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Sensors in agriculture: towards an Internet of Plants

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To ensure a sustainable future and combat food scarcity, we must boost agricultural productivity, improve climate resilience and optimize resource usage. There is untapped potential for dense wireless sensor networks in agriculture that can increase yields and support resilient production when linked to smart decision and control systems.

Sensor technologies have advanced rapidly and are now widely adopted in consumer electronics. However, their adoption in agriculture is proceeding at a slower pace. Even in modern greenhouse horticulture there is often only one sensor box per ~1,000 m^2, measuring environmental parameters like temperature, humidity, CO_2 concentration and irradiance. The adoption of dense agricultural sensor and actuator networks can substantially enhance agricultural productivity and climate resilience, while also reducing emissions and the use of natural resources. These sensor networks, referred to as the Internet of Plants (IoP), can serve as the eyes, nose and touch of farmers, capable of measuring parameters that cannot be detected by humans (Fig. 1). Functional IoP sensor networks must be able to sense various environmental parameters and monitor plant physiology at high spatial and temporal resolution. By coupling IoP networks with systems that control plant climate, irrigation and nutrition, they can provide farmers with valuable insights, actionable advice and even enable autonomous crop management. For IoP networks to be widely adopted, they need to be low cost, easily implementable, robust and effective. However, proving their effectiveness is time-consuming and difficult, which may explain their slow adoption rate. Here, we present a vision on the future of IoP and discuss the challenges on the route to implementation.

Sensing environmental parameters

Plant growth is strongly affected by the environment[1], and accurate, high-resolution information on environmental parameters is essential for predicting and managing biomass production. Atmospheric sensors measuring air pressure, temperature, irradiance and humidity are widely available at low cost (~€1 per sensor) as they are integrated in mobile devices. Gas sensors for measuring CO_2 levels and volatile organic compounds are also becoming available, at somewhat higher costs (~€10 per sensor), mainly used for indoor climate control. To assess airflow rates within plant canopies, anemometers can be used at moderate costs. Similarly, the rooting medium can be evaluated using soil moisture sensors that use electrical, gravimetric and microwave techniques. Conductance and optical techniques can provide insights into soil pH and ionic composition. There is a wide range of sensor technologies to meet the requirements of plant sensing networks. However, ensuring reliable operation while keeping costs sufficiently low remains challenging.

Sensing plant physiology

Advances in human health sensors, such as smartwatches measuring various vital signs, have promoted healthier lifestyles. Similarly, emerging plant physiology sensors in agriculture have the potential to revolutionize crop production. These sensors, once fully developed and implemented, can provide real-time insights into crop responses to the environment, detecting stressors that reduce growth. Examples of current crop monitoring sensors[2] include weight measurement devices, sap flow sensors for assessing plant transpiration, stem diameter sensors, multispectral cameras and chlorophyll fluorescence analysis equipment. Electrophysiological[3] and ultrasound[4] sensors are emerging for characterizing plant health and detecting biotic and abiotic stresses. Electronic noses that can smell or taste diseases, insect infestation and/or plant defensive chemicals have the potential to enhance food safety, especially with the rising occurrence of extreme weather events due to climate change that can amplify agricultural pests.

Wireless sensor networks

Achieving high spatial resolution is crucial to accurately represent variable conditions in the field. To enable dense sensor networks, ease of installation and operation are key. Ideally, sensor modules should operate autonomously and communicate wirelessly, using low-power electronics powered by batteries, energy-harvesting modules that could use solar power or more advanced methods based on electrochemical energy[5] derived from the plant. IoP networks can use communication techniques and antennas designed for Internet of Things applications and might also benefit from synergy advantages, like using the plant itself as part of the antenna[6]. It is challenging to mount the sensor modules in the field without disrupting normal farming operations. Potential solutions include installing dedicated posts near crops, attaching sensor modules to the crops themselves or even developing biodegradable sensor modules that are disposed of after harvest. Currently, greenhouse or vertical farm settings offer the most favourable conditions for implementing such sensor networks[7].

Another emerging approach involves using sensor-equipped mobile robots or drones for crop monitoring. This approach requires fewer sensors, allowing for higher sensor costs and lower installation expenses. However, this approach may not be suitable for sensors that need to be mounted directly on the plant, such as sap flow meters, and may result in lower time resolution of the data due to reduced sampling frequency.

Viable implementation of IoP

The development of a network that continuously measures a wide variety of environmental and plant-related parameters is itself

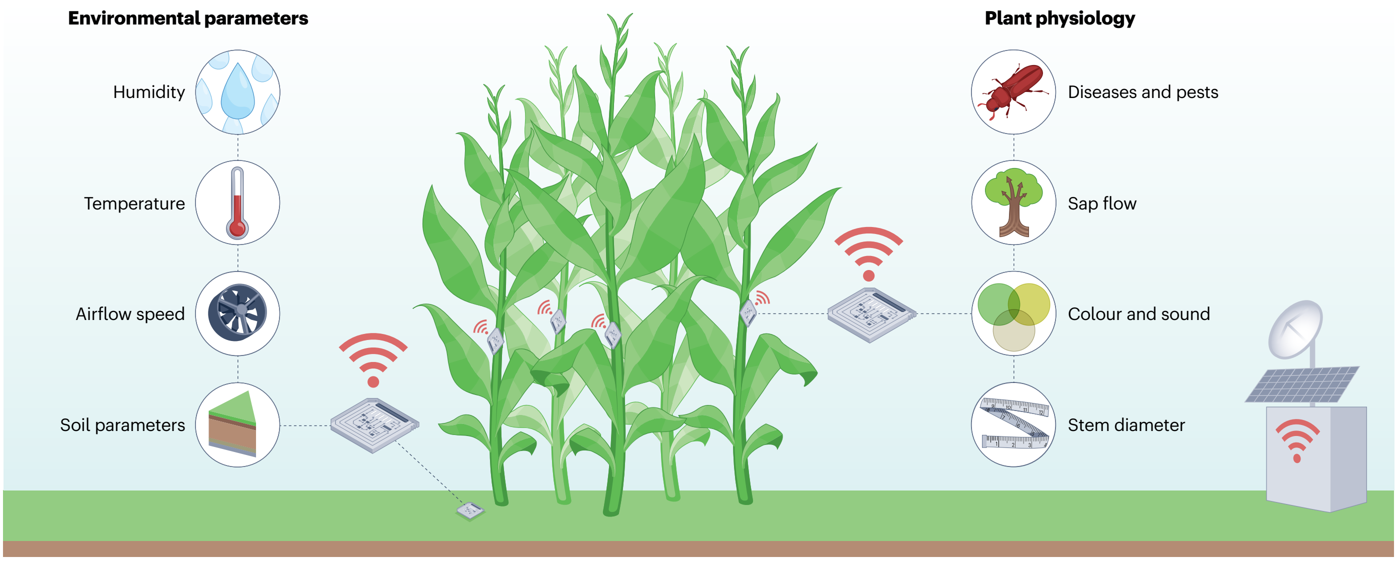

Fig. 1 | Envisioned architecture for the Internet of Plants. Sensor modules comprising environmental sensors, physiological sensors and dedicated electronics for power and communication are distributed throughout the crops and wirelessly connected to a central processor.

challenging. Another notable difficulty lies in effectively using this information to enhance crop yield. To address this challenge, increased collaboration is needed among plant scientists, farmers, electrical engineers and sensor experts. Projects like the 4TU Plantenna project should be encouraged to facilitate such collaborations. Given the complexity of genotype–environment interactions, it is challenging to predict the exact relationship between environmental parameters and plant growth. Therefore, comprehensive studies using dense sensor networks are needed. Such studies will determine the predictive value of various sensors, enabling sensor technologists to focus on further development of the most useful agricultural sensors.

Another complex question is how to use IoP sensor data to optimize crop growth conditions and maximize yields in an economically and environmentally sustainable manner. This question could be addressed through IoP studies that involve the development of advanced plant growth models, including those using machine learning approaches[8]. The answers to these questions will depend on plant physiology, sensor cost and type, but also on the control parameters for optimizing growth conditions.

Outlook

In the coming decades, we anticipate a gradual realization of various implementations of IoP networks in agriculture. Sensor technologies will undergo maturation and thorough testing, following an evolutionary process in which agricultural sensors providing the most valuable data will survive and evolve. There will be ongoing advancements in the knowledge and technology required to integrate multiple sensors with control strategies, enabling collection of precise plant data at a resolution that optimizes crop yields. Ultimately, these advancements will result in context-dependent and customized agricultural sensor solutions tailored to user needs. These collective efforts will substantially increase the adoption of sensors in agriculture, ensuring reliable and sustainable food production in the twenty-first century and beyond.

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Author contributions

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Competing interests

The authors declare no competing interests.