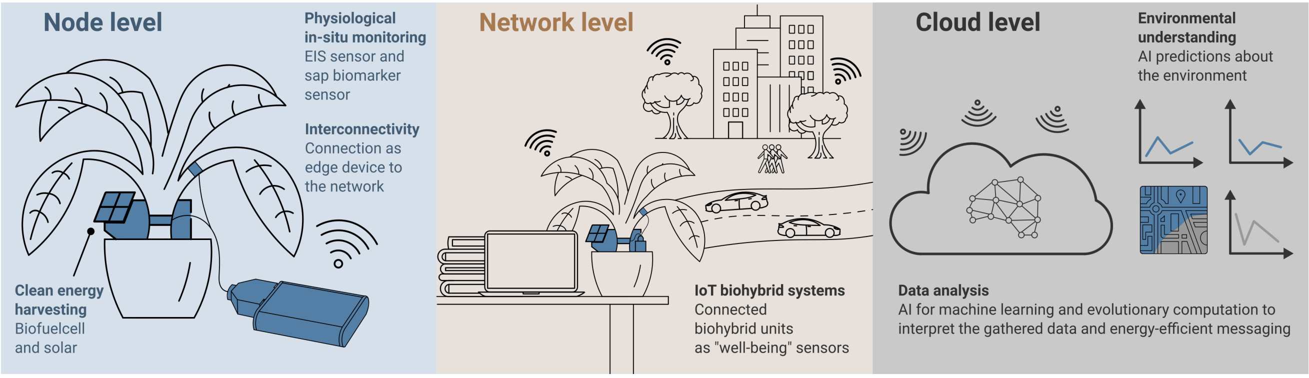

Figure 2. Schematic overview of WatchPlant IT technologies regarding data collection and energy harvesting (node level), communication capabilities between biohybrid systems (network level) and AI capabilities and data access to citizens (cloud level).

As mentioned earlier, the electronic components in the sensor network will harvest energy from the environment and natural plants (e.g., based on extracting sap). Still, energy will be scarce and fluctuating, therefore, one of the main challenges is to keep the sensor network being energy-efficient. To achieve this challenge, Watchplant plans to use methods from AI to optimize primarily radio communication, which is the main energy user, but also the required computational efforts. To optimize radio communication, the sensor nodes should make clever decisions about whether, what, and when to communicate. Using methods from machine learning (ML), the system can acquire knowledge from the phytosensor's measured time series, derive a model of the system, and try to predict future measurements. We know that the sensor data obtained from plant experiments is a complex and difficult to understand signal that shows both stochastic and deterministic dynamics. For example, the electrophysiological and tissue-impedance electric signals of plants are suitable candidates for the analysis in a model-based approach with ML (Chatterjee et al., 2015, Pereira et al., 2018).

Key research questions connected to developing self-powered sensors with minimal energy consumption and strategies to work with low-density power are: (i) What are suitable statistical/ML models that can be trained online (i.e., after deployment) or offline to predict this sensor signal? (ii) Which type of model will make consistent predictions? (iii) How can we usefully balance the trade-off between prediction quality and computational complexity in the network by using ML methods? The simplicity of the predictor (ML architecture) is an important concern here because our vision is to run it on resource-constrained embedded systems (cf. edge computing), such as a biohybrid system forming a complex system of interacting agents with half of them being alive (plants and humans) and half of them are constantly adapting artificial agents (sensor nodes). Once a predictive model of sufficient quality is available, it can be used to reduce the communication overhead within the network. If both sender and receiver possess an instance of the same prediction model, then the sender doesn't have to send the measured data when it was correctly predicted.

Another approach envisioned is to use methods from evolutionary computation (EC) to evolve artificial neural networks (ANNs) that compress the measured data (Marcelloni et al, 2010). The compression method can be fully adapted to a particular type of signal and could even be optimized online. This efficient compression helps to reduce the payload of communicated messages. Another interesting scenario is to use a sink (edge device) to process the time-series and to predict the measurements captured by sensor nodes. The advantage would be to decrease the frequency rate of measurement. As a consequence, the data processing and power consumption can be decreased.

4 WatchPlant impact to social good

The developed biohybrid organisms will provide new data for IT for social good, using plants as new source of information in a distributed/decentralized way by communication capabilities between nodes which will interact locally to share data and to optimize their communication and onboard local models. Thus, an intelligent net of sensors will be connected in a network that minimizes the communication payload and the computational complexity, possibly even using online adaptation thanks to AI. The sensor network would be highly adaptive and could maintain a high degree of (energy) autonomy. Afterwards, is worth to highlight that data centralized in specifics nodes would need to end up in a cloud to make it accessible to the global models and citizens in a further step (Figure 2).

Later on, when the data are collected, two major environmental models will be developed, tested and implemented in WatchPlant to make possible the impact to social good. In a first stage a statistical modelling task will evaluate the fluctuations of air pollutants to contrasted physiological variables, like stomatal conductance, photosynthesis and parameters of the sap, all of them measured by the developed plant sensors in situ and online. The objective is to detect the plant sensitivity to pollution. In a second stage, it will be correlated with the atmospheric concentrations of air pollutants measured with reference air quality stations and low-cost instruments (included in WatchPlant device), with changes in physiological variables and sap parameters yielded by the phytosensors. To this end conventional environmental epidemiology modelling tools used extensively in air quality and human health studies will be adapted and modified to cover the needs of our models. However, the otherwise unspecific plant response can handle their applicability in real scenarios. To address this issue, AI will be also employed to combine the use of sensor outputs with physiological process-based models to extract the relevant information in order to put the state of the monitored plant into a physiological context. Gathered data will be used to develop robust algorithms in our bio-hybrid system for signal interpretation in order to correlate and integrate it with knowledge about the physiological response of plants to pollutants or other stresses from the environment. Thus, WatchPlant will address the challenge of air quality monitoring as proof-of-concept of the new bio-hybrid system to evaluate risks of air pollution exposure for humans (using the effect of these contaminants in plants for early detection). However, it is envisioned a huge applicability of this novel eco-integrated biorobots in other plant-related fields such as agri-food industry for precision agriculture, silviculture or ecosystems preservation, between others. This advance will support citizens to face the challenges of our future cities with a positive impact in key aspects such as climate change and early reaction to pollutants, which can have a huge impact on human health and economy in many scenarios. In summary, WatchPlant sensing capabilities combined with its efficient energy use provided by the clean self-powered capabilities, could lead to increased efficiency and competitiveness, social inclusion, new business models and opportunities, and renewal of governance models through improved participation of society for specific and efficient environment management in the upcoming years.

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